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Experimental and Numerical Investigation of Combined Photovoltaic-Thermal Solar System in Hot Climate

A. A. Ghoneim[1*] and A. M. Mohammedein[1]

[1]Department of Applied Sciences, College of Technological Studies, Public Authority for Applied Education and Training (PAAET), Shuwaikh 70654, Kuwait.

Authors' contributions

This work was carried out in collaboration between both authors. Author AAG designed the study, carried out experimental measurements, performed the theoretical analysis, wrote the protocol, wrote the first draft of the manuscript and managed literature searches. Author AMM carried out experimental measurements and managed the analyses of the study. Both authors read and approved the final manuscript.

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ABSTRACT

Hybrid photovoltaic-thermal solar system (PVT) which generates electricity and heat simultaneously is well known technology; however they are still need more development and collaboration. The proposed combination can offer economical advantages compared to a combination of separate thermal and photovoltaic panels In the present work, an outdoor test facility is designed and installed to experimentally investigate the thermal and electrical yield of a hybrid PVT in Kuwait climate. Linear regression analysis is adapted to determine the thermal and optical parameters of the PVT system from measurements. A simulation model compatible with TRNSYS is developed to analyze the performance of Hybrid PVT solar system (PVT) with hot water storage tank. The simulation model can provide the transient and long term evaluation to predict the system performance in different weather conditions. The simulation model presented is a steady state model based on solving the heat balance equations for the different layers in the

**Corresponding author: E-mail: aa.ghoniem@paaet.edu.kw;*

PVT system. The simulation results obtained from present model is found to agree well with the experimental data. The performance measurements indicated that the combined photovoltaic-thermal collector produces a higher yield per unit area than a conventional thermal collector. Compared with individual PV and solar collector of the same aperture area, it was found that PVT system produces a higher yield. Maximum energy generation from the PVT collector corresponds to a collector slope of 25° (latitude -5°) and facing south. In addition, PVT with monocrystalline silicon cells achieves the highest energy production among the three PV cell types studied.

Keywords: Hybrid Photovoltaic-Thermal collector; thermal efficiency; optical efficiency; electrical efficiency.

NOMENCLATURES

A_c : *collector area (m^2)*
b : *distance between the glass and the PV (m)*
c_p : *specific heat of working fluid (J/kgK)*
E_A : *avoided CO2 emission (tonne CO2)*
F : *view factor (-)*
F_E : *plant emission factor (tonne CO2 /kWh)*
F_R : *heat removal factor (-)*
G : *global solar radiation (W/ m^2)*
h_{ba} : *heat transfer coefficient from collector back to ambient (W/ m^2K)*
h_{PVp} : *heat transfer coefficient from PV laminate to absorber plate (W/ m^2K)*
h_w : *wind heat transfer coefficient (W/ m^2K)*
I_{mp} : *current at maximum power point (A)*
k_{air} : *thermal conductivity of air (W/mK)*
k_g : *thermal conductivity of glass (W/mK)*
$\dot{m}$: *mass flow rate of water (kg/s)*
Nu : *Nusselt number (-)*
P_g : *power generation (kWh)*
Q_{ba} : *heat transferred from collector back to ambient (W)*
Q_{conva} : *heat transferred by convection in air gap (W)*
Q_{convs} : *heat transferred by convection to sky (W)*
Q_{gt} : *heat transferred from the upper surface of the glass cover (W)*
Q_{rada} : *heat transferred by radiation in air gap (W)*
Q_{rads} : *heat transferred by radiation to sky (W)*
Q_{PVg} : *heat flow from PV cells to glass (W)*
Q_{PVp} : *heat flow from PV cells to absorber plate (W)*
Q_u : *useful energy gained by PVT collector (W)*
T_a : *ambient temperature (°C)*
T_{gtdown} : *temperature of the lower surface of the glass cover (°C)*
T_{gtup} : *temperature of the upper surface of the glass cover (°C)*
T_{in} : *collector inlet temperature (°C)*
T_{out} : *collector outlet temperature (°C)*
T_o : *reference ambient temperature (K)*
T_P : *absorber average temperature (°C)*
T_{PV} : *solar cell temperature (°C)*
T_{PVg} : *temperature of the PV glass (°C)*
T_{ref} : *temperature of PV cell at reference temperature (°C)*
T_s : *sky temperature (K)*
U_L : *overall heat loss coefficient (W/ m^2K)*
v_w : *wind velocity (m/s)*
V_{mp} : *voltage at maximum power point (V)*

GREEK LETTERS

Δx_{gt} : *glass cover thickness (m)*
Δx_{PVg} : *PV laminate thickness (m)*
ε_g : *glass cover emissivity (-)*
ε_{PV} : *PV cell emissivity (-)*
η_{PV} : *electrical efficiency of the PV cells (-)*
η_{ref} : *efficiency at reference condition (-)*
η_t : *collector thermal efficiency (-)*
η_{PVT} : *overall PVT thermal efficiency (-)*
ψ_{PVT} : *overall PVT exergy efficiency (-)*
μ : *PV efficiency temperature coefficient (°C^{-1})*
σ : *Stefan-Boltzmann constant (W/m^{2}K^4)*
$\tau\alpha$: *transmission-absorptance coefficient without PV power output (-)*
$(\tau\alpha)_{PV}$: *transmission- absorptance coefficient of pure PV module (-)*

1. INTRODUCTION

In recent years, energy consumption and greenhouse gases (GHG) emissions have become a worldwide concern. If the rate of energy consumption and GHG emissions are not reduced, global warming will accelerate and have dramatics effects on the planet. A combined photovoltaic-thermal collector (PVT) is considered as one of the most interesting applications of solar energy. The combined collector system consists of a photovoltaic laminate that functions as the absorber of a thermal collector. PVT collectors combine a photovoltaic module and a solar thermal collector, forming a single device that converts solar energy into electric and thermal energy at the same time. The heat from PV modules can be removed in order to increase their electrical performance; this heat can be converted into useful thermal energy. As a result, PVT collectors can generate more energy per unit area than photovoltaic modules or solar thermal collectors. The created combined device can convert solar energy into both electrical and thermal energy and both hot water and electricity are produced simultaneously. The combined PVT offers economical advantages compared to a combination of separate thermal and photovoltaic panels. There are certain components as the supporting frame and transparent cover which are common in thermal and photovoltaic panels, but they are shared in combined system. The integration of PV and thermal collector into one system changes the characteristics of both systems. The thermal yield of the solar collector is varied by the increased heat transfer resistance between the absorber and the fluid. Also, the electrical yield of the solar cells is influenced by the collector flow temperature. Reducing the temperature of the PV modules to a lower level also increases the effective life of the PV modules as well as stabilizing the current-voltage characteristic curve of the solar cells. In addition, in a hybrid PVT system the natural or forced circulation of a heat removing fluid can be used not only for PV cooling but also for heat generation. In this way, the absorbed solar energy which is not converted into electricity can also be utilized for thermal applications.

Kalogirou [1] studied the optimum water flow rate, the mean annual efficiency of the used PV and the payback period of the PVT system. The studied system consists of 5.1 m^2 of collector area, 150 litres of water consumption per day and a mono-crystalline solar cell under the climate of Cyprus. He concluded that the PVT system could increase the mean annual PV efficiency from 2.8% to 7.7% and that it can satisfy 49% of the hot water needed. Zondag et al. [2] presented an analytical method for nine different designs of PVT collectors. Their results showed that the best efficiency of PVT using multi-silicon as an absorber was with the channel below-transparent-PV type. Tiwari and Sodha [3] developed a thermal model of an integrated photovoltaic and thermal solar system. Tripanagnostopoullos et al. [4] have examined experimentally a hybrid system and found that the addition of a booster diffuse reflector increases the performance of the system giving possibilities for more interesting practical applications. The thermal models accompanying these studies were basically for steady state analysis. Vokas et al. [5] reported a theoretical study of a PVT system for domestic heating and cooling in Athens, Heraklion and Thessaloniki for different collectors areas. The analysis results showed that for the PVT system operating in different geographical regions, the percentage of the domestic heating and cooling load is greatly affected by the location. Coventry and Lovegrove [6] carried out a study to compare the value of electrical and thermal output from a domestic PV-thermal system. They concluded that the ratio between the value of electricity and thermal energy plays an important role in minimizing the energy cost of the PV-thermal system. Sandnes and Reskstad [7] designed a polymer solar collector combines with crystalline silicon PV cell in a hybrid generating unit by modifying the Hottel and Willier model of the flat plate thermal collector. The experiments show that attaching PV cells onto an absorbing surface reduces the solar energy absorbed by about 10%. This is because the absorptivity of PV cell is lower compared to the black absorber. Coventry [8] measured the performance of a parabolic trough photovoltaic/thermal collector with a geometric concentration ratio of 37. A thermal efficiency around 58% and electrical efficiency around 11%, therefore a combined efficiency of 69% has been recorded by Coventry. Chow et al. [9] constructed an aluminum-alloy flat-box type PVT collector for domestic water heating purpose, with its fin efficiency equal to unity. Their test results showed that a high hot water temperature in the collector system can be achieved after a one-day exposure. They concluded that this equipment is capable of extending the PV application potential in the domestic hot water applications. Zakherchenko [10] showed the importance of having good thermal contact between the solar cells and thermal absorber. Their study indicates that some commercial PVT modules should not be used directly in PVT system. Chow [11] presented an explicit dynamic model for operation of PV/T collector since it is not suitable to use a steady state model to predict the working temperatures of the PV module and the heat removal fluid was also under fluctuating irradiance or intermittent fluid flow. For that reason, the transient case can more accurately predict the outcome of experiments. That model was developed based on the control-volume finite difference approach. The proposed model can provide a detailed analysis of the transient energy flow through different types of collector components and the instantaneous energy output can also be monitored. Fujiwa and Tani [12] used exergy analysis to evaluate the experimental performance of a designed PV/T system since exergy can be used to qualitatively compare the thermal and electrical energy based on the same standard. Garg and Agarwal [13] utilised the finite difference method to investigate PV/T system with different solar cell areas and flow rate. The system comprised of a storage tank, pump, differential controller and PV modules. The optimum flow rate of this experiment was 0.03kg/s, for maximum thermal efficiency. It was shown that the electrical efficiency decreased at this flow rate and was minimum when the insolation was maximum (as the temperature of absorber is maximum). A hybrid solar system with high temperature stage is described by Vorobiev et al. [14]. The system contains a radiation concentrator, a photovoltaic solar cell and a heat engine or thermoelectric generator. The possibilities of using semiconductor materials with different band gap values are analyzed. Their calculations showed that the proposed hybrid system is practical and efficient.

Tripanagnostopoulos [15] presented a new type of PVT collector with dual heat extraction operation, either with water or with air circulation. This system is suitable for building integration, providing hot water or air depending on the thermal needs of the building. The modified dual PVT collectors achieved a significant increase in system thermal and electrical energy output. Elswijk et al. [16] also claimed that PVT collector arrays installed on multi-family buildings could save about 38% in area. This is very vital due to the availability of the roof top space per house. The disadvantage of this system is that the shading angle of PVT collector must be smaller than the conventional solar thermal collector because of the shading effect. The actual optical and thermal performance of PVT system has been presented by Krauter and Hanitsch [17]. Sopian et al. [18] presented a steady state simulation of the single and double pass combined photovoltaic thermal air collector. The simulations indicated that the double pass photovoltaic thermal collector has superior performance during the operation. The difference of thermal efficiency for single and double pass combined photovoltaic thermal collector is about 10%. The air flow in the double pass combined thermal collector can absorb more thermal energy than that in the single pass. Therefore, the thermal efficiency of the double pass is higher than that of the single pass. Due to the large amount of heat absorbed by the air flow, the temperature of the photovoltaic module decreased significantly and this causes the electrical efficiency of the double pass was higher than single pass as well. Tripanagnostopoulos et al. [19] presented a hybrid PV/T experimental model to investigate the temperature effect on PV electrical efficiency. A booster diffuse reflector was also utilized to enhance the electrical and thermal performance of the system. Assoa et al. [20] developed a simplified steady-state two-dimensional mathematical model of a PVT bi-fluid (air and water) collector with a metal absorber. Then, a parametric study is undertaken to determine the effect of various factors such as the water mass flow rate on the solar collector thermal performances.

Adnan et al. [21] conducted experiments to investigate the effect of mass flow rates on the electrical and thermal efficiencies of combined PVT system. Water was used as a heat transfer medium in spiral flow absorber collector and air for the Single pass rectangular tunnel absorber collector. Results showed that the single flow absorber collector generates combined PV/T efficiency of 64%, electrical efficiency of 11% and power maximum achieved at 25.35 W. They concluded that the best mass flow rate achieved for spiral flow absorber collector is 0.011 kg/s at surface temperature of 55% and 0.0754 kg/s at surface temperature of 39℃ for single pass rectangular collector absorber. It was recommended to use other type of photovoltaic cell such as amorphous silicon cell that posses the black mat surfaces property that will improve its thermal absorption. Dupeyrat et al. [22] reviewed several PVT typologies. A Solar Heating and Cooling system including photovoltaic/thermal (PVT) collectors is considered by Francesco et al. [23]. They considered PVT collectors operating up to 80℃. A case study for a university building located in Naples (Italy) is developed and discussed. The PVT produces electricity which is utilized by the building lights and equipments. Energy production and economic analysis of the system performance is evaluated using zero-dimensional transient simulation model. The economic results show that the system is feasible. In addition, the overall energetic and economic results are comparable to those reported in literature for similar systems.

Touafek et al. [24] studied the electrical performance of the hybrid photovoltaic thermal (PVT) collector and concluded that system may be improved at increased intensity of solar radiation. Buonomano et al. [25] analyzed an innovative renewable energy plant used for indoor/outdoor swimming pool located in Naples. In order to properly design and size the proposed renewable energy system, different thermal pool loss formulations for the calculation of the swimming pool thermal balance, in indoor and outdoor regimes, are adopted. Electricity is completely utilized by the facility, while the produced thermal energy is primarily used to meet the pool thermal demand. The developed simulation model enables the calculation of both the indoor and outdoor swimming pool thermal losses and the overall energy and economic system performance. The simulation results showed remarkable energy performance of the system due to the full utilization of the energy produced. A photovoltaic/thermal sheet and tube collector has been numerically investigated by Rajeb et al. [26]. Their model is applied to optimize the operation of the PVT collector in the semi-arid climate. The theoretical model is validated by comparing the obtained simulation results with experimental results available in literature. They also evaluated monthly thermal and electrical energies. Othman et al. [27] studied the integration of Water and air with the conventional PV/T collector. At radiation level of 800 W/m^2, air flow rate at 0.05 kg/s and water flow rate at 0.02 kg/s; the outlet temperature indicated reading of 27.4℃. The electrical efficiency achieved was 17% with average electrical power of 145 W and thermal efficiency of 76%.

The present work investigates the thermal and electrical yield of a combined photovoltaic-thermal collector in Kuwait climate. The collector test facility installed at the College of Technological Studies, Kuwait is adapted to carry out the present measurements. In addition, a numerical model is implemented to simulate the performance of the combined collector. The well-known Hottel and Whillier [28] flat plate collector formulas have been modified to take into account the effects of adding the PV modules. In addition, the present work examines the performance of three types of PV panels monocrystalline silicon cells, polycrystalline silicon cells and amorphous silicon cells which are used as the absorbers of the PVT collectors.

2. EXPERIMENTAL SETUP

A schematic diagram of the hybrid photovoltaic-thermal collector (PVT) configuration studied is presented in Fig. 1.

The hybrid system is constructed by pasting a PV laminates into the absorber plate of a conventional glass covered sheet and tube flat plate collector. A thin layer of silicon adhesive is used to paste the PV laminates into the absorber plate.

A test facility rig (Fig. 2) is designed and installed on the roof of the main building at the College of Technological Studies, Kuwait (latitude 30°) to measure the performance of PVT system. The collector test facility consists of a solar collector, storage tank of 100 liters capacity, cross flow heat exchanger, constant temperature circulator and a circulator pump to overcome the pressure resistance of the system. Several non-return valves are fitted in the pipeline to define the flow direction and a control valve is used to regulate the flow rate through the circuit with the aid of a valve in the pump by-pass line. Filters, pressure relief valve and an air bleed valve are also included in the circuit.

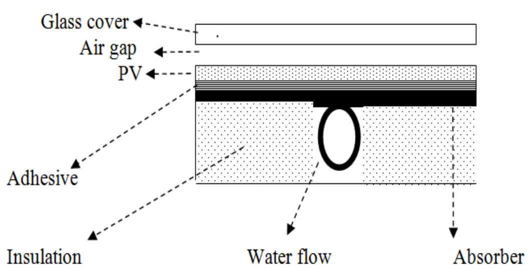

Fig. 1. Schematic diagram of PVT collector

The closed-loop circuit is equipped with both a cross flow heat exchanger and a constant temperature circulator, to control the inlet fluid temperature to the collector. A heating/cooling circulator is capable of supplying water at operating temperature ranges from –50 to 200°C with accuracy of ±0.01°C is provided. The heat exchanger is used for low inlet fluid temperature experiments. The solar collector has an aluminum frame of 2x1x0.1 m and is inclined 30° on the horizontal. The collector is constructed from 0.5-mm thick copper absorber plate coated with black paint. Eight copper tubes of 12.5-mm outer diameter are distributed and bonded to the absorber plate. These tubes are running between two copper headers made of 42 mm outer diameter. The bottom and sides of the collector are lagged by thermal insulation of 40-mm thickness to reduce back and edge heat losses. A clear white, low iron glass sheet of 6-mm thick is used as a cover with an air gap of about 60-mm thickness left between the absorber plate and the glass cover. The three solar panels types examined have the same collector area. The solar panels consist of 72 encapsulated mono-crystalline silicon cells with a low iron glass front and can generate a peak power of 100 watts. The air gap between the PV laminates and the outer glass cover of the flat plate collector is approximately 20 mm. A set of resistances were used to measure the current-voltage characteristics of the solar panels. The electrical output of the PV panels is connected to a data acquisition system.

1. PVT
2. radiation pyranometer
3. storage tank
4. const. temp. circulator
5. cross flow heat exchanger
6. centrifugal pump
7. pressure relief valve
8. air vent
9. flow meter
10. flow control valve
11. filter
12. non return valve
13. anemometer

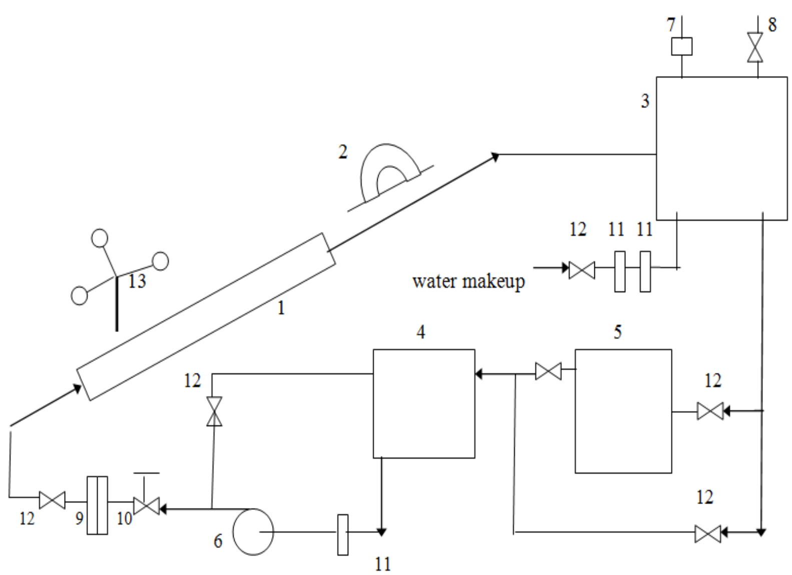

Fig. 2. Schematic diagram of the PVT test facility

The intensity of the global and diffuse solar radiation incident on the collector surface are measured and recorded by two Eppley Precision Spectral Pyranometers (PSP model) connected to the data acquisition system. The pyranometer used to measure the diffuse solar radiation is fitted with a shading ring such that the detector is shielded from direct solar radiation to measure the diffuse radiation only. During tests, the diffuse radiation should not exceed 20% of the total radiation incident on the collector surface [29]. Three standard resistance thermometer detectors (RTD-PT100) are used to monitor the surrounding ambient temperature, inlet and outlet fluid temperatures of the collector. This guarantees high accuracy for these critical temperatures. It is to be noted that the RTD sensor of the ambient temperature is shaded from direct and diffuse solar radiation. Ten pre-calibrated type-K thermocouples are distributed on the absorber plate to determine the longitudinal and transversal temperature distribution. Another thermocouple of the same type is used to measure the glass temperature. All temperature sensors are connected to the data acquisition system.

The water flow rate through the collector is measured using a turbine meter suitable for 0.2 to 5 liters/min with accuracy of 3%. The flow meter is outfitted with both digital display and analogue output of 0-5V, which is connected to the data acquisition system. A data acquisition system (Keithley Model 2700 Multimeter/ Data Acquisition) capable of recording 40 channels is used to record the instantaneous measurements of solar intensities, fluid temperatures, ambient temperature, flow rates and electrical output of the PV panels. The data acquisition system has a resolution better than 0.01°C for thermocouple readings and for 4-wires RTD readings.

3. EXPERIMENTAL PROCEDURE

A number of initial tests have been performed first to examine the durability and reliability of the collector against extreme conditions. These tests are static pressure test, high temperature stagnation test, thermal shock/water spray test and collector time constant test. Such tests are performed according to the certification of operation issued by Florida Solar Energy Center [30].

The experimental work incorporates measuring the performance of both the conventional flat plate solar collector and the performance of the combined PVT collector. The experiments are carried out for global solar radiation between 650 and 1000 W/m^2, on a 30°-tilted collector surface with average ambient temperatures from 30 to 40°C. The water flow rate of all the experiments ranges from 1.25 to 2.0 kg/min and the inlet water temperature is changed from around the ambient temperature up to 80°C in 10°C steps.

The experimental procedure is started by flushing the system. Then, the system is filled with water and the flow rate is adjusted to the required value. The predetermined inlet fluid temperature is fixed using the cross flow heat exchanger and the constant temperature circulator. The solar collector is allowed to run for over 30 minutes (about 5 times the collector time constant) to achieve quasi-steady-state conditions before the data collections were started. The data acquisition system records all readings of ambient, fluid and plate temperatures, flow rate, and global and diffuse solar intensity every minute. Each experiment continued for 90 minutes, after that the inlet fluid temperature is changed and a new experiment is started until the set of runs is completed for this arrangement. It should be mentioned that the experiments are performed before noon and repeated after noon to provide similarity around the solar noon. This would minimize the collector heat capacity effect [31].

The collected data are examined to ensure that it presents quasi steady state conditions according to the recommendations outlined by ASHRAE [29]. Then, the concluded data are divided into test periods, each of which is 15 minutes (more than double the collector time constant). The yield of the collector is defined as the amount of useful energy produced by the collector. Knowing the inlet (T_i) and the outlet fluid (T_o) temperatures and the mass flow rate of water $(\dot{m})$, the useful energy (Q_u) gained by the collector can be represented as:

$$Q_u = \dot{m} c_p (T_o - T_i) \tag{1}$$

where c_p is the specific heat of the working fluid

On the other hand, the collector thermal efficiency is defined as the yield divided by the amount of solar energy received by the collector. So, the collector thermal (η_{th}) and electrical efficiency (η_{PV}) can be expressed by the following equations:

$$\eta_{th} = \frac{Q_u}{A_c G} = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c G} \quad (2)$$

$$\eta_{PV} = \frac{V_{mp} I_{mp}}{A_c G} \quad (3)$$

where A_c is the combined collector area, V_{mp} and I_{mp} are the voltage and current at maximum power point and G is the global radiation on the collector surface.

In the present model, the photovoltaic conversion efficiency is modeled as a linear function of the cell temperature (T_{PV}) in the form:

$$\eta_{PV} = \eta_{ref} [1 - \mu (T_{PV} - T_{ref})] \quad (4)$$

where η_{ref} and T_{ref} are the efficiency and the cell temperature at a reference condition and μ is the PV efficiency temperature coefficient.

The amount of solar energy absorbed by the combined collector (Q_u) is reduced since the electrical energy is extracted from the solar cells. The electrical efficiency, which is a function of the temperature, is subtracted from the transmission-absorption coefficient to find the thermal efficiency of the hybrid collector:

$$\eta_{th} = F_R \ (\tau\alpha - \tau\eta_{PV}) - F_R \ U_L \ \frac{(T_i - T_a)}{G} \quad (5)$$

where $\tau\alpha$ is the transmittance-absorptance product, T_a is the ambient temperature, U_L overall heat loss coefficient and η_{PV} is the PV efficiency. The heat removal factor (F_R) is calculated from the well-known Hottel-Whillier equations [28].

4. THEORETICAL MODELS

Two models are required to determine the performance of the combined PVT collector. The first model is an optical model and is required to determine how much irradiation is absorbed by the PVT collector. The optical model is used to calculate the transmission-absorption coefficient of the PVT collector ($\tau\alpha$) and this value is then inserted as a constant into the thermal model. The second model is required to determine the heat flows within the PVT collector.

4.1 Optical Efficiency

The optical model adapted for the present study is based on the net radiation method. The net radiation method solves the energy flux balance at each interface in the PVT collector configuration. The values for the coefficients of reflection are determined from the well known Fresnel equations. This method is applied to all the interfaces in the PVT collector which generates a set of equations that is can be solved by matrix methods. Since both the coefficient of extinction (K) and the index of refraction (n) depend on the wavelength, the equations are solved for each wavelength interval separately and then integrated over the solar spectrum. The present calculations are based on the assumption of specular reflection, so diffuse reflection is not taken into consideration.

However, the PV laminate introduces more complication to the problem as the PVT laminate does not present a homogeneous surface but consists of different parts. These parts are active PV area, the top grid and the spacing between the cells. For each part, the value for ($\tau\alpha$) is calculated separately and then ($\tau\alpha$) of the entire PVT collector is evaluated by taking the average of these values, weighed with the respective surface areas. The average value of ($\tau\alpha$) is found to be approximately equal to 0.68. The average value of ($\tau\alpha$) is then inserted into the thermal model to calculate the overall thermal efficiency of the combined collector.

4.2 Thermal Efficiency

The thermal model is a steady state model based on solving the heat balance equations for all the layers in the PVT collector. The average value of the transmittance-absorptance product ($\tau\alpha$) which is 0.68 is then inserted into the thermal model. The electrical efficiency, which is a function of the temperature, is subtracted from the transmission-absorption coefficient to find the thermal energy that was absorbed by the system. So, the amount of solar energy absorbed by the combined collector (Q_u) is reduced since electrical energy is extracted from the solar cells. Thus, one can obtain the amount of absorbed energy that contributes to the thermal yield as:

$$Q_u = GA_c (\tau\alpha - \tau_{PV} \ \eta_{PV}) \quad (6)$$

The transmittance-absorptance product ($\tau\alpha$) is assumed to be the same for the absorber plate and the PV cells. The heat flows through the combined collector can be represented by a set of heat energy balance equations. The heat removed by the water (Q_u) is given by:

$$Q_u = Q_{PVp} - Q_{ba} \quad (7)$$

where Q_{PVp} is the heat flow from PV cells to the absorber plate, and Q_{ba} is the heat transferred from collector back to the ambient. Since an adhesive layer is used to connect the PV laminate to the absorber, then the heat transfer between the PV cells and the absorber can be expressed as:

$$Q_{PVp} = h_{PVp} \, (T_{PV} - T_p) \quad (8)$$

$$Q_{ba} = h_{ba} \, (T_p - T_a) \quad (9)$$

where h_{ba} and h_{PVp} is the heat transfer coefficient from collector back to the ambient and from PV laminate to absorber plate, respectively.

The heat energy balance at the different layers of the combined photovoltaic thermal collector also gives:

$$Q_{PVp} = (\tau\alpha - \tau_{PV}\eta_{PV})\,G - Q_{PVg} \quad (10)$$

$$Q_{PVg} = Q_{conva} + Q_{rada} \quad (11)$$

$$Q_{conva} + Q_{rada} = Q_{gt} \quad (12)$$

$$Q_{gt} = Q_{convs} + Q_{rads} \quad (13)$$

$$Q_{rads} = F_s\varepsilon_g\sigma(T_{gtup}^4 - T_s^4) + F_e\,\varepsilon_g\,\sigma\,(T_{gtup}^4 - T_a^4) \quad (14)$$

$$Q_{convs} = h_w \, (T_{gtup} - T_a) \quad (15)$$

$$Q_{rada} = \frac{\varepsilon_g\varepsilon_{PV}}{\varepsilon_g + \varepsilon_{PV} - \varepsilon_g\varepsilon_{PV}}\sigma\,(T_{PVg}^4 - T_{gtdown}^4) \quad (16)$$

$$Q_{conva} = h_a \, (T_{PVg} - T_{gtdown}) \quad (17)$$

$$Q_{PVg} = \frac{k_g}{\Delta x_{PVg}}\,(T_{PV} - T_{PVg}) \quad (18)$$

$$Q_{gt} = \frac{k_g}{\Delta x_{gt}}\,(T_{gtdown} - T_{gtup}) \quad (19)$$

Nusselt number correlations for both laminar and turbulent flow are employed in the developed numerical model. All previous notations are defined in the nomenclature.

The thermal resistance of the different layers of material between the solar cells and the copper absorber is minimized by using highly conductive glue. The heat transfer coefficient (h_{PVp}) is calculated by measuring the temperature difference between the glass surface of the solar cells and the absorber. A numerical technique is developed to solve the heat energy balance equations to obtain the unknown temperatures required to determine the thermal and electrical performance of PVT collector.

5. EXERGY EFFICIENCY

The overall performance of PVT can be evaluated by the first law efficiency (η_{PVT}) which is equal to thermal and electrical efficiency. Thermal energy cannot produce work until a temperature difference exists between a high temperature heat source and a low temperature heat sink, whereas electrical energy can completely transform into work irrespective of the environment. So, the fist law efficiency is not comprehensive for evaluating the PVT overall performance. Exergy (ψ_{PVT}) is defined as the available energy obtained by subtracting unavailable energy from total energy and is equivalent to the work transformable. The use of exergetic efficiency (second law efficiency) thus enables qualitative evaluation of PVT overall performance by comparing electrical and thermal energy based on the same standard. The overall energy efficiency of PVT collector assuming a thermal conversion factor of 0.38 is given by [32]:

$$\eta_{PVT} = \frac{\eta_{PV}}{0.38} + \eta_t \quad (20)$$

The exergy efficiency is defined as the ratio of total exergy output to total exergy input [32]. The exergy efficiency of PVT collector (ψ_{PVT}) can be expressed as [33]:

$$\psi_{PVT} = \eta_{PV} + \eta_t[1 - \frac{T_o}{T_o + (T - T_a)}] \quad (21)$$

6. RESULTS AND DISCUSSION

The experimental results are presented in forms of graphs that presents the collector efficiency variation against the reduced temperature parameter $(T_i–T_a)/G$. All the presented data grant a quasi steady state for each test period (The test period is the duration in which 15 data points are averaged and shown as a single point in the presented results). This is confirmed by the fact that, within the test period (15 min), the maximum variations in ambient, inlet and outlet temperatures are ±0.5°C, ±0.1°C and ±0.3°C, respectively, while in global radiation is ±16 W/m^2. Also, diffuse radiation did not exceed 15% of global radiation in any experiment [29].

To examine the reliability of the present developed numerical model, the calculated performance of the combined PVT with monocrystalline solar cells is compared to the corresponding performance obtained from the experimental data. For the sake of clarity, the linear curves only obtained from linear regression analysis of the experimental data are presented in Fig. 3 along the theoretical values. The values of $F_R(\tau\alpha)$ and F_RU_L for PVT collector obtained from measurements are 0.56 and 5.9 which agree well with the values of 0.59 and 6.1 predicted by the theoretical model. The results clearly confirm the reliability of the present numerical model as the theoretical predictions agree well with the experimental data. The maximum difference between the two predictions is less than 4%.

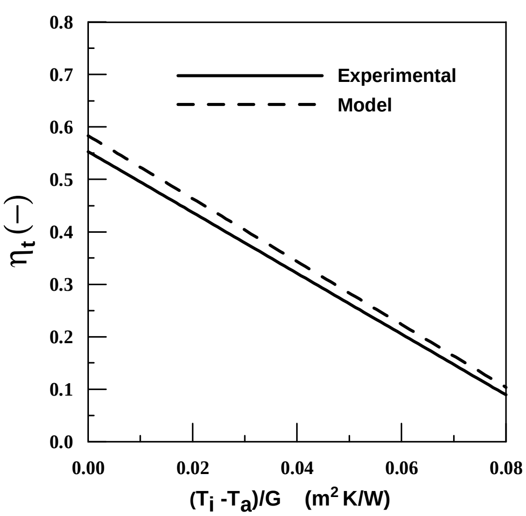

Fig. 3. Calculated and measured PVT efficiency

To evaluate the performance of the combined PVT collector, its performance is compared to the performance of the conventional thermal collector. Fig. 4 shows the variation of thermal efficiency with the reduced temperature parameter $(T_i–T_a)/G$ for the conventional thermal collector and the combined PVT collector. The average points of the experimental data are shown in the figure. The scatter of the data around the straight line is mainly attributed to the angle of incidence variations, wind speed and the dependence of U_L on the plate temperature. Also, the variations of the relative proportions of beam diffuse and ground reflective components of solar radiation are participating in the data scattering, so scatters in the data are expected.

Linear regression analysis is adapted to fit the experimental data to linear curves for both cases. The line intersection with the y-axis gives $F_R(\tau\alpha)$, while the value of the parameter F_RU_L is equal to the slope of the line. Table 1 presents the values of the parameters $F_R(\tau\alpha)$ and F_RU_L for both combined (PVT) and conventional thermal (T) collector along the variance (R^2) obtained from the regression analysis.

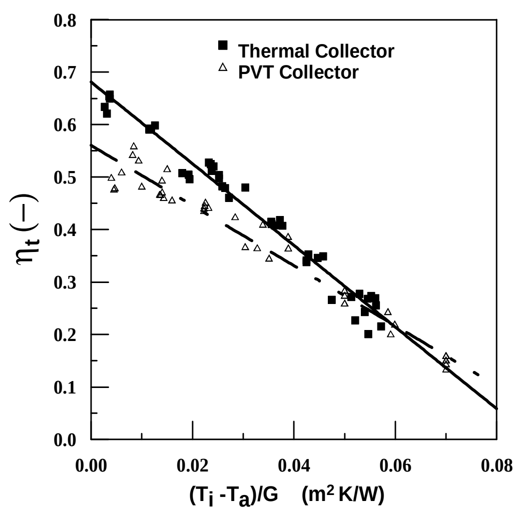

Fig. 4. Comparison between PVT and T collector

Table 1. Thermal efficiency parameters for collectors

Collector	$F_R(\tau\alpha)$	F_RU_L	R^2
PVT	0.56	5.9	0.974
T	0.67	8.3	0.971

The value of F_RU_L of PVT collector is reduced by about 30% compared to the value of conventional thermal collector. On the other hand, the optical efficiency of the combined collector is reduced by about 18% only. These results show the significant improvement accomplished when using combined photovoltaic thermal collector.

It is worth to mention that the effect of optical efficiency is dominant at low temperature difference, whereas the effect of heat loss is important at high temperature difference. Thus, the efficiency of the combined collector is better than the efficiency of the conventional thermal collector particularly at medium and high temperatures. On the other hand, the conventional thermal collector gives better efficiency for limited low temperature range.

A comparison is carried out between the energy efficiency (first law) and exergy performance (second law) to study the effect of different parameters on the overall performance of PVT collector. As an example, the variation of overall energy efficiency (η_{PVT}) and overall exergy efficiency (ψ_{PVT}) with solar radiation is presented in Fig. 5. It is obvious that the increase in solar radition leads to a decrease in overall energy efficiency but at the same time it leads to increase in overall exergy efficiency of the combined PVT collector. In general, it is observed that if a parameter change is favorable for the thermal exergic efficiency, then it is unfavorable for the photovoltaic exergic efficiency.

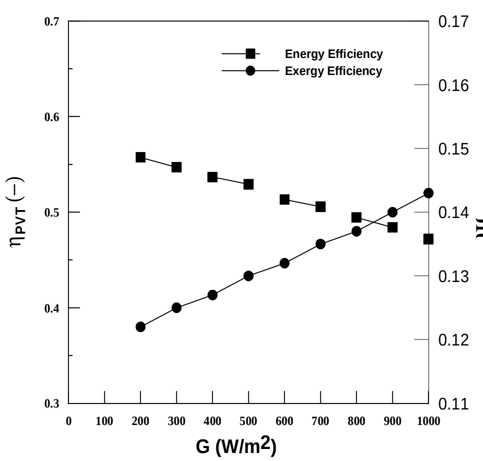

Fig. 5. Variation of overall efficiency with solar radiation

The uncertainty analysis shows an experimental error of about 0.8, 1.3, 2.4, 3.4, 3.9 and 5.1% for F_RU_L, $F_R(\tau\alpha)$, (η_t) (η_{PV}), (η_{PVT}), and (ψ_{PVT}) respectively. The uncertainty analysis for the experimental data revealed that the optical efficiency, $\tau\alpha$, is more sensitive to experimental error than the heat loss coefficient, U_L. The total experimental error for the collector thermal efficiency (η_t) and the photovoltaic efficiency (η_{PV}) is calculated based on the calculation of the combined error from all measured parameters.

The relative effect of PV electrical output on η_{th} was examined by running PVT system with the monocrystalline PV modules in an alternating on/off cycle. The resulting thermal energy is plotted versus reduced temperature as shown in Fig. 6. Figure indicates that extracting electrical energy from the PV panels reduces the solar energy absorbed by the combined collector, and consequently reduces the thermal efficiency of the combined collector by approximately 13% as predicted from the figure.

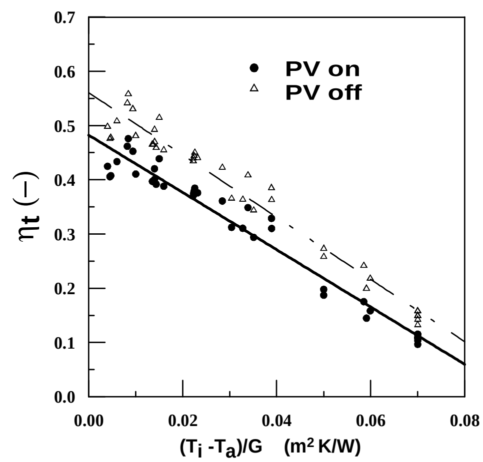

Fig. 6. Thermal efficiency of PVT collector with and without PV power output

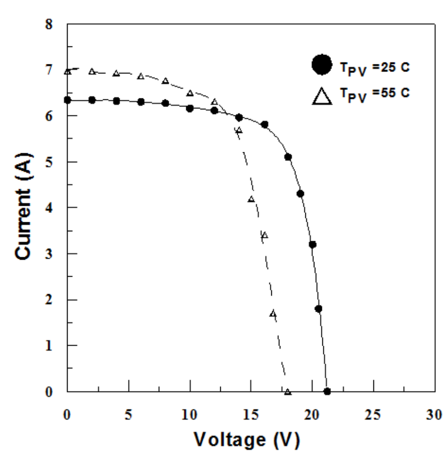

Fig. 7. IV characteristics of PV laminate at different temperatures

The photovoltaic efficiency (η_{PV}) is calculated from the measured voltage over a set of standard resistances. The I-V characteristics of the monocrystalline PV laminate at 55°C and 25°C is presented in Fig. 7. The figure clearly illustrates the effect of cooling on the photovoltaic output. Increasing the cell temperature decreases the open circuit voltage (V_{oc}). That is can mainly attributed to the diode reverse saturation current which increases exponentially with temperature [34]. So, the most significant effect of the PVT collector is the cooling effect for the solar cells. This fact puts an upper limit on the system temperature, which must be considerably lower than the desired cell temperature. Thus the PVT collector can be used successfully in systems that demand a relatively low operating temperature as domestic hot water systems.

7. ENERGY OUTPUT FROM DIFFERENT PVT SYSTEMS

The energy output of PVT system with three types of PV panels mono-crystalline, polycrystalline and amorphous silicon cells is evaluated using TRNSYS [35]. The PVT system consists of a PVT Collector, circulating pump, hot water storage tank and differential temperature controller. Predicting the annual performance of PVT solar system requires hourly meteorological data for the entire year. In this study, the meteorological hourly data of Kuwait measured at the College of Technological Studies, Kuwait is employed. Real hourly data throughout a year of electricity and hot water consumption measured at typical Kuwaiti residential house is employed to evaluate the influence of energy loads on PVT performance. The variation of annual electrical and thermal energy outputs of the mono-crystalline, polycrystalline and amorphous silicon cells with water flow rate ranging from 10 to 70 kg/hr.m^2 is studied. It is found that the maximum annual thermal energy output achieved is 4.7x10^3 MJ and the maximum annual electrical energy output achieved is 1.2x10^3 MJ using the mono-crystalline cells and corresponding to mass flow rate of 39 kg/hr.m^2. The PVT system has a temperature differential controller that manages the circulating pump to switch on when the temperature difference between water outlet and inlet of the collector is greater than the setting point. As the water flow rate increases higher, the temperature difference drops significantly, this results in losing the time of operation of the circulating pump. Therefore the annual heat outputs decreases and consequently the electrical and thermal efficiencies decreases at high water flow rate as seen from Figs. 8-10 for the three types of PV cells studied. It is noted also that the electrical and thermal efficiencies of the three types is maximum at the mass flow rate of 39 kg/h.m^2 as shown from Figs. 8-10. The maximum thermal efficiencies obtained are 42.7%, 40.3% and 38.9% for the mono-crystalline, polycrystalline and amorphous silicon cells, respectively. On the other hand, the maximum electrical efficiencies obtained are 12.2%, 9.9% and 6.5% for the mono-crystalline, polycrystalline and amorphous silicon cells, respectively. This demonstrates that the mono-crystalline silicon cells exhibits the best performance among the PV types studied.

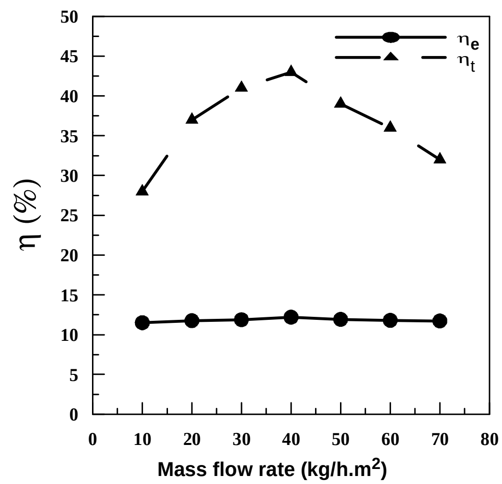

Fig. 8. Variation of electrical and thermal efficiency with mass flow rate for mono-crystalline PVT system

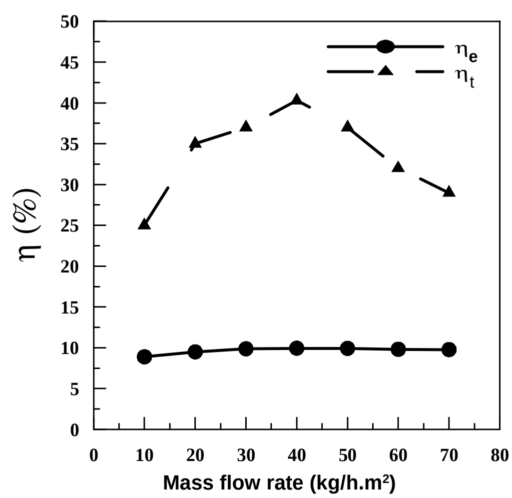

Fig. 9. Variation of electrical and thermal efficiency with mass flow rate for polycrystalline PVT system

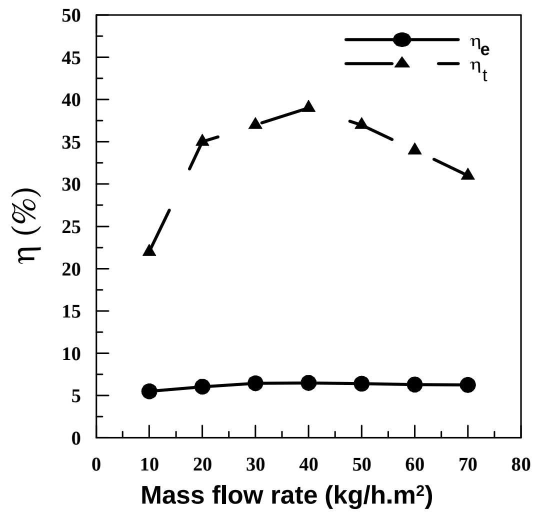

Fig. 10. Variation of electrical and thermal efficiency with mass flow rate for amorphous PVT system

8. CONCLUSIONS

Based on the present results, the following conclusions can be drawn out:

- The PVT collector reduces the heat loss coefficient significantly and this reduction is more important than the loss in optical efficiency.
- The performance of the PVT collector is better than that of conventional one due to the lower heat loss coefficient.
- Extracting electrical energy from the PV panels reduces the thermal efficiency of the combined collector by approximately 12%.
- Maximum energy generation from the PVT collector corresponds to a collector slope of 25° (Kuwait latitude-5°) and facing south (azimuth angle=0°).
- The combined PVT collector produces a higher yield per unit area than a thermal collector and a PV laminate placed next to each other.
- Exergy is a useful tool which can be used in the assessment of overall performance of hybrid PVT collector.
- The present simulation results show that the optimum water mass flow rate for all types of PVT systems is 39 kg/hr.m^2.
- PVT with mono-crystalline silicon cells achieves the highest energy production and consequently the highest performance among the three PV cell types studied.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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