Experimental study and simulation of hybrid Photovoltaic/Thermal solar system in the climate of Saudi Arabia

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PV/T air system, Modeling, Thermal model, Simulation, Comsol.

ABSTRACT

In order to obtain a high electrical efficiency for photovoltaic (PV) system, it is necessary to cooling it; a Photovoltaic Thermal (PV/T) solar system is one of the most important methods for cooling photovoltaic modules.

In this study, a thermal model of a PV/T air solar system was developed, validated from experimental data and then used to study the effects of various parameters on the performance of the system. The thermal model is based on the energy balance of the PV/T air module in which all essential heat transfer mechanisms between the module to the environment and related electrical output are modeled to observe the net change in PV/T air module temperature. The thermal model of PV/T module, developed for the present study, has been numerically solved using finite element method (FEM) with Comsol Multiphysics.

The main objective of the thermal model is to investigate the dependence of PV/T air module temperature on the global solar irradiation and on air flow velocity. The results obtained from the proposed thermal model are validated experimentally. The results indicate that increasing the air mass flow rate when the design parameters are optimum will result into a significant increase in the overall performance of the system.

دراسة تجريبية ومحاكاة لنظام شمسي هجين كهروضوئي/ حراري في مناخ المملكة العربية السعودية

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المُستلخص

من أجل الحصول على الكفاءة الكهربائية العالية للنظام الكهروضوئي، كان من الضروري تبريده. يعتبر النظام الشمسي الهجين الكهروضوئي الحراري هو واحد من أهم الطرق لتبريد الوحدات الكهروضوئية.

في هذه الدراسة، تم تطوير نموذج حراري للنظام الشمسي الهجين الكهروضوئي الحراري و الذي يتم تبريده باستعمال الهواء، و قد تم التحقق من صحة هذا النموذج الحراري من خلال البيانات التجريبية كما سيتم استخدامه بعد ذلك لدراسة تأثير المتغيرات المختلفة على أداء النظام. ويستند هذا النموذج الحراري على معادلات توازن الطاقة و التي تعتمد على جميع الآليات الأساسية لنقل الحرارة بين النظام الشمسي الهجين الكهروضوئي الحراري و البيئة و الطاقة الكهربائية ذات الصلة لمراقبة التغير الصافي في درجة حرارة هذا النظام الشمسي. تم حل هذا النموذج الحراري عدديا ببرنامج "كومسول" باستخدام طريقة العناصر المحدودة. الهدف الرئيسي من هذا النموذج الحراري هو مدى اعتماد درجة حرارة النظام الشمسي الهجين على الإشعاع الشمسي و على سرعة تدفق الهواء. لقد تم تجريبيا التحقق من صحة النتائج التي تم الحصول عليها من النموذج الحراري المقترح وتشير النتائج إلى أن زيادة معدل تدفق الكتلة الهوائية في الظروف المثلى سوف يؤدي إلى زيادة كبيرة في الأداء العام للنظام الشمسي الهجين الكهروضوئي الحراري.

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الكلمات الدالة

PV/T air system, Modeling, Thermal model, Simulation, Comsol.

Introduction

In Saudi Arabia, renewable energies are going to be a main substitute for fossil fuels in the coming years for their clean and renewable nature. Solar energy is one of the most significant renewable energy sources that world needs particularly in Saudi Arabia.

The major applications of solar energy can be classified into two categories: solar thermal system, which converts solar energy to thermal energy, and photovoltaic (PV) system, which converts solar energy to electrical energy. Usually, these systems are used separately. In the solar thermal system, external electrical energy is required to circulate the working fluid through the system.

One of the main problems connected with the operation of photovoltaic panel (PV) is the decrease of electric conversion efficiency at the increase of temperature. This effect is well known and a correlation to determine the panel efficiency as a function of temperature, underlines the linear correlation between these two variables. According to the above mentioned observations, it is of paramount importance to find a way to cool the PV panels, in order to improve their efficiency, especially in the months when more solar radiation is available.

In order to overcome this problem, it is necessary to reduce the operating temperature of the module. Many researches and studies have been carried out on increasing the PV efficiency by different cooling techniques. Generally, some techniques, like air cooling and water cooling, are utilized to cool the PV module to maintain lower operating temperature.

A Photovoltaic/Thermal solar system (PV/T) is one of the most important methods for cooling photovoltaic modules, as it is more coolant that is efficient. Besides the higher overall energy performance, the advantage of the PV/T system lies in the reduction of the demands on physical space and the equipment cost through the use of common frames and brackets as compared to the separated PV and solar thermal systems placed side-by-side.

Many experimental and numerical studies have been conducted to find out the most efficient and low cost hybrid PV/T system. In a number of other studies, attention is focused on modifying the configuration of PV panel. The changes in the PV/T configurations have influences on electrical and thermal performances of the PV/T system. In the last years several of works have been carried out in order to analyze the thermal performance of different PV/T configurations and to develop numerical model for simulating purposes. (Tiwari, et al., 2006) have validated the theoretical and experimental results for PV module integrated with air duct for composite climate of India. They concluded that an overall thermal efficiency of the PV/T system has significantly increased (18%) due to utilization of thermal energy from PV module. (Tiwari, et al., 2006) have proposed parametric study of various configurations of hybrid PV/T air collector. These systems are differentiated by the presence or absence of glazing and tedlar. The results showed that glazed PV/T without tedlar gives the best performance (Joshi, et al., 2006) have evaluated the energy and exergy analysis of a hybrid PV/T air collector. The results experimentally validated indicate that energy and exergy efficiency of PV/T air heater varies between 55- 65 and 12-15%, respectively. (Othman, et al., 2007) have carried out the theoretical and experimental study of thermal and electrical productivity of a finned double-pass PV/T solar air collector. The results show that the use of fins increases both the thermal efficiency and electrical performance of the collector. (Tripanagnostopoulos, et al., 2007) has presented a new type of PV/T collector with dual heat extraction operation with aspects and improvements of PV/T solar energy systems.

(Zondag, et al., 2008) has performed a rigorous review on research work of a PV/T collector and system, carried out by various scientists till 2006. His review includes history and importance of photovoltaic hybrid system and its application in various sectors. It also includes characteristics equations, study of design parameters and marketing, etc.

(Joshi, et al., 2009) have developed a thermal model for the PV module integrated with solar air collector and validated it experimentally. They have indicated that PV module temperature can be controlled and reduced in consequence of changing the mass flow rate of air in solar collector and the efficiency of PV module can be increased.

(Chow, et al., 2010) has done a review on PV/T hybrid solar technology especially PV/T air collector systems. His article gives a review of the trend of development of the technology, in particular the advancements in recent years and the future work required. Energy and exergy analysis of hybrid microchannel photovoltaic thermal module has been carried by (Agrawal, et al., 2011) and they concluded that microchannel photovoltaic thermal module gives better results.

(Kumar, et al., 2011) have critically reviewed PV/T air collectors for air heating providing useful results relating to the practicability of these collectors for preheating air to suit a large variety of applications. (Rajoria, et al., 2012) have performed overall thermal energy and exergy analysis of hybrid PV/T array considering four array configuration and concluded that the performance of case III is better than rest of the cases.

(Agrawal, et al., 2012) have given the design and indoor experiment analysis of glazed hybrid photovoltaic thermal tiles air collector connected in series and concluded that if the numbers of glazed PV/T tile are connected in series then it will be more beneficial from overall energy and overall exergy point of view. (Singh, et al., 2012) have performed comparative study of different types of hybrid photovoltaic thermal air collectors and reported that overall annual thermal energy, exergy gain and exergy efficiency of unglazed hybrid PV/T tiles air collector was improved by 32%, 55.9% and 53% respectively, over the conventional PV/T air collectors. (Yang, et al., 2014) presented a prototype open loop air-based building integrated photovoltaic thermal system with a single inlet is studied through a comprehensive series of experiments in a full scale solar simulator recently built at Concordia University. (Singh, et al., 2015) have developed a model for single channel unglazed PV/T module and optimized design parameter using Genetic Algorithms and concluded that the maximum overall exergy efficiency is 16.88% at optimized parameters. Recently the development of cooling techniques continues (Makki, et al., 2015). (Mahjoubi, et al., 2012) presented an energy-balance model to estimate the real-time performances from a PV/T water pumping systems in Medenine, Tunisia. Theoretical results from this model were validated by experimental measurements and compared with those results in previous literatures. In order to estimate the thermal and electric performances of a PV/T solar hybrid system, (Robles-Ocampo, et al., 2007) constructed an experimental model of an original PV/T water-heating collector with a bifacial PV module to enhance electric energy production of hybrid PV/T systems. Via finite difference control volume approach, (Chow, et al., 2015) introduced a numerical simulation model of a building-integrated photovoltaic and water heating system to evaluate the system dynamic behavior under external excitations. The theoretical predictions were compliance with the measured values acquired from experimental facilities in Hong Kong. (Ji, et al., 2009) presented a dynamic model of a novel PV/T solar-assisted heat pump system with a specially designed PV evaporator to simultaneously produce heat and electricity. The spatial distributions of refrigerant conditions and the temperature distribution of the evaporator were derived under given solar irradiance and ambient temperature through the numerical model. The simulation results were in good agreement with the experimental measurements.

Both water and air have been utilized as heat removal medium for different applications. It is generally accepted that water-based PV/T systems are theoretically more desirable and effective than air-based systems due to the less temperature fluctuation caused by variation in solar radiation. However, air-based PV/T systems are practically preferred for minimal use of materials and lower operating cost despite of poor thermo physical properties of air.

By changing the structure of the PV/T systems, the variation of performance of the system can be observed, such as (Sopian, et al., 1996) and (Charalambousa, et al., 2007). (Dubey, et al., 2009) reported the efficiency of different configurations of PV/T air collector. It was shown that the case of glass to glass PV with a cooling duct can give the highest efficiency among the four cases considered by the author. The annual average efficiency varied between 10.41% and 9.75% for the cases considered.

This paper aims to develop a thermal model which are capable of estimating the two dimensional temperature at any time and at any point of the surface of a PV/T air module. This model uses the hourly global solar irradiation, the hourly Wind speed and the hourly ambient temperature as the input, moreover, the characteristics of PV/T system (inclination, material compositionetc.).

The thermal model of PV/T module, developed for the present study, has been numerically solved using finite element method with Comsol Multiphysics.

The main objective of the thermal model is to investigate the dependence of PV/T air module temperature on the global solar irradiation and on air flow velocity. The results obtained from the proposed thermal model are validated experimentally.

PVT/ air collector system composition

The PVT/ air system studied in this work is consists of a PV laminate, a rectangular air duct, a back absorber plate and back insulation as shown in Fig. 1.

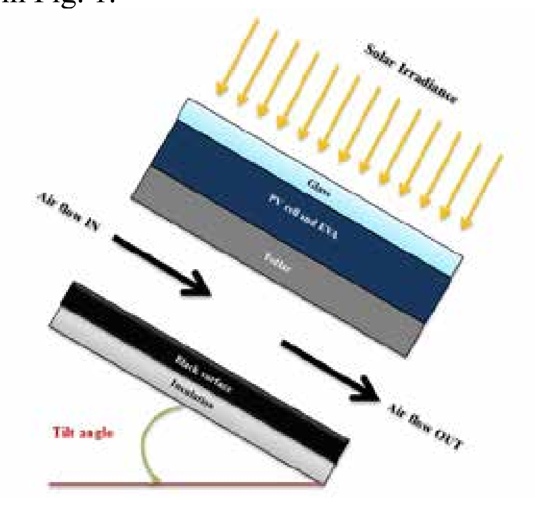


Fig. 1. The cross-sectional view of a PV/T air module.

Mathematical formulations for the simulation work

1. Theoretical Model

The thermal model required for the estimation of the PV/T module's working temperature is quite intricate. The PV/T system converts incident solar energy into both electrical and thermal energy; besides interior procedures occurring in the semiconductor material during its bombardment by photons, which promote the production of electricity, the module also releases the non-converted incident sunlight in the form of thermal energy through different heat transfers modes such as conduction, convection and radiation. Hence, overall energy balance on the module must be taken into account to estimate the module temperature.

The practical energy transfer processes inside a PV/T solar air collector are complicated. To simplify the mathematical calculations, several simplifying assumptions are made to perform this study regarding the conceptual PV/T module construction, atmospheric conditions, air flow characteristics, and other factors, which impact this thermal analysis:

- The materials properties of each layer of PV panel are homogeneous and isotropic.
- The solar irradiance imparted on the entire surface of the PV/T module equally.
- All solar irradiance that is not used to produce electricity in the PV panel will be developed into heat.
- No dust or any other agent is deposited on the PV/T module surface affecting the absorptivity of the PV/T module.
- The flow through the top surface of the module is considered to be fully laminar and incompressible at uniform temperature.
- The air temperature at inlet is equal to the ambient temperature surrounding the PV/T module (298 K).

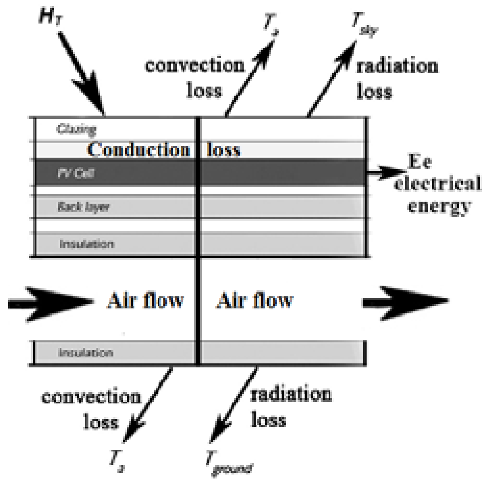


Fig. 2. Main heat transfer path to and from the PV/T module.

The module temperature is calculated by considering the heat transfer through the module to the environment. For the simulation work, the PV/T module materials are assumed to be homogenous and isotropic. Fig. 2 shows the main heat transfer paths to and from the module. In non-steady state conditions, the PV/T module temperature operating is derived assuming that is equal to the incident energy on solar cell (qs) minus the electrical energy output of the module (Ee) plus the sum of the energy losses due to conduction, convection and radiation. The resulting energy balance equation is given as (Jones, et al., 2001):

$$C_{moduléPVT} \cdot \frac{\partial T}{\partial t} = q_s(t) - q_{conv}(t) - q_{cond}(t) - q_{rad}(t) - E_e(t)$$

where: Cmodule PVT is the module heat capacity (J/K).The different terms such as energy loss due to conduction, convection and radiation, are discussed in the following section.

The heat transfer inside the PV/T system may be evaluated following Eq. (2):

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = Q$$

where Q is heat source and Cp is specific heat capacity of each layer.

In Eq. (1) Cmodule PVT represents the heat capacity of PV/T module materials which depends on itsmass. Since the PV/T module is constructed by composition of different layers, the lumped heat capacity can be given by adding heat capacity of each component together which can be written as:

$$C_{modulePVT} = \sum A d_m \rho_m C_m$$

where m denotes each layer of materials in the PV/T module.

2. Numerical Modeling

The Finite Element Method is the numerical technique applied by COMSOL for finding approximate solutions to boundary value problems.

This section proposes the simulation steps for the thermal analysis of the proposed model. For each analysis, a brief summarization of the specific parameters and boundary settings is presented.

All three modes of heat transfer are involved when considering the heat flow through the PV/T module. Heat is transferred within the PV module and its structure by conduction. Heat is transferred to the PV module surroundings by both free and forced convection. Heat is also removed from the module by radiation (in the form of long-wave radiation) (Jones, et al., 2001).

The thermal analysis has been developed using the Comsol's Conjugate heat transfer module.

In the Conjugate Heat Transfer Module, the following conditions were manually added to the model:

• Heat Transfer in Solid

The PV/T air system studied in this work consists of an assembly of elements which are a rectangular air duct, the transparent cover, a mono-crystalline photovoltaic module, the insulation ensured by glass wool.

• Heat Transfer in Fluid

COMSOL numerically solves the continuity and momentum equations, which are the governing equations for the fluid flow, and are shown below in equation (4) and equation (5), respectively (Byron, et al., 2007).

$$\nabla(\rho u) = 0 \quad (4)$$

$$\rho u.\nabla u = -\nabla p + \nabla.(\mu(\nabla u + (\nabla u)^T)) \quad (5)$$

Where: ρ , u, p , and μ are density, velocity, pressure, and dynamic viscosity of air on the front face of the module, respectively.

• Conduction heat transfer

Heat transfer by conduction to the panel structural framework is often ignored due to the small area of contact points; however, it will be considered throughout the COMSOL simulations from the PV/T module surface and through the duct casing. Steady-state heat conduction through the PV/T module surface to the duct enclosure casing is given byEq. (6) :

$$\nabla.(k\nabla T) = 0 \quad (6)$$

• Convection heat transfer

The forced convection on the top and bottom of PV/T module is solved by the convection equation (Jones, et al., 2001):

$$q_{con} = -h_{c,forced}.A.(T_{PV} - T_a) \quad (7)$$

The forced convection through the duct is solved by the conduction convection equation:

$$\rho C_p u.\nabla T = \nabla.(k\nabla T) \quad (8)$$

T (K) is air temperature, Cp (J/kg·K) is the specific heat at constant pressure, ρ (kg/m3) is the fluid density, u is the air flow velocity (m/s), k (W/m·K) is the thermal conductivity.

• Radiation heat transfer

The long wave radiation heat loss can be calculated from Eq. (9) (Jones, et al., 2001):

$$q_{lw} = \varepsilon.\sigma.(T_{PV}^4 - T_a^4) \quad (9)$$

Where: ε ,σ , *TPV,* and T_a are surface emissivity of PV module of value 0.91 on its front surface (Notton, *et al.*, 2005), and 0.85 on its rear surface (Bazilian, et al., 2002), Stefan Boltzmann Constant (5.67 10^{-8} $W/m^2.K^4$), module surface temperature, and ambient temperature, respectively.

• Electrical energy output

The electrical energy output of PV/T module can be expressed by the following relation (Dubey, et al., 2013):

$$E_e = I_m V_m = FF \times I_{SC} V_{OC} = \eta A H_t \quad (10)$$

Where Im is current and Vm is Voltage output at maximum power, FF is fill factor, and Isc and Voc are open circuit current and voltage respectively. Both the open-circuit voltage and the fill factor decrease substantially with temperature (as the thermally excited electrons begin to dominate the electrical properties of the semiconductor), while short-circuiting current increases, but only slightly (Zondag, et al., 2008). Thus, the net effect leads to a linear relation in the form of

$$E_e = \eta_{ref}\left[1 - \beta_{ref}(T_{PV} - T_{ref}\right] \quad (11)$$

Where: βref is mainly material property, having a value of about 0.004 K-1 for crystalline silicon modules [28]. The above equation represents the traditional linear expression for the PV electrical efficiency [29]. The quantities ηref and βref are given by the PV manufacturer. Therefore, the total electrical energy output of the panel is given by

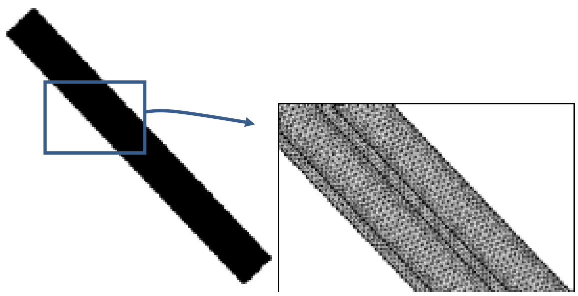
$$E_e = \eta_{ref}\left[1 - \beta_{ref}(T_{PV} - T_{ref}\right] A H_t \quad (12)$$

Mesh Dependency And Computational Procedure

The partial differential equations are subject to the boundary and initial conditions may be solved numerically by using heat transfer module of the commercial software COMSOL 5.0 which is based on the (FEM) . Geometry, functions, and properties of the PV/T panels were defined in COMSOL Multi-Physics. Simple linear free triangular elements are used to create the overall mesh (Fig. 3). The mesh dependence study is performed in order to determine the appropriate size of elements for further study and to provide an accurate mesh independent solution and limiting the overall calculation time. Three meshes were initially studied using 99,784, 101,136 and 152,884 elements. The average temperature was used for dependency test and the difference between the 101,136 and 152,884 elements was only 0.251%. So for time saving, a mesh size based on 152,884 elements (as shown in Fig. 3) was selected for all simulations with automatic time stepping.

Fig. 3. Geometry Meshing

Experimental set-up



The experimental setup consists of one polycrystalline silicon PV module (30 W) with a dimension of 600 mm wide x 350 mm high x 180 mm depth and 11 kg integrated with an air duct. The experiments have been carried out in the Department of Mechanical Engineering, College of Engineering, University of Hail (Saudi Arabia), which is located at (27°38'17.5''N, 41°44'37.6''E). The Photograph of the experimental setup is shown in Fig. 4.

Fig. 4. Photograph of PV/T module

The PV/T module is mounted on a supporting structure so that the surface azimuth angle and the inclination angle of the modules are zero and 27°, respectively.

Generally, the panel slope of PV is fixed, it is necessary thus to know the annual average optimum value of the angle of inclination. For that and by simple calculation an average angle of 27° was obtained for Hail city.

The data acquisition system used is TecQuipment's Versatile Data Acquisition System. The proposed system consists of a set of sensors for measuring both meteorological (e.g. solar irradiance, temperature etc.) and photovoltaic parameters (photovoltaic voltage and current etc.).

The experimental data is registered in a data logger. The information from the data logger will be transmitted to the PC at any time via RS 232 or USB cable, where they are processed using the data acquisition software.

TecQuipment's Versatile Data Acquisition System allows accurate real-time data capture, monitoring, display, calculation and charting of all the important readings on a computer (computer not supplied). Fig. 5 shows the interface of data acquisition software.

Fig. 5. Interface of data acquisition software.

The global irradiation on an inclined and horizontal surface (Ht, H) are the principal measuring parameter, the ambient temperature (Ta), temperature of PV/T module (Tpv) in different points, voltage and current of photovoltaic field (V, I) and battery are also measured in order to construct a complete data base of the site and the system. The following transducers have been used for the various measurements. Pyranometers type Kipp & Zonen have been used to measure the solar radiation in the horizontal plane and in the plane of the PV arrays. The accuracy of the pyranometers is 10 W/m2 or ±5%. Ambient temperature and the temperature of PV/T module in different points have been measured using a series of Thermocouples type K. The uncertainty in the measurement of temperature is ±0.5°C. The wind velocity was measured through a sensitive anemometer with an accuracy of ± 5%.

The experimental data registered in a data logger during one complete year at a time interval of one hour and transmitted to the PC are analyzed.

Results and discussion

Experimental results

Using the experimental-setup, an experimental study have performed, which consists of measurement of hybrid PV/T air module temperature, ambient temperature, wind velocity and solar radiation of Hail city at each hours of the day.

The hourly variation of solar irradiation and ambient temperature of Hail city for four typical days during the month of January, March, July and October are shown in Fig. 6 and Fig. 7 respectively. During these four days, the solar radiation intensity rises to a peak value at 12:00 and then decreases, while the ambient temperature rises to a peak value at 14:00 and then decreases.

Fig. 8 represents the ambient temperature (Ta), the temperature of studied PV/T module in the front (Tpvfront) and in the back (Tpvback) during typical day July, 15th. From this figure, it is clearly shown that the module temperature in the front and in the back rises to a peak value at 12:00 and then decreases, with small variation between front and back surfaces.

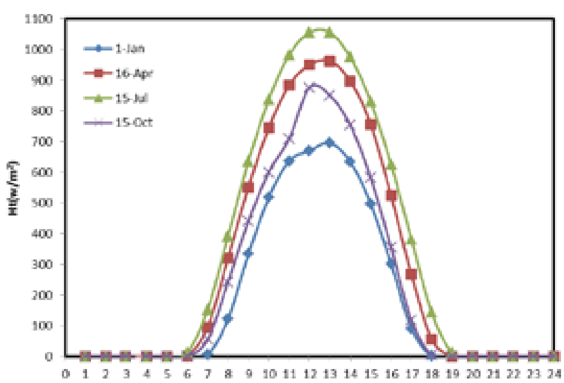


Fig. 6. The hourly variation of solar irradiation for typical days for Hail city

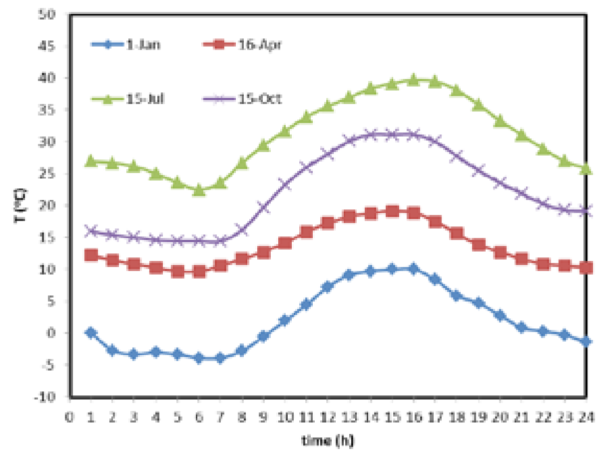


Fig. 7. The hourly variation of ambient temperature for typical for Hail city

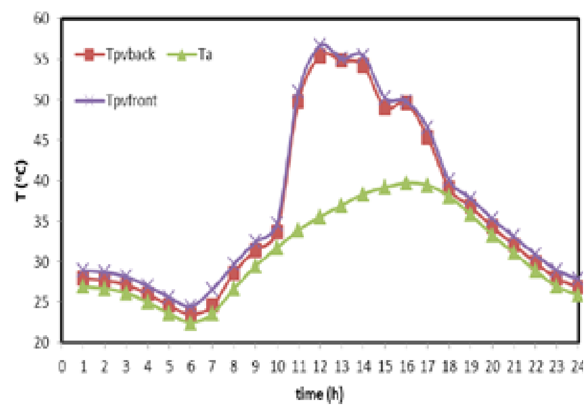


Fig. 8. The hourly variation of the ambient temperature (Ta), the temperature in the front and in the back surfaces of studied PV/T module during typical day July, 15th.

Fig. 9 shows the variation of wind velocity during four typical days during the month of January, March, July and October for Hail city, which affects the module temperature substantially. From this Fig, it is clearly shown that higher wind velocity (in the month of April) reduces ambient temperature and PV/T module temperature due to forced convection effects.

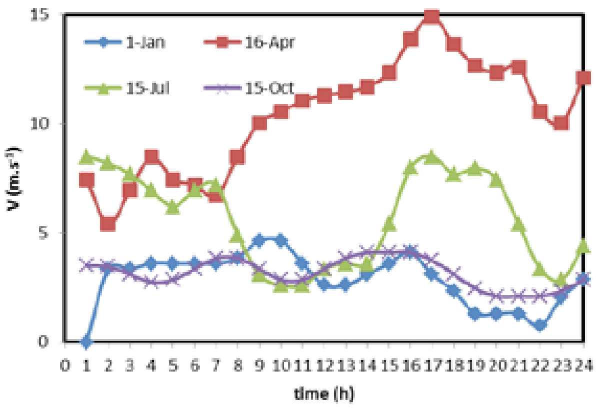
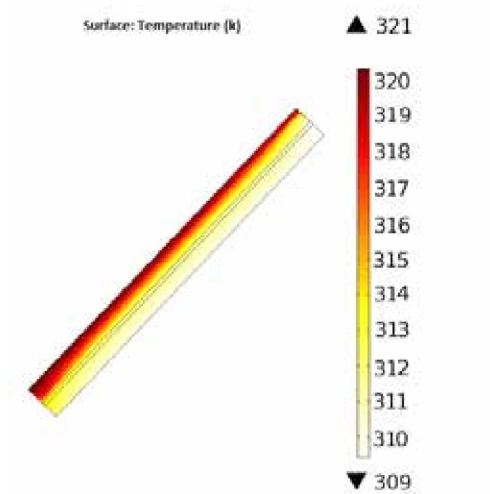


Fig. 9. The hourly variation of wind velocity for Hail city

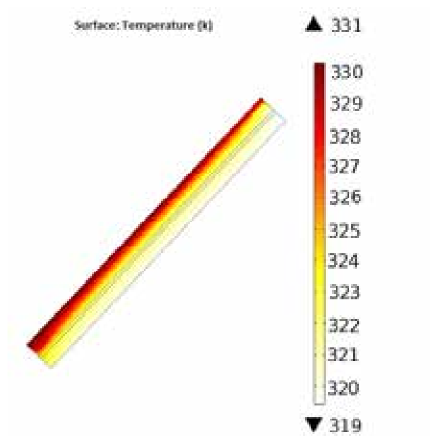


April, 16th

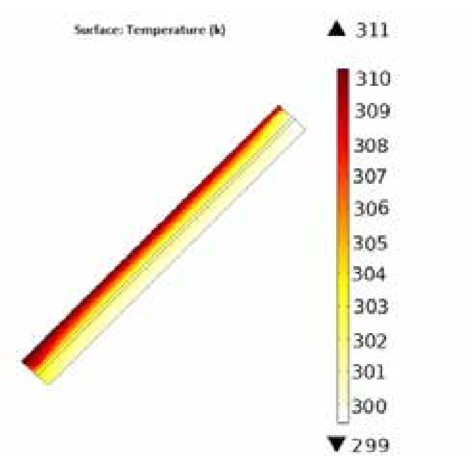
Numerical simulation

Using the meteorological data of Hail city and boundaries conditions as the input, the data extracted from COMSOL Multiphysics following each simulation include the hourly variation of the temperature at any point of the surface of studied PV/T air module and the hourly variation of the Velocity field for different four typical days during the month of January, March, July and October.

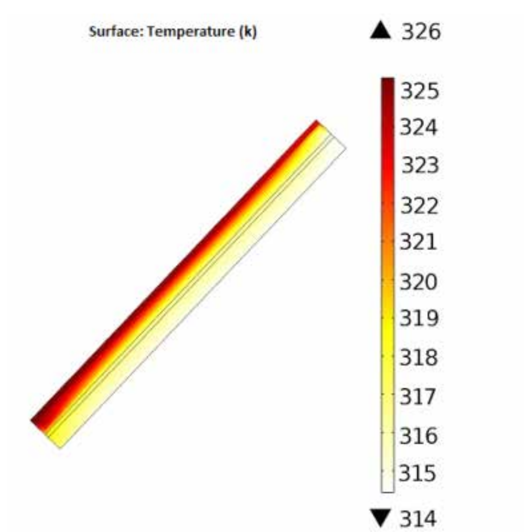
By comparing the PV/T air module temperatures on the different standard days, at a well-defined time (12:00 h), it is clear from the Fig. 10, that the maximum temperatures are reached in the month of July when the ambient temperatures are maximum.



July, 15th



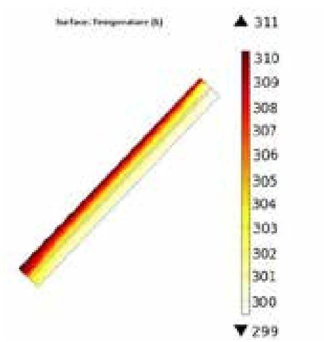
January, 1th



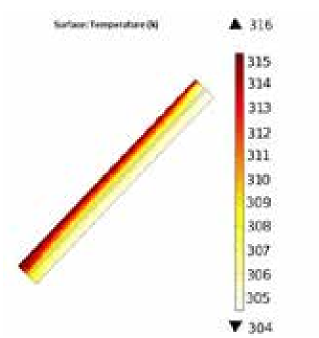
October, 15th

Fig. 10. Simulated temperature field of PV/T module (at 12:00 h) for different typical days.

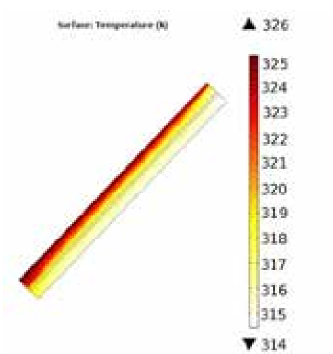
The temperature thus measured has been compared with the simulated temperature of PV/T module in different hours, 6:00, 8:00, 10:00, 12:00, 14:00, 16:00, 18:00, respectively, during typical day July, 15th. Fig. 11 shows the validation of the simulated results of the thermal model with experimental results. The simulated results are in good agreement with the variation of 5–8% approximately with experimental data, it is found that the conventional model consistently over-predicts the measurements at all times. This is expected since the model does not account for local weather conditions such as the presence of cloud and dust.



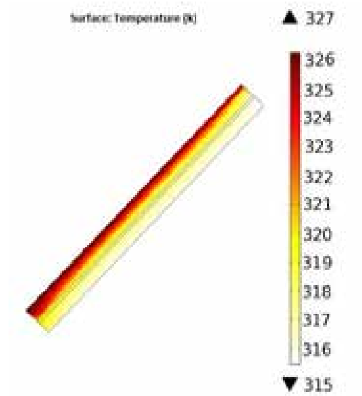
6:00



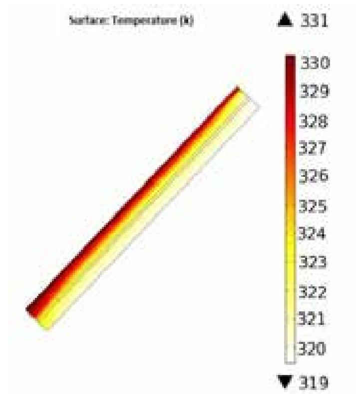
8:00



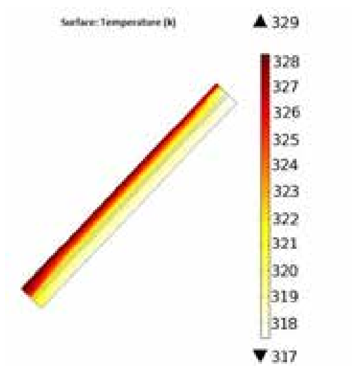
10:00



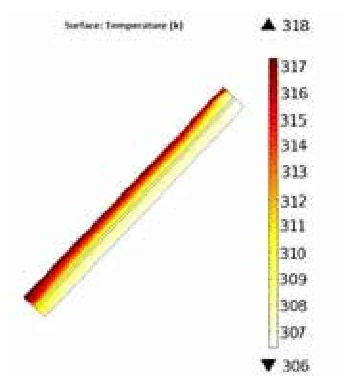
16:00



12:00



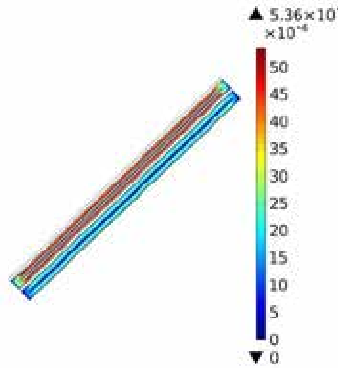
14:00



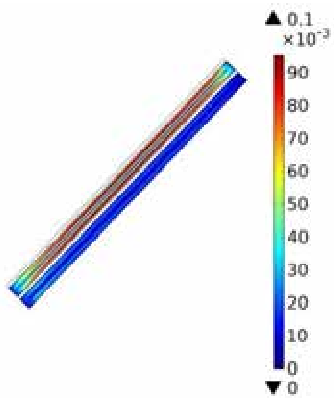
18:00

Fig. 11. Simulated temperature field of PV/T module for different time at the day of July, 15th.

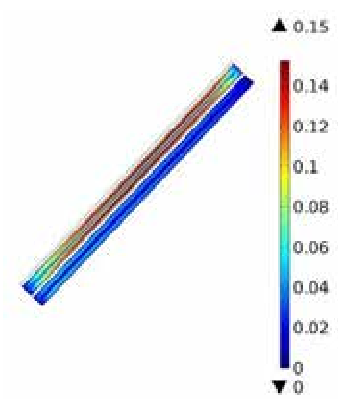
Figure 12, presents the velocity profile inside the PV/T module. As shown from this figure, an intensification of the velocity occurs for higher solar irradiance. This intensification is due to the augmentation of the temperature which causes huge variation of density and thus an enhancement of the floatability forces.



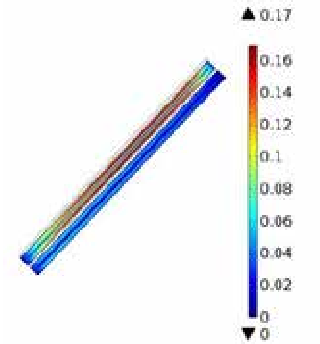
6:00



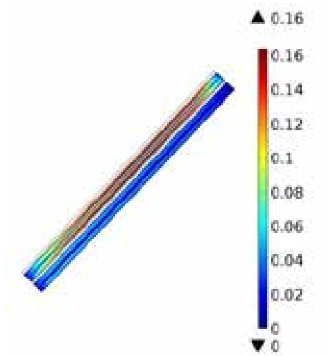
8:00



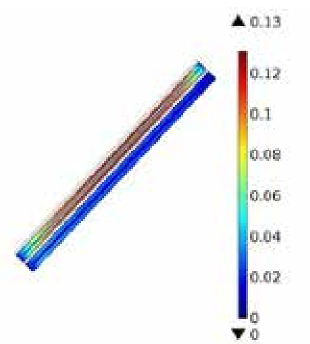
10:00



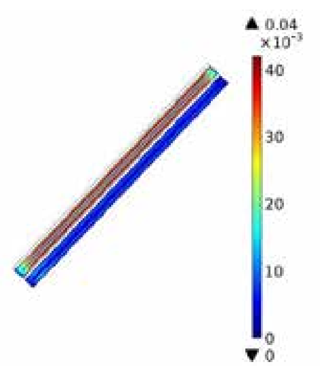
12:00



14:00



16:00



18:00

Fig. 12. Simulated Velocity field for different time at the day of July, 15th.

Conclusion

In this work, thermal model based on the energy balance of the PV/T air module was developed and analyzed using a commercial finite element software package, COMSOL Multiphysics: Version 5.0. The PV/T air module evaluated consisted of monocrystalline PV cells that were bound with a back rectangular air duct; which air flowed, a back absorber plate and back insulation. The energy balance model considers convection and radiative exchange with the ambient environment as well as conduction through the cover, PV cell, and the back absorber plate and back insulation.
The main objective of the thermal model is to investigate the dependence of PV/T air module temperature on the global solar irradiation and on air flow velocity. The results of the proposed thermal model obtained from COMSOL Multiphysics are compared with experimental measurements of temperature of PV/T air module in the climate of Hail city in the north of Saudi Arabia; the simulated thermal model shows good agreement with the measured data with approximately variation of 5-8%. The experimental results showed that the continuous convection of air on the back surface of PV module has important effects on the operation of the system. It reduces the module temperature by absorbing the heat generated by the PV module. The results indicate that increasing the air mass flow rate when the design parameters are optimum will result into a significant increase in the overall performance of the PV/T module.

Acknowledgment

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Nomenclature

A: Area of surface (m2)
FF: Fil factor model constant (1.22 K m2)
Cm: Specific heat capacity of material (J/kg K)
Cmodule: Module heat capacity (J/K)
dm: Depth of material in module (m)
E: Incident irradiance (W/m2)
Ee: Energy delivered by the PV array (Wh)
Fxy: View factor, fraction of energy leaving surface x that reaches surface y
g: Acceleration of gravity (m/s2)
H: Hourly global solar irradiation on a horizontal surface (Wh/m²)
H:t Hourly irradiance in the plane of the PV array (Wh/m²)
k1: Constant = K/I0 (= 106 m2/W)
Lx: Long wave irradiance emitted per unit area of surface x (W/m2)
Ee: DC electrical power generated by module (W)
PV: Photovoltaic
PV/T: Photovoltaic/Thermal
qconv: Rate of net energy exchange at module by convection (W)
q1w: Net rate of long wave energy exchange at module surface (W)
T: Temperature (K)
Tambient: Ambient temperature (K)
Tground: Ground temperature (K)
Tmodule: Module temperature (K)
Ta: Hourly ambient temperature (°C)
Tc: Average module temperature (°C)
Tr: Reference temperature (= 25°C)
VW: Hourly wind speed (m/s)

Greek symbols

α: Absorptivity
τ: Transmisivity
ε: Emissivity
εground: Emissivity of surface of ground
εmodule: Emissivity of the PV module
εsky: Emissivity of the sky
ρ: Density of water (kg/m3)
ρm: Density of material (kg/m3)
ηf: Factor accounting for friction losses in the piping (m)
ηp: Array average efficiency (%)
ηr: PV module efficiency (%)
σ: Stefan-Boltzmann constant (5.669 × 108 W/m2 K4)