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PERFORMANCE INVESTIGATION OF A SOLAR POWERED THERMOELECTRIC REFRIGERATOR

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ABSTRACT

This paper describes the development stages and performance of a solar powered thermoelectric refrigerator. It is carried out by installing a conventional thermoelectric refrigerator in a stand alone photovoltaic system for household usage. This photovoltaic driven refrigerator is powered by a field of solar panels, a battery bank, a solar charge controller, and an inverter. In this project, the output power of the photovoltaic system and the capability of the battery bank are determined. A compact thermoelectric refrigerator of 22 watts is applied to be investigated in respect to cooling effect produced. To make the device portable, daytime use and nighttime use of the refrigerator are treated in different ways. The effect of door-opening upon the cooling temperature produced by the photovoltaic driven thermoelectric refrigerator is investigated too. In order to efficiently operate this solar powered refrigerator, the sizing of this stand-alone photovoltaic system and the optimum tilt angle of the photovoltaic array must firstly be determined to maximize the electricity generation for matching the load requirement.

Keywords: Thermoelectric refrigeration, Solar powered refrigerator, photovoltaic system

NOMENCLATURE

B_P	Number of battery in parallel
B_{rc}	Battery capacity (Ah)
B_S	Number of battery in series
B_{SC}	Capacity of selected battery (Ah)
B_T	Total battery
$(DOD)_{\max}$	Maximum depth of discharge of battery
D_S	Battery autonomous day
$E_{C(Ah)}$	Collected load in ampere-hour (Ah)
$E_{d(Ah)}$	Load demand in ampere-hour (Ah)
$E_{d(Wh)}$	Energy demand (Wh/day)
G	Lowest daily sunshine hour
I_D	Designed current hour load (A)
I_{DE}	Derated designed current (A)
I_p	Peak current of the selected solar panel (A)
I_T	Maximum current (A)
L	Latitude (°)
n	Day of the year
N_P	Number of solar panel in parallel
N_S	Number of solar panel in series
N_T	Total solar panel
P_i	Power of inverter (W)
P_{rated}	Wattage of refrigerator (W)
P_{rated_tot}	Total rated wattage (W)
q	Quantity of refrigerator
S	Tilt angle (°)
V_{nbv}	Nominal battery voltage (V)
V_{nsv}	Nominal system voltage (V)
V_p	Peak voltage of the selected solar panel (V)
α	Solar altitude angle (°)
δ	Declination (°)
ω	Hour angle (°)
η_b	Battery efficiency
η_M	Module derate factor
η_{pce}	Inverter efficiency
η_T	Temperature correction factor

1 INTRODUCTION

Most of the world's energy consumption and electricity generation is principally dependent on fossil fuel and is being used extensively due to continuous escalation in the world's population and development. On the other hand, in process of electricity generation, by means of these fuels, a number of poisonous by-products adversely affect the conservation of natural eco-system. Therefore, this valuable resource needs to be conserved and its alternatives need to be explored. In this perspective, dissemination and utilization of renewable energy especially solar energy has gained worldwide momentum since the onset oil crises of 1970s (Saidur *et al*., 2007; Shaahid and Elhadidy, 2003).

Refrigeration is closely related to the demand for cooling foodstuffs and many other commodities as a normal part of commercial domestic life. Solar refrigeration is thought of as one of the best alternatives to address this issue and it may be accomplished by using one of the refrigeration systems: vapor compression, absorption or thermoelectric refrigeration system. Thermoelectric refrigeration system, which has the merits of being light, reliable, noiseless, rugged, and low cost in mass production, uses electron rather than refrigerant as a heat carrier, low starting power and is feasible to be used in cooperation with solar cells, in spite of the fact the its coefficient of performance is not as high as for a vapor compression cycle (Dai *et al.*, 2003). The thermoelectric refrigerator is a unique cooling device, in which the electron gas serves as the working fluid. In recent years, concerns of environmental pollution due to the use of CFCs in conventional domestic refrigerators have encouraged increasing activities in research and development of domestic refrigerators using Peltier modules. Moreover, recent progress in thermoelectric and related fields have led to significant reductions in fabrication costs of Peltier modules and heat exchangers together with moderate improvements in the module performance. It is now possible to develop an economically-viable thermoelectric refrigerator which has improved performances and the inherent advantages of environmentally-friendly silent operation, high reliability, and ability to operate in any orientation. Although the COP of a Peltier module is lower than that of conventional compressor unit, efforts have been made to develop thermoelectric domestic refrigerators to exploit the advantages associated with this solid-state energy-conversion technology (Min and Rowe, 2006).

For utilizing solar energy efficiently and cost effectively, proper design of reliable solar devices and system have to be attempted to suit the radiation climate and socio-economic conditions. From this perspective, sizing of PV system involves finding the cheapest combination of array size and storage capacity that will meet the anticipated load requirement with the minimum acceptable level of security. The information required is including the daily or hourly load requirement, peak current and voltage characteristics of the solar module, the number of autonomous days, the estimated percentage of energy losses in the battery and power conditioning equipment, and the estimated losses in the array due to module mismatch, cable, dust and shading (Bhuiyan and Asgar, 2003; Kaushika *et al.*, 2005).

2. METHODOLOGY

A set of photovoltaic components and equipments associated with the experimental procedures is installed for the purpose of data acquisition. The theory of photovoltaic sizing and optimum tilt angle for photovoltaic array is being applied.

2.1 Photovoltaic component

In order to develop a stand alone photovoltaic (PV) system in this research project, there are some PV components need to be prepared. These components are: solar panel, solar charge controller, inverter, and lead acid battery. The appropriate sizing and configuration of these components is necessary for efficient running of the refrigerator.

2.1.1 Solar panel

A solar panel is a photovoltaic module which is built up by a certain combination of solar cells. The material of the solar cell for the solar panel used in this research project is multi-crystalline silicon. A solar panel functions by directly converting the solar radiation into direct current electricity. In this project, a combination of four solar panels is applied to build a solar array, in which two units are configured in series and another two in parallel. Such combination is essential for efficiently charging the lead acid batteries and then operates the refrigerator. Each of the solar panels with the specifications of 17.5V (maximum power point voltage), 5.7A (maximum power point current), and 100W (nominal peak voltage) is used in this PV system. Figure 1 shows the 4 solar panels installed.

Figure 1 Solar panels

2.1.2 Solar charge controller

A solar charge controller is applied in this solar powered domestic refrigerator system. It is installed between the solar array and the battery bank. A solar charge controller's primary function is to protect the battery bank from overcharging and underdischarging that will permanently damage the battery bank. It has the specification of 12A (maximum charge & load current) and 24V (system voltage). The solar charge controller is shown in Figure 2.

Figure 2 Solar charge controller

2.1.3 Inverter

An inverter is a power conditioning equipment which is used to transform the direct current (DC) electricity into alternating current (AC) electricity. This equipment is needed since the solar array will only produce direct current whereas the thermoelectric refrigerator is operated using the alternating current. The specifications of this component are: 150W (output power), 24V (DC input voltage), 220 – 240V (AC output voltage) and 85% (efficiency). Figure 3 shows the configuration of an inverter with a solar charge controller.

Figure 3 Configuration of inverter with solar charge controller

2.1.4 Lead acid battery

Four lead acid batteries are selected to function as energy storage or battery bank in this stand alone photovoltaic system. They are also configured as two units in series and another two in parallel. Their function is to store the electrical energy produced by solar panels in order to be provided to the refrigerator at night or during cloudy days and rainy days. The specifications of this component are: 12V (nominal voltage), 12Ah (capacity), and 80% (efficiency and maximum depth of discharge). Figure 4 shows the configuration of 4 lead acid batteries used in this PV system.

Figure 4 Lead acid batteries

2.2 Equipments

The equipments applied in carrying out the data acquisition for this solar powered thermoelectric refrigerator comprise of pyranometer, digital power, data logger, multimeter, and thermocouple.

2.2.1 Pyranometer

A pyranometer is a type of actinometer used to measure broadband solar irradiance on a planar surface and is a sensor that is designed to measure the solar radiation flux density (in watts per meter square) from a field of view of 180 degrees. A typical pyranometer does not require any power to operate. The pyranometer used in this project is a data logging pyranometer which consist of a pyranometer sensor connected to a data hog connector.

2.2.2 Digital power meter

By using the power meter, the energy consumption is measured. This digital power meter is interfaced to a personal computer through a cable. Power meter software is installed into the personal computer for data storage analysis for the energy consumption. This meter shows the data in parameters of watt-hour (Wh), watt (W), voltage (V), ampere (A), and time (t).

2.2.3 Data logger

In this project, a data logger is used to monitor and record the temperatures measured by thermocouples in order to be analyzed. This equipment used in this research project consisted of 20 channel multiplexers. Thermocouples can be interfaced with the data logger via a personal computer so that temperature can be measured and stored for analysis.

2.2.4 Digital multimeter

A multimeter or a multitester, also known as a volt/ohm meter or VOM, is an electronic measuring instrument that combines several functions in one unit. A standard multimeter may include features such as the ability to measure voltage, current and resistance. It is used to measure the output power of the PV system.

2.2.5 Thermocouple

The type of this component used is called as Teflon Thermocouple. It is used to measure the temperature at the points like cabinet walls inside the refrigerator, cold side and hot side of the refrigerator's heat exchanger as well as the room temperature. Such measurements are carried out for evaluating the thermal performance of the refrigerator.

2.3 Test unit

The test unit applied in this project is a compact thermoelectric fridge. It is shown in Figure 5 while its structure schematic diagram is shown in Figure 6.

Figure 5 Thermoelectric refrigerator

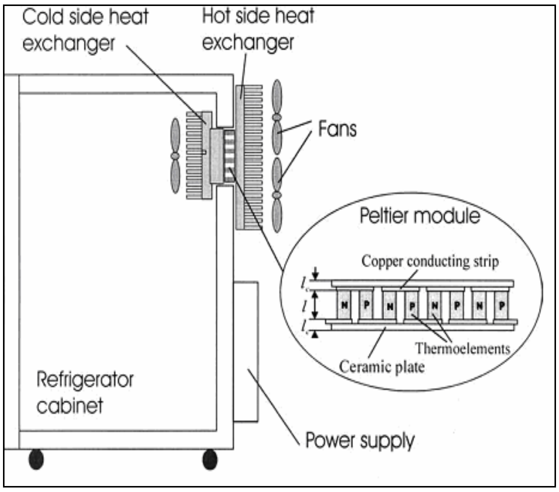

Figure 6 Schematic diagram of the structure of thermoelectric refrigerator

2.5 Experiment setup and test procedures

The performance of the refrigerator, capability of the battery bank and the output power of the PV system are determined through a series of experimental procedures.

2.5.1 Performance of refrigerator and capability of battery bank

All the equipments are installed as shown in Figure 7. Each thermocouple is placed at the every surface of interior wall of cabinet as well as in the water put inside the refrigerator. The thermocouples are connected to the data logger. The system would be then started, followed by recording the temperatures. After that, analyze the data and calculate its coefficient of performance. In order to investigate the capability of battery bank, the procedures should be repeated by disconnecting the solar array from the solar charge controller. The number day for the refrigerator operated by the lead acid batteries alone is recorded

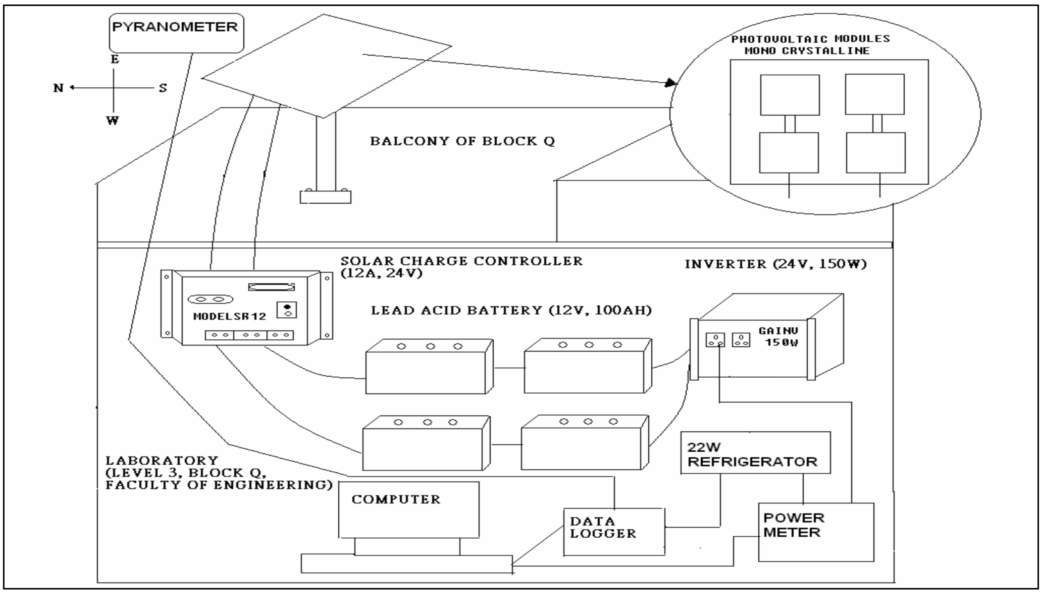

Figure 7 Schematic diagram for experiment setup

2.5.2 Output power of photovoltaic system

The circuit configuration shown in Figure 8 is made. In order to measure voltage of the PV system, the multimeter is connected parallel to the photovoltaic array while it is configured in series to measure the current rating. The data is recorded in 10 minutes interval. With the current and voltage obtained, the output power can be calculated.

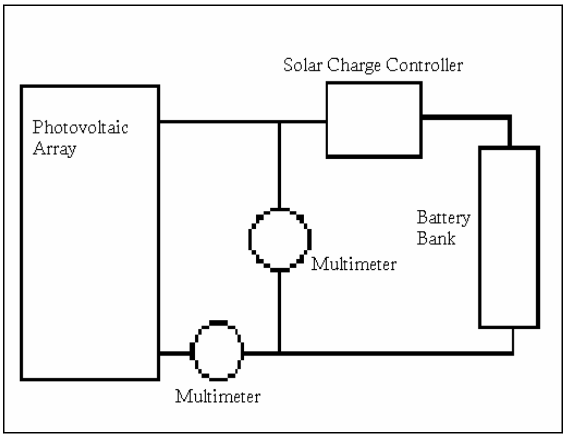

Figure 8 Schematic diagram of experiment setup

2.6 Sizing of photovoltaic stand-alone system (Bhuiyan and Asgar, 2003)

(a) Load estimation

Total rated wattage: $P_{rated\_tot} = q \times P_{rated}$ (1)

Energy demand: $E_{d(Wh)} = P_{rated\_tot} \times H$ (2)

Load demand: $E_{d(Ah)} = \dfrac{E_{d(Wh)}}{\eta_{pce} V_{nsv}}$ (3)

Corrected load: $E_{C(Ah)} = \dfrac{E_{d(Ah)}}{\eta_b}$ (4)

(b) Battery sizing

Battery capacity: $B_{rc} = \dfrac{E_{c(Ah)} \times D_s}{(DOD)_{\max} \times \eta_T}$ (5)

Number of battery in parallel: $B_P = \dfrac{B_{rc}}{B_{sc}}$ (6)

Number of battery in series: $B_S = \dfrac{V_{nsv}}{V_{nbv}}$ (7)

Total battery: $B_T = B_P \times B_S$ (8)

(c) PV array sizing

Design connected current load: $I_D = \dfrac{E_{c(Ah)}}{G}$ (9)

Rated design current: $I_{DE} = \dfrac{I_D}{\eta_M}$ (10)

Number of solar panel in parallel: $N_P = \dfrac{I_{DE}}{I_p}$ (11)

Number of solar panel in series:

$$N_S = \frac{V_{nbv} \times B_s \times 1.2}{V_p} \quad (12)$$

Total solar panel: $N_T = N_P \times N_S$ (13)

(d) Charge controller sizing

Maximum current: $I_T = N_P \times I_P$ (14)

Thus, a charge controller with current > I_T and system voltage of V_{nsv} is chosen.

(e) Inverter sizing

Power rating of inverter: $P_i = \dfrac{P_{rated\_tot}}{\eta_{pce}}$ (15)

Thus, an inverter with power rating > P_i with DC input voltage of V_{nsv} is selected.

2.7 Optimum tilt angle and total solar radiation for solar array (Kacira *et al*, 2004; Jui, 1986)

Declination: $\delta = 23.45 \sin\left[\dfrac{360}{365}(284+n)\right]$ (16)

where n = day of the year

Hour angle: $\omega = \dfrac{1}{4}$ (minutes from local solar noon) (17)

Solar altitude angle:

$$\alpha = \sin^{-1}\left(\left[\cos(L)\cos(\delta)\cos(\omega)\right] + \left[\sin(L)\sin(\delta)\right]\right)$$

(18)

Tilt angle: $S = 90 - \alpha$ (18)

3. RESULT AND DISCUSSION

The result and discussion for this project comprises of sizing of photovoltaic stand alone system, optimum tilt angle, solar radiation, output of photovoltaic array, capability of the battery bank, electrical performance of the refrigerator, and thermal performance of the refrigerator.

3.1 Sizing of photovoltaic stand-alone system

In this project, a thermoelectric refrigerator of 22 watt has been selected to serve as a solar powered one in a stand-alone photovoltaic system. However, the sizing of this stand-alone photovoltaic system must firstly be determined in order to efficiently operate the fridge by matching its load requirement. This calculation is done according to the energy consumption of the refrigerator, number of autonomous day required, efficiency of the selected solar equipments, electrical specifications of the solar equipments, nominal system voltage, sunshine hour, and losses due to shading effect. Using equation (1) to (15), the sizing of the photovoltaic system is shown in Table 1.

Table 1 Sizing of photovoltaic system

Equipment	Model	Specifications	Quantity
Solar panel	GA 100	P_p = 100W, V_p = 17.5V, I_p = 5.7A	4
Lead acid battery	GP 12-100	V_{nbv} = 12V, C= 100 Ah	4
Solar charge controller	SR 12L	I = 12A, V = 24V	1
Inverter	GAINV 150	P = 150W, V = 24V	1

3.2 Optimum tilt angle
The optimum tilt angle for the photovoltaic array must also be firstly calculated so that it may maximize the absorption of the solar radiation. This factor is extremely important to make sure that the output power generated by the photovoltaic array is able to be maximized to match the load requirement. Using equation (16) to (19), the optimum tilt angle of the photovoltaic array for every month is shown in Table 2.

Table 2 Optimum tilt angle

		For Average Day of Month				
Month	**n for *i*th Day of Month**	**Date**	**n**	**δ/ ^{0}**	**α/ ^{0}**	**S/ ^{0}**
January	*i*	17	17	-20.9	66.0	24.0
February	31 + *i*	16	47	-13.0	73.9	16.1
March	59 + *i*	16	75	-2.4	84.5	5.5
April	90 + *i*	15	105	9.4	83.7	6.3
May	120 + *i*	15	135	18.8	74.3	15.7
June	151 + *i*	11	162	23.1	70.0	20.0
July	181 + *i*	17	198	21.2	71.9	18.1
August	212 + *i*	16	228	13.5	79.6	10.4
September	243 + *i*	15	258	2.2	89.1	0.9
October	273 + *i*	15	288	-9.6	77.3	12.7
November	304 + *i*	14	318	-18.9	68.0	22.0
December	334 + *i*	10	344	-23.0	63.9	26.1
					S_{ave}	15.0

From Table 2, it is observed that the optimum angle for the photovoltaic array varies from month to month and its average value is found to be 15 degrees from horizontal plane. The highest value of the optimum tilt angle for the photovoltaic array is 24 degree in January while the lowest is 0.9 degree in September. The changes of the tilt angle are due to the changes of solar positions in relation to earth. Since the photovoltaic system set up in this project is a fix system instead of the tracking system, the photovoltaic array is fixed at 15 degree from horizontal plane and oriented facing south.

3.3 Output power of photovoltaic array
Figure 9 shows the variation of output power generated by a photovoltaic array built up by the configuration of 4 solar panels in a stand-alone photovoltaic system in a sunny day. The characteristic of this output power is performed in period of 10 operating hours that is from 8am to 6pm. From the graph, it is found that the power increase gradually from about 30 watt at 8am to a peak power of 230 watt at 12pm. It is worth observing that this output power decrease slightly to about 200 watt afterward and then remain almost constant at this value until 2pm when it begin to decrease gradually till its minimum value of 10 watt at 6pm. The result shown in Figure 9 is actually characterized by the intensity of solar radiation radiated by the sunlight since the solar panels work in a mechanism of transforming solar insolation to direct current electricity. This means that the higher the intensity of solar radiation absorbed by the photovoltaic array, the higher the amount of electrical energy produced by the solar cells and vice-versa. From the view of this perspective, it can be said that the maximum intensity of solar radiation at the 12pm resulting the maximum output power generated by photovoltaic array at this peak hour whereas the decreasing of sunlight will

lead to the decreasing of output power as shown in the graph. From the result shown, the power produced is found sufficient to efficiently run the thermoelectric refrigerator of 22 watt used in this research project most of the time.

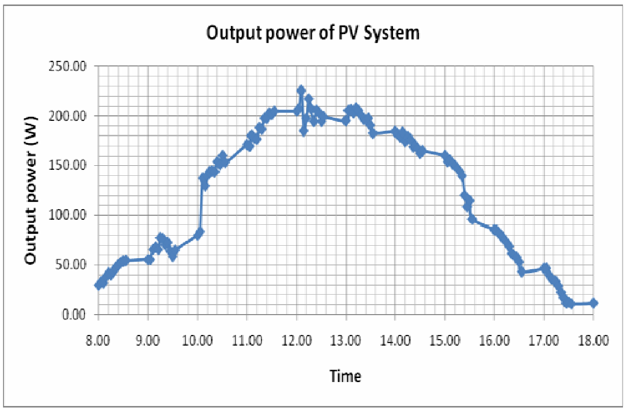

Figure 9 Output power of the photovoltaic array

At the same time, this electrical energy is applied for the purpose of charging the 4 lead acid batteries installed in the stand-alone photovoltaic system. On the contrary, the thermoelectric fridge will only be automatically powered up and run by the back up energy supply from about 5.30 pm when there is a too low intensity of solar radiation till to the next morning when there is no solar radiation radiated for the whole night. Such result is only valid in a sunny day.

However, the maximum power generated by the photovoltaic array is still considered as low compared to its ideal value of 400 watt as promised in its specification. This inconsistent result is exactly due to the relatively low efficiency of the solar panels and solar charge controller that is able to contribute to a significant loss of the output powered measured. Also, cable that connecting those equipments is considered as another source of power losses since there is internal resistance inherited in it. This resistance may definitely lead to a loss in output current and then the output power measured too. The longer the connection cables of solar equipments made the higher the cable internal resistance and therefore the higher the value of output power losses. Besides that, the result discrepancy between the maximum output power generated by the photovoltaic array and its ideal maximum value shown is due to the shading effect caused by the surrounding buildings of the installation site of photovoltaic array. These building obstructions have significantly reduced the amount of solar radiation absorbed by the photovoltaic array which is needed in generating direct current electricity. In fact, the ideal value mentioned is only can be obtained in an ideal condition with the absence of the drawbacks discussed earlier.

3.4 Capability of battery bank

In most of the cases for PV system, lead acid batteries are applied to act as battery bank or electrical energy storage. Hence, in this stand-alone photovoltaic system, the capability of the battery bank to act as backup energy supply is performed by its duration of autonomous days in powering and running a load in the absence of the sunlight such as in rainy days and cloudy days. In this project, this investigation for capability is however carried out in terms of the operating hours of the thermoelectric fridge powered up by the battery bank which is made up of 4 lead acid batteries.

The variation of power consumption of the thermoelectric over its operating hours is shown in Figure 10. From the figure, it is noticed that the lead acid batteries are able to supply the electricity to run that thermoelectric refrigerator up to 69 hours without additional power supply from the sunlight and conventional electric grid. This result is nearly matched to the requirement of 3 autonomous days (72 hours) which is designed in this research project. It can be said that the minor power losses of the lead acid batteries is the cause that lead to the discrepancy of 3 operating hours as shown in by the graph in Figure 10. This condition is most probably due to the internal resistance incorporated in them. The power losses will be worsened in case the lead acid batteries are not kept in good operational condition which may result in a poor charging rate. From the view of this perspective, the lead acid batteries should be checked and maintained from time to time in order to make sure that they are always in good functional condition.

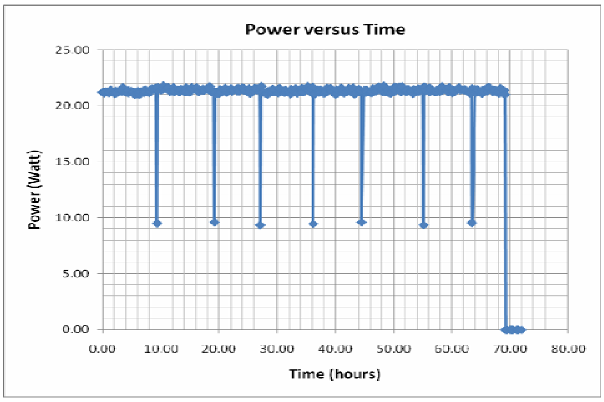

Figure 10 Power consumption over the operating hours.

On the other hand, it is found that there is a decrease of power consumption to about 9 watts for every time interval of 9 operating hours when the refrigerator attains a steady cooling temperature. This condition will cause the refrigerator to consume less power to operate. Nevertheless, this value is found to be increased back to 22 watts within 10-15 minutes when there is a rise in its cooling temperature. From the figure, it is shown that the measurement is stopped automatically and its value decreased directly to zero when the energy storage is lacking of capability is supplying sufficient electricity to run that thermoelectric refrigerator.

3.5 Energy consumption of the refrigerator

The energy consumption of the thermoelectric refrigerator is determined by power meter in respect of watt-hour over the operating period of 24 hours. Figure 11 shows the variation of amount of electrical energy consumed by the thermoelectric fridge over 24 operating hours. From the figure shown, it is noticed that the curve grows gradually from its minimum value upward to its ultimate value of about 520Wh at the end of operating hours. In other word, the total electrical energy needed to power up and run the thermoelectric refrigerator in this stand-alone photovoltaic system for 24 operating hours is about 520Wh.

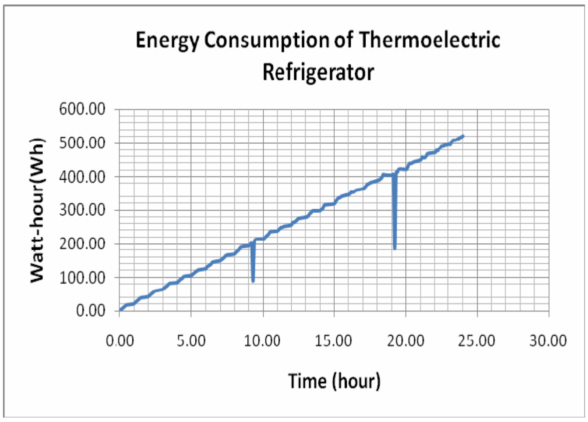

Figure 11 Energy consumption of refrigerator

Apart from this, it is noticed from Figure 11 that there is a decrease of energy consumption of the refrigerator in the time interval of 9 hours. This figure shows that the energy consumption drops drastically from about 201Wh at 9.3th hour to 90Wh at 9.5th hour before increasing back to 208Wh after 10 minutes. Meanwhile, the energy consumption drops drastically again from about 406Wh at 19.2th hour to 185 watt-hour at 19.3th hour before arising back to 412 watt-hour at 19.5th hour. It can be said that such characteristic is caused by the cooling effect produced by the refrigerator. When it achieves the steady state of cooling temperature, the refrigerator will consume less electrical energy to operate whereas a little bit increase of the interior temperature within 10 minutes will drive this sensitive fridge to consume more energy back to operate.

3.6 Cooling temperature

The cooling effect produced by the thermoelectric refrigerator is investigated by the cooling temperature produced inside the cabinet of the refrigerator. It is measured by thermocouple and recorded by the data logger for 24 operating hours. Figure 12 shows the variation of interior temperature of the fridge at different locations inside the cabinet over operating period of 24 hours. These locations are including left wall, right wall, upper wall, lower or bottom wall, rear or back wall, and mineral water put inside the cabinet.

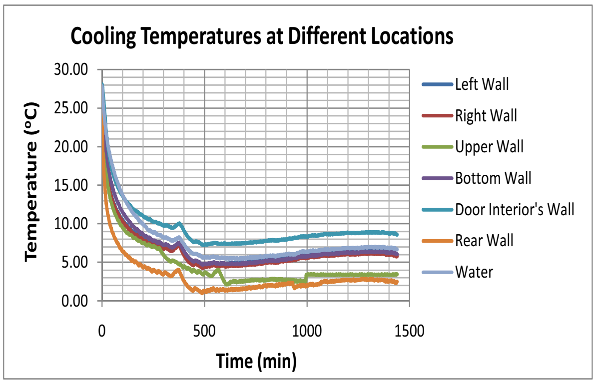

Figure 12 Cooling temperatures at different locations

From Figure 12, it is found that all the curves show the similar characteristic over 24-hour. These curves decrease drastically from their initial temperature to their lowest temperature at about 490 minutes and then increase a few until 1000 minutes. These values will then maintain almost constant till the end of operating hours. The initial and lowest temperatures of the left wall's surface, right wall's surface, upper wall's surface, bottom wall's surface, rear wall's surface and the water are (27.8°C and 4.6°C); (27.7°C and 4.3°C); (27.6°C and 3.2°C); (27.8°C and 4.7°C); (27.9°C and 7.3°C); (24.5°C and 1.0°C); and (27.9°C and 5.5°C) respectively. For the mineral water kept inside the refrigerator, its temperature turns to about 6.7°C at the steady state after 1000 minutes operating time. The result shows that all the lowest temperatures measured are at least 20°C below their initial temperatures. This characteristic is the property promised by the technical specifications of the thermoelectric refrigerator. In other word, this refrigerator is successfully to serve as a photovoltaic powered refrigerator in this project since it can be efficiently operated in a stand-alone photovoltaic system. Apart from these, the surface temperature of the rear wall achieves the lowest temperature among the temperatures measured in the cabinet whereas the door interior surface attains the highest. This phenomenon is due to the distance of those locations from the cold side of heat exchanger of the thermoelectric refrigerator. For this reason, the rear wall's surface which is the nearest location to the cold side of the heat exchanger will be cooled the most as compared to the door interior surface which will be cooled the least since it is located too far from the cold side of heat exchanger.

3.7 Hot side, cold side and room temperature

The variation of temperatures at the hot side and cold side of the heat exchanger as well as the room temperature over operating period of 24 hours is shown in the Figure 13. From the figure, it is worth observing that the room temperature drops from 27.8°C to 24.2°C only after 15 minutes. The ambient temperature attains its stable value of about 24.2°C – 24.4°C afterward till the end of operating hours. These are the room temperatures that need to be achieved. The achievement of ambient temperature of 24°C is most probably controlled by the surrounding condition like air conditioning system, good building envelope of the laboratory, and the location of the laboratory which minimizes the exposure of the experiment room to the sunlight.

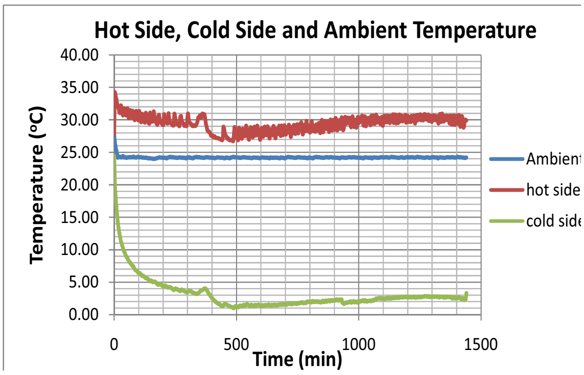

Figure 13 Hot Side, Cold Side and Room temperature

On the other hand, the cold side temperature drops drastically from 25°C to 1.28°C in 500 minutes. It maintains nearly constant till the end of operating hour. By contrast, the temperature of the hot side of heat exchanger is found to be decreased from 32.3°C to 26.7°C, its lowest temperature after operating in 500 minutes. Its temperature will be then increased slightly and fluctuates between 29°C and 30°C. The relatively high temperature of the hot side location is due to the heat released by the heat exchanger. This is because the heat exchanger of thermoelectric refrigerator acts as a solid-state active heat pump which transfers heat from the cabinet (cold side) to its hot side against the temperature gradient with consumption of electrical energy. This working mechanism is called as thermoelectric effect.

3.8 Cool-down and warm up characteristics

Figure 14 shows the comparison of the cool-down and warm-up characteristics of the cold side of the refrigerator operating with non-sinusoidal input from the inverter. The point of study is the rear wall surface of the cabinet. From the figure, it is observed that the cool-down process of the refrigerator occurs drastically from ambient temperature of 24°C to about 8°C in only 60 minutes. Then, it proceeds to decrease gradually to 3°C in 240 minutes and maintains nearly constant at that temperature afterward till the end of operating hours. In fact, the thermal stabilization for cool-down process occurs only after the refrigerator operated for 4 hours. The high rating of cool-down characteristic shows that the refrigerator is able to be operated efficiently by the photovoltaic system.

On the other hand, from the warm-up characteristic of the refrigerator shown in Figure 14, it is found that the interior cabinet temperature will not rise above 5°C even 60 minutes after the refrigerator turned off. The warm-up curve shows that the temperature rise gradually from about 3°C to 6°C in 100 minutes before rising drastically back to ambient temperature after 4 hours. This temperature will then remain constant at 24°C. It can be said that the low rate of warm-up process accomplished by this thermoelectric is influenced by its good insulation property of the insulator surrounded it as well as its good configuration that prevents air leakages. The prevention of air leakages is extremely essential in avoiding the occurrence of infiltration and also the exfiltration of air which may greatly warm up the cabinet's temperature.

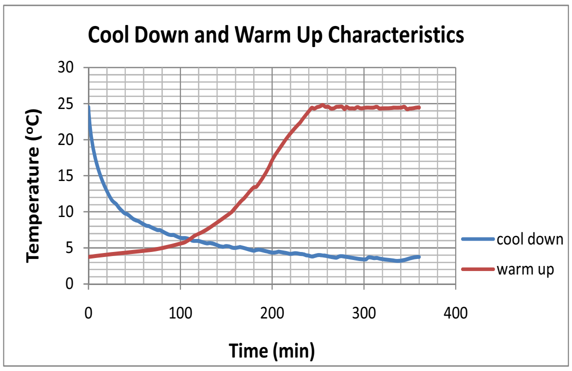

Figure 14 Cool-down and warm-up characteristics of the refrigerator

3.9 Door-opening effect

Figure 15 shows the influence of the opening of the refrigerator door on its thermal performance when powered by the inverter in a stand-alone photovoltaic system. The surfaces selected for study are left wall, right wall and rear wall. For this investigation, the door is kept open for 30 seconds at 30 minutes intervals. It is observed from the figure that all the curves perform the similar characteristics. Due to the infiltration of warmer air into the cabinet as well as the exfiltration of the cooled air from the cabinet, all the surfaces temperatures increase drastically at the moment the door kept opened. These temperatures will only decrease gradually when the door is closed. On the left wall of the cabinet, the temperature increase with the highest rate and has reached above 10°C. This is not unexpected as the refrigerator door is hinged on the right and whenever the door is opened, the left wall is exposed to the ambient first. Meanwhile, the right wall and the rear wall are less influenced by the air infiltration because of their more far distance from the door opening. It is hence, recommended that the load like bottles of mineral water should be stored as close to the right wall and rear wall as possible.

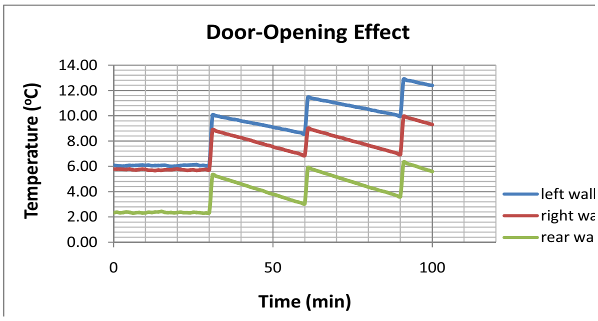

Figure 15 Cabinet temperature variations in open door test

This is extremely important to prevent the load which is to be cooled from being easily warmed up by the infiltration of warmer air from the ambient. From the result shown, it is also not recommended for opening the refrigerator with a high frequency for a long time intervals each since it may affect the cooling effect produced by the refrigerator.

4. CONCLUSION

A thermoelectric refrigerator which is developed in stand alone photovoltaic system for domestic usage has been presented in this paper. The photovoltaic sizing required for efficiently running the thermoelectric refrigerator with energy consumption 520Wh is including 4 solar modules of 5.7A, 17.5V and100W; 4 lead acid batteries of 12V and 100Ah, a solar charge controller of 12A and 24V; and an inverter of 24V and 150W. For maximizing the electricity generation, the photovoltaic array should be oriented at 15 degrees from horizontal and is installed facing south. The peak power produced by the photovoltaic array is 230 watt. It has been shown that the battery bank is able to act as a back up energy supplier for 3 autonomous days. The thermoelectric refrigerator can maintain the temperature in refrigerated space at 1~7 ^{o}C and at averagely 4^{o}C. The warm up time for the cooling temperature to increase back to ambient temperature after being switched off is about 4 hours. Instead of using vapor compression refrigerator, thermoelectric refrigerator is applied due to its lower starting power, environmental friendliness, and noiselessness. The performance of this refrigerator can be improved by adding insulation to the refrigerator's body as well as improving its heat exchanger efficiency. It is recommended for not opening the photovoltaic driven thermoelectric refrigerator more than 30 seconds each time.

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