Mathematical investigation on performance of photovoltaic (PV) combined with direct-expansion heat pump system (DX-SAHPS)

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Abstract: Decreasing photovoltaic (PV) module temperature is reported to result in enhanced solar-to-electricity conversion efficiency. Heat removal fluids, such as air and water, were passed through pipes/ducts that were attached to the back of a PV array for the purpose of absorbing cell temperature and improve electrical efficiency. This study reports the use of refrigerant R134a as a heat removal fluid in a photovoltaic/thermal (PV/T) collector being coupled with a heat pump system that acts as an evaporator/collector. This arrangement is expected to improve photovoltaic efficiency and heat pump coefficient of performance (COP) due to factors such as low boiling temperature and absorbed heat. A PV/T evaporator/collector, fabricated from copper tubes, PV module, and aluminium sheet, all work in tandem to function as an evaporator of the heat pump system. The model was simulated using Engineering Equation Solver (EES) tool embedded with Hottel-Whillier equations to quantify enhancement to the heat transfer due to the refrigerant in the context of the weather during 19th March at Kuala Lumpur, Malaysia. The values reported by the photovoltaic solar assisting heat pump system (PV-SAHPS) confirmed that the maximum COP reached 6.84, and the average electricity efficiency, thermal efficiency, and overall efficiency were 11.65, 81.6, and 93.2, respectively.

Keywords: ***Photovoltaic/thermal evaporator, heat pump system, Thermal and electrical efficiency, COP***

I. INTRODUCTION

The limited availability of fossil fuel sources necessitates the shift towards renewable energy sources, such as solar energy. Solar based energy can be used for cooling, heating and power generation, encompassing multiple possible applications. Photovoltaic (PV) technology is currently quite prevalent in power generation. However, the majority of PV modules converts only 4 –17% of incoming solar radiation into power, based on its types and mechanisms [1]. The energy that unconverted into electricity by the PV cells, must be removed to prevent excessive cell heating, which would undoubtedly lead to poor cell performance. This makes solar cell cooling system integral part of PV systems, especially in the case of concentrated PV designs, as it helps mitigate the effect of increased temperatures upon the PV module [2].

The majority of studies reported the usage of air [3,4] and water [5,6] for the purpose of PV cooling via a thermal unit installed at the back of the module, resulting in a photovoltaic/thermal (PV/T) collector that remove excessive heat from the PV. Air is governed by two factors in the context of heat removal; low-density and small heat capacity, both of which curtailed its ability to enhance the performance of air PVT collectors. However, liquid cooling, due to its efficient utilization of captured thermal energy, represents a better alternative. Liquid-based PVT collectors are less prone to temperature fluctuations compared to its air counterpart, rendering it more predisposed towards a homogenous temperature distribution upon the surface of the PV modules. Water represents the most common option in liquid-based cooling of PV systems, however, refrigerants that are quick to undergo phase changes at low temperatures have also been considered and duly investigated, revealing superior performances [2] In this study, combining PV modules and heat pumps, both of which are categories of the PV/T solar-assisted heat pump system (SAHPS), was utilized to cool flat plate PV panel using refrigerant R134a. The cold side of the evaporator absorbs the solar thermal energy from the PV panels via its evaporator tubes installed under the PV modules to decrease its temperature, which increases its electrical efficiency. The absorbed heat supports the coefficient of performance (COP) of the heat pump. At the other side of the heat pump, on the condenser, heat can be used for agriculture drying [7] water heating [8] or space heating supply [9]. Therefore, simultaneous operation of the PV modules and heat pump system is better than both components working separately.

The development of PV/T systems are motivated by several factors, such as the provision of higher efficiency compared to individual PV and thermal collector systems, which shortens the payback period of the system [1]. There have been many attempts at finding efficient cooling technology via the analyses of the performance of solar cells utilizing different technologies and a multitude of cooling liquids. The aim of this study is to cool the PV panel using a refrigerant (134a) as a coolant fluid. Thus, this work focuses on enhancing the performance of PV/T solar assisted heat pump system.

II. SYSTEM DESCRIPTIONS

The PV/T solar assisted heat pump system comprises of four major parts: compressor, expansion valve, water-cooled condenser, and PV/T evaporator/collector. The PV/T evaporator/collector is made up of 6 PVs module of Polycrystalline silicon, aluminium sheet, and copper tubes as its key parts of the system. The refrigerant (R134a) enters evaporator/collector tubes at a given (pressure, quality and temperature) at state (4), where it is vaporized by the absorbed solar energy heating. The refrigerant exits the evaporator/collector as the superheated vapour at state (1), and then passes through the compressor. The higher pressure and temperature vapour at state (2) enters the water-cooled condenser and transfers heat to water. The condensed liquid refrigerant at state (3) is next throttled to the evaporating pressure by the expansion valve (capillary tube) and enters directly the evaporator/collector at state (4). The outlet hot water can be utilized for many domestic applications. The detailed technical data relating to the PV-HPS components are given in Table 1 and Fig.1 shows PV/T solar assisted heat pump system, while table 2 shows the characteristic parameters of the PV module. The absorber tube, installed in the aluminium plates, form U-Form grooves, which provides an excellent surface contact between the aluminium sheet and copper tube, and both with the PV module. This affect a continuous and uninterrupted heat transfer from the aluminium sheet to the refrigerant, and with the addition of the layer of thermal insulation installed behind the absorber, to achieve high insulation results. Some of the advantages of the direct expansion solar assisted heat pump (IDX-SAHP) are [10,11]:

1) Direct vaporization of the refrigerant in the solar collector–evaporator resulted in increased heat transfer coefficients.

2) The use of the solar collector as an evaporator decreases the cost of the overall system, as it eliminates the need for an additional evaporator common in traditional SAHP systems.

3) Problems that are prevalent in water collectors (i.e. corrosion, night freezing) becomes a non-issue due to the refrigerants being used as a working fluid, which extends the system's life.

4) Utilizing refrigerants as a working fluid in the heat pump cycle decreases the temperature during the evaporation process within the solar collectors, resulting in decreased system losses, due to the fact that the collector loss value is dependent upon the difference of the collector to ambient temperature.

5) The collector, including bare flat-plate collectors, functions efficiently due to the low collector-to-ambient temperature differences, resulting in minimized cost.

6) The usage of a PVT evaporator in the heat pump system result in high performance and the cogeneration of solar electricity and thermal heat.

TABLE 1
DESIGN PARAMETERS OF THE PV-HP OPERATION.

Parameters	Value	Unit
Inside tube diameter	11.84	mm
Outside tube diameter	12.7	mm
Tube spacing	80	mm
Evaporator absorber area	2.1	m^2
Thickness of thin aluminium plate	1	mm
Thickness of insulation material	15	mm
Inlet refrigerant temperature	10	°C
Compressor power input	1	kW
Tilt angle	14	°
PV efficiency	12	%
Dimension of PV module	1470 x 662 x 45	mm
Rated Power, **(**Pmax**)**	120 ± 3%	W
Open circuit voltage, **(**Voc**)**	21.5	V
Short circuit current, **(**Isc**)**	7.63	A
Voltage at Pmax**,** (Vmp)	17.40	V
Current at Pmax**,** (Imp)	6.89	A
Nominal Operating Cell Temperature**,** (NOCT)	43.6	°C

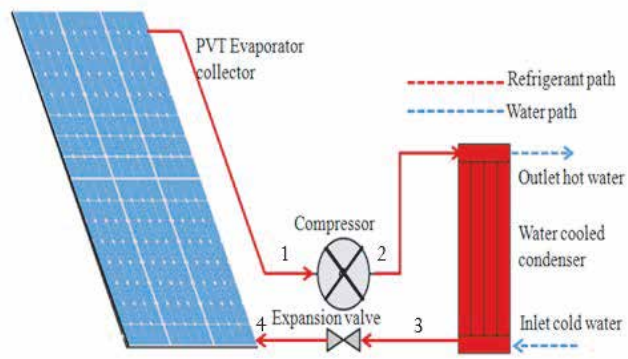

Fig. 1: Schematic diagram of PV/T-Heat Pump system direct-expansion (DX-SAHP) and Water heating system.

TABLE 2
PHOTOVOLTAIC CHARACTERISTICS OF THE PV PANEL UNDER STANDARD TESTING CONDITIONS.

Open- circuit voltage (Voc)	21.5 V
Short – circuit current (Isc)	7.63A
Voltage at Pmax (Vmp)	17.40V
Current at Pmax(Imp)	6.89A

3. Performance analysis of PV/T evaporator/collectors

A hybrid PV/T evaporator collector is basically a combination of a flat plate thermal collector and a PV module using refrigerant as heat removal fluid. Therefore, theory of flat-plate thermal collectors and theory of PV modules will be investigated separately.

The steady state thermal efficiency (η_{th}) of the conventional flat plate solar collector is calculated using the formula below [12]:

$$\eta_{th} = \frac{Q_u}{G} \tag{1}$$

By utilising energy balances equation of evaporator collector, the useful evaporator collected heat gain (Q_u) by refrigerant is given by:

$$Q_u = \dot{m}_R(h_1 - h_4) \tag{2}$$

The difference between the absorber solar Radiation and thermal heat losses is identified by Hottel-Whillier equations is calculated as follows [10]:

$$Q_u = A_C F_R[(\tau\alpha).G_T - U_L(T_i - T_a)] \tag{3}$$

Collector heat removal efficiency factor (F_R), can be calculated as below:

$$F_R = \frac{mC_P}{A_C U_L}\left[1 - \exp\left(-\frac{A_C U_L \acute{F}}{mC_P}\right)\right] \tag{4}$$

Where the collector efficiency Factor ($\acute{F}$) is calculated using:

$$\acute{F} = \left[\frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L(D+(W-D)F)} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]}\right] \tag{5}$$

In Previous Equation (5), (F) is fin efficiency factor calculated as follows:

$$F = \frac{\tanh\left[M\left(\frac{W-D}{2}\right)\right]}{M\left(\frac{W-D}{2}\right)} \tag{6}$$

Where

$$M = \sqrt{\frac{U_L}{(K_{abs}\, L_{abs}) + (K_{pv} + L_{pv})}} \tag{7}$$

For electrical efficiency of PV modules dramatically decreases with increasing cell temperature. This change in η_{el} can be given by the following equation:

$$\eta_{el} = \eta_r\left(1 - \beta\left(T_{pm} - T_r\right)\right) \tag{8}$$

In Equation (8), η_r is the reference efficiency of a PV module (η_r= 0.12) which is obtained for the standard test conditions at (G =1000 W/m^2 and T_r = 25 ºC). β is the PV module temperature coefficient.

III. 4 RESULTS AND DISCUSSION

A simulation program was developed via the Engineering Equation Solver (EES) tool and Hottel-Whillier equations for the purpose of evaluating the performance of the proposed system involving the thermodynamics analysis in the form of mathematical model. The operation condition was set for a full day, from 09:00-17:00 hours. The data of hourly average variation of solar irradiation and ambient temperature of a typical day in 19th March in the case of Malaysia is shown in Figure 2. It was obtained from (TRNSYS 16) the typical meteorological year (TMY) data sets derived during 30 years of National Solar Radiation Database (NSRDB). From the figure it can be seen that solar irradiation is maximum at noon, at a value of 944 W/m^2. The ambient temperature increased from 21.95ºC at 08:00, to 34.4ºC at 17:00.

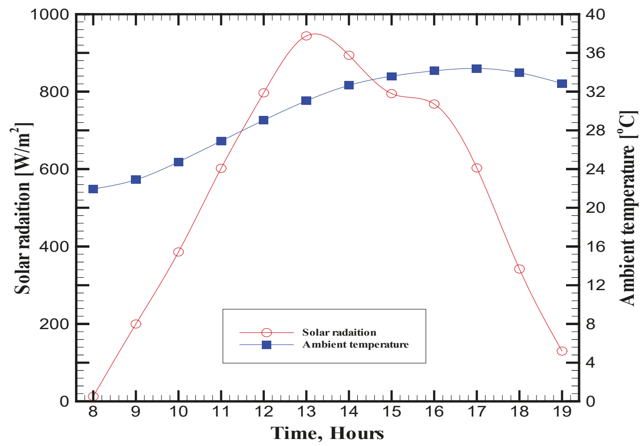

Fig. 2 Average hourly radiation and ambient temperature with time

Fig. 3 shows both the daily variation of COP and the condenser's capacity. It is evident that COP runs the gamut from 4.5 at 09:00, to 6.84 at 13:00, averaging to 5.84/day. The condenser's capacity runs the gamut from 765 W/m^2 (per PV area) at 09:00, to 1110 W/m^2 (per PV area) at 13:00, averaging to 965.8 W/m^2 (per PV area). When compared to the ones shown in Fig. 2, it can be seen that the COP and condenser capacity are mainly influenced by solar radiation, where both are directly proportional to solar radiation. It is also obvious that the ambient temperature is minimally influential upon both COP and condenser's capacity. At 09:00 and 13:00, solar radiation was 200 W/m^2 and 944 W/m^2, corresponding to ambient temperatures of 22.9 ℃ and 31.05 ℃, respectively, which then increased to 34.4 ℃ at 17:00, after which it reported a slight decrease. The daily average ambient temperature was reported to be 29.85 ℃.

Fig. 4 show the daily variation of electrical efficiency and PV power outputs. It is evident that the electrical efficiency runs the gamut from 0.1225 at 09:00, to 0.1142 at 14:00, with its minimum value reported to be at noon, averaging to 0.1165/day. The PV power output was reported to be 24.5 W/m^2 (per PV area) at 09:00, and 108.2 W/m^2 (per PV area) at 13:00, averaging to 76.95 W/m^2 (per PV area). When compared with the ones shown in Fig.2, it can be seen that both the electrical efficiency and PV power output were mainly influenced by solar radiation. The electrical efficiency is inversely proportional to solar radiation, while the PV power output is directly proportional to radiation. It is also evident that the ambient temperature has a minimal effect on both the electrical efficiency and PV power output, meaning that both the electrical efficiency and PV power output decreased slightly in tandem with increasing ambient temperature.

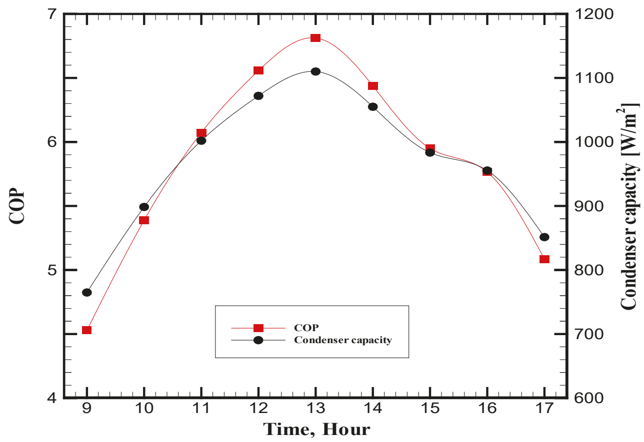

Fig.3 Variation of COP and condenser capacity

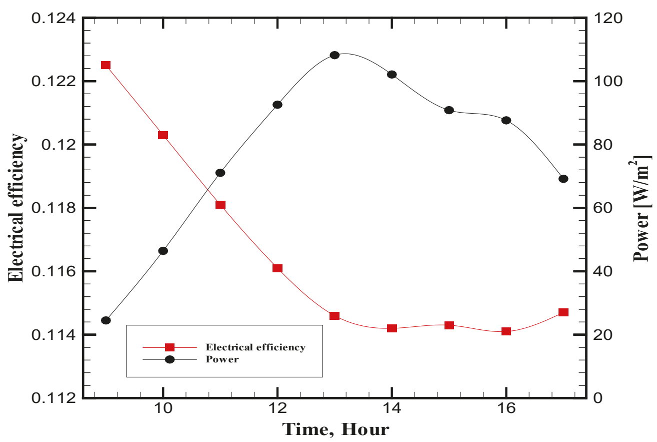

Fig. 4 Variation of electrical efficiency and PV power output

The fluctuations pertaining to evaporator capacity and thermal efficiency are detailed in Figure 5. The former changes as per the variation associated with solar irradiance. It rapidly increases in the morning, peaking at 270.7 W (per PV area) at 13:00, then gradually decreases. The thermal efficiency reported changes from 0.9421 W at 09:00, to 0.779 W at noon, which is opposite to that of the evaporator capacity. From 09:00 to 11:00, thermal efficiency reported a steady decline, then stabilizing from 11:00 to 14:00, finally slightly increasing afterwards. Based on the theoretical analysis of the PV/T evaporator, the thermal efficiency is mostly influenced by the PV surface temperature, ambient temperature, sky temperature, and wind velocity. Increasing solar radiation will increase the surface temperature alongside heat loss to the environment. Increasing ambient temperature decreases heat loss to the environment. Therefore, it can be surmised that thermal efficiency is mainly controlled by solar radiation and ambient temperature. In both early mornings and afternoons, the minimal solar irradiance renders the surface temperature low, which translates into higher thermal efficiency. During noon, the solar irradiance is maximized, which increases both the surface temperature and the corresponding heat loss. Therefore, thermal efficiency is definitely lower at noon compared to that in the mornings or late afternoons. Even at similar solar irradiance levels, the thermal efficiency of afternoons exceeds that of mornings due to the higher ambient temperature. Wind velocity and sky temperature are also influential upon environmental heat losses, which adds a layer of complexity to the thermal efficiency of the PV/T evaporator.

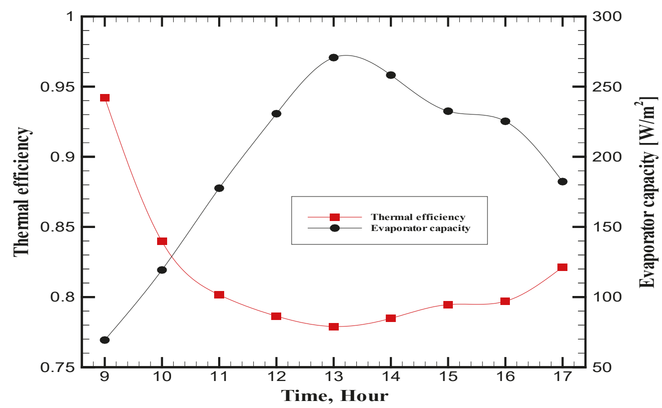

Fig.5 Variation of thermal efficiency and evaporator capacity

Figure 6 details the overall efficiency of the PV/T evaporator. It is made obvious that the overall efficiency runs the gamut from 1.06.5 at 09:00, to 0.8936 at 13:00 during the simulation period. This trend is also evident in the thermal efficiency. In early mornings and late afternoons, it remained quite high, but it decreased starting noon.

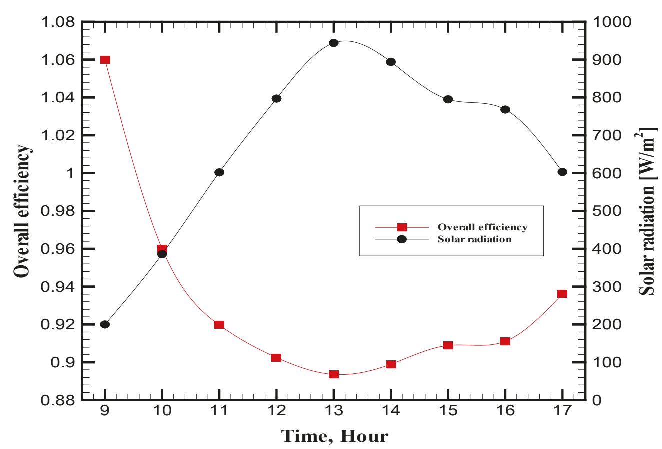

Figure 6. Variation of overall efficiency of PV/T evaporator

Overall efficiency was reported to be higher in the mornings and afternoons due to the influence of the (higher) ambient temperature, while efficiency was reported to be lowest during noon, which is attributed to the high solar radiation increasing the surface temperature of the PV. When the surface temperature of the evaporator decreases to levels under the ambient temperature, the evaporator collect heat not only from solar radiation, but it also absorbs heat from the environment. In this specific case, the overall efficiency of the PV/T evaporator could well exceed 1.0.

IV. CONCLUSIONS

This paper detailed a hybrid PV/T heat pump system. Mathematically steady models have been established for each component of the heat pump system and parts of the PV/T collector/evaporator to be used to predict their respective energy performances using the weather data of 19th March in Kuala Lumpur, Malaysia. We concluded that:

1) The COP of the PV/T heat pump system runs the gamut from 4.5 to 6.8, averaging at 5.8/day. The condenser capacity runs the gamut from 764.9 W/m2 to 1110 W/m2, averaging at 965.8 W/m2 per day. The energy performance of the PV/T heat pump system exceeds that of other reported heat pump systems.

2) The electrical efficiency is inversely related while the PV power output is directly related to the solar radiation. The daily average electrical efficiency and PV power output was reported to be 0.1165 and 76.95 W/m2, respectively.

3) The thermal efficiency is inversely related to the solar radiation, while the heat gains in the PV evaporator is directly proportional to the solar irradiance. The daily average thermal efficiency and PV evaporator capacity were reported to be 0.816 and 196.2 W/m^2, respectively. The thermal efficiency exceeds that of traditional solar collectors.

4) The overall efficiency runs the gamut from 1.065–0.893, while the average overall efficiency was reported to be 0.93 during the simulation period, which is echoed in the trend of thermal efficiency.

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