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The Effect of Porous Media on Photovoltaic/Thermal Systems: A Review

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Abstract:
Solar photovoltaic/thermal system is widely used in all industries because it generates both thermal and electrical energy. The most significant challenge for photovoltaic thermal (PV/T) systems in maintaining operating temperature is high-performance cooling. To enhance the rate of heat transfer in a PV/T system, multiple methods were used. Porous media is one of these methods to enhance thermal efficiency by providing a larger dissipation area and irregular motion of the fluid flow. This paper provides an in-depth examination of the advancements and applications of porous materials to improve heat transfer performance in a PV/T system.

Keywords: Heat Transfer, Porous Media, Photovoltaic/Thermal System, Solar Radiation, Thermal Efficiency

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تأثير الوسائط المسامية على الأنظمة الكهروضوئية/الحرارية: مراجعة

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الملخص
يستخدم النظام الشمسي الكهروضوئي/الحراري على نطاق واسع في جميع الصناعات لأنه يولد الطاقة الحرارية والكهربائية معاً. التحدي الأكبر الذي يواجه النظام الحراري الكهروضوئي (*PV/T*) في الحفاظ على درجة حرارة التشغيل هو التبريد عالي الأداء. لتعزيز معدل انتقال الحرارة في نظام *PV/T*، تم استخدام طرق متعددة. تعد الوسائط المسامية إحدى هذه الطرق لتعزيز الكفاءة الحرارية من خلال توفير مساحة تبديد أكبر وحركة غير منتظمة لتدفق السوائل. تقدم هذه الورقة فحصًا متعمقًا للتطورات وتطبيقات المواد المسامية لتحسين أداء نقل الحرارة في نظام PV/T.

الكلمات المفتاحية: انتقال الحرارة، الوسائط المسامية، النظام الكهروضوئي/الحراري، الإشعاع الشمسي، الكفاءة الحرارية.

Introduction

The sun serves as the primary source of energy that reaches the Earth's surface via electromagnetic radiation, commonly referred to as solar radiation [1]. The Earth intercepts an estimated 1.8 x 1011 MW/second of solar power [2]. Solar energy stands out as one of the most abundant renewable energy sources. Solar panels possess the capability to directly convert this energy into electricity [3]. Global warming conditions cause a severe shortage of energy supply. As a result, renewable energy sources must be introduced. [4]. To utilise the solar energy resources that exist in a given location, hybrid photovoltaic/thermal systems prove particularly appealing. The PV/T system combines photovoltaic

(PV) and thermal (T) solar system components. This system is capable of producing both electricity and heat. [5], as shown in Fig (1) [6]. PV solar cells convert just visible light from solar radiation, and the remainder of the energy absorbed via the cell is dissipated as heat. As a result, the efficiency of conversion of PV systems is low. The thermal system is relatively efficient, yet it is less useful because it uses low-grade energy. [7]. The incident radiation, as well as the operating temperature of the photovoltaic panels, have a direct influence on the system output energy. The operating temperature should be retained as low as possible to preserve the system's efficiency. As a result, numerous analytical and empirical research studies have addressed temperature reduction to improve system performance and efficiency. [8, 9]. One of the methods suggested was the use of porous media because it provides great dissipation area and irregular motion of the fluid flow [10].

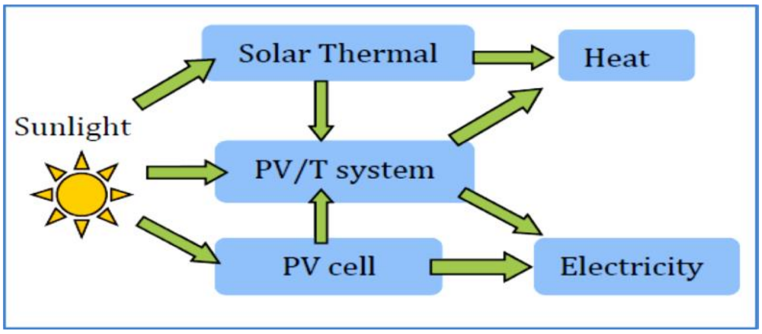


Figure 1: Hybrid Photovoltaic Thermal System [6]

Material and methods

Porous media

A porous medium is defined as a material comprising a solid matrix with interconnected voids [11]. The solid matrix is typically rigid, although it may undergo slight deformation. This structure allows one or more fluids to flow through the material due to the interconnectedness of the voids (pores). The arrangement of pores in natural porous media is non-uniform in terms of size and shape. Examples of natural porous media include sandstone, beach sand, rye bread, limestone, wood, and the human lung. Man-made porous media encompass composite materials, ceramics, and highly porous metallic foams [11]. A porous medium has two advantages. The dissipation area is larger than traditional heat-convection fins, and fluid flow round the singular beads is uneven, which mix the fluid efficiently [12]. Darcy's law is the fundamental law that governs the fluid's flow via porous media [13]. It might also be known as the linear flow law, which represents the linear relationship between flow rate and pressure difference when fluid flows through porous media [14,15]. As a result, the momentum equation of porous media is [16]:

$$\nabla P = -v \frac{\mu}{K}$$

Where μ: fluid's viscosity, K: porous media permeability, v: seepage velocity of a fluid.

Darcy's law is appropriate for low porosity. Furthermore, it does not permit the application of no-slip requirements to a boundary surface [16]. The shift from linear to nonlinear drag is seamless when Darcy velocity increases. This transition does not represent laminar to turbulent flow because when Reynolds numbers are low, the flow remains laminar through pores. Instead, the collapse in linearity is because the form drags caused by solid hurdles are now similar to the surface drag caused by friction. Dupuit-Forchheimer suggested the convenient amendment to Darcy's equation [11]:

$$-\nabla P = \underbrace{\frac{\mu}{K} v}_{\text{Darcy term}} + \underbrace{\frac{\rho C_f}{\sqrt{K}} |v| v_i}_{\text{Forchheimer term}}$$

Where C_f: is the inertia coefficient., P: pressure, ρ: Density (kg/m^3)

Flows through porous media are classified into three categories based on the Reynolds number, laminar, turbulent, and non-linear laminar [10]. The permeability (K) Reynolds number (Re) that used to determine the flow regime is [17]:

$$Re_K = \frac{\rho v K^{\frac{1}{2}}}{\mu}$$

Porous Media Properties

Porosity (ε), permeability, inertia coefficient and the effective thermal conductivity (k_{eff}) of porous media will be described in this section.

Porosity (ε)

Porosity is the proportion of the pore volume in porous media to its overall bulk volume, and can be articulated in the following manner [18]:

$$\varepsilon = \frac{V_p}{V_T} = \frac{V_T - V_p}{V_T}$$

Where: V_p: void volume (pore volume), V_T: total volume.

The porosities for sintered porous plates were calculated based on the weight and dimensions of the sintered porous plate by (Jiang et al., 2004) [19]:

$$\varepsilon = 1 - \frac{M_t - \rho_c \sigma_c w_p L}{\rho_p(\sigma_t - \sigma_c) w_p L}$$

Where: M_t: total weight of sintered porous plate, σ: Thickness, w_p: a sintered porous plate width, L: channel length, c: the copper

For laminar flow with porous block, the porosity defined by (FU et al., 1996) [20]:

$$\varepsilon = \varepsilon_e [1 + r_1 e^{\frac{-r_2 \Delta s}{d_p}}]$$

Where: Δs: Short distances between the porous block's boundaries and the estimated position (m), $\mathrm{d_p}$: Particle diameter (m).

Boomsma and Poulikakos calculated analytically aluminum foams porosity where the cells were taken in their linked state. The representative part was chosen based on symmetry [21]:

$$\varepsilon = 1 - \frac{\sqrt{2}}{2}\left[de^2 + \frac{1}{2}\pi d^2(1-e) + \left(\frac{1}{2}e - d\right)e^2 + \pi d^2\left(1 - 2e^{\sqrt{2}}\right) + \frac{1}{4}e^3\right]$$

Where: d: the radius of dimensionless foam ligament, e: the length dimensionless cubic node.

In order to compute aluminum foams' compressed porosity, uncompressed porosity and compression factor (M) are used (Boomsma et al., 2003) [22]:

$$\varepsilon_{compressed} = 1 - M(1 - \varepsilon_{uncompressed})$$

Permeability (K) and Inertia Coefficient (Cf)

The permeability of a porous medium represents the degree of ease with which a fluid can traverse the medium. An increase in permeability results in a higher flow rate for a given hydraulic gradient. Additionally, it is characterized as the statistical mean of fluid conduction across all flow channels within a solid body. This average conductivity accounts for variations in shape, size, correlation, and orientation of all flow channels [23]. An inertial coefficient is a dimensionless coefficient, employed for porous media and relies on the channel's geometry inside the porous media [24]. There are several formulations to compute the permeability and the inertia coefficient listed in Table (1) (Raed et al., 2015) [10].

Table 1 Formulations of permeability and the inertia coefficient.

Relation	Reference
$K=\dfrac{d_p^2\varepsilon^3}{150(1-\varepsilon)^2}$ $c_f=\dfrac{1.75}{\sqrt{150}\,\varepsilon^{1.5}}$	Jiang and Lu [25]
$K^*=\dfrac{1}{2Ct}\left(\dfrac{n\varepsilon}{3n+1}\right)^n\left(\dfrac{50K}{3\varepsilon}\right)^{(n+1)/2}$	Nebbali and Bouhadef [26]
$K=\dfrac{d^2\varepsilon^2}{36\chi(\chi-1)}$ $c_f=0.095\dfrac{C_D}{12}G^{-0.8}\sqrt{\dfrac{\varepsilon}{3(\chi-1)}}\left(1.18\sqrt{\dfrac{(1-\varepsilon)}{3\pi}}\dfrac{1}{G}\right)^{-1}$	Bhattacharya et al. [27]
$K=0.00073d_p^2(1-\varepsilon)^{-0.224}\left(\dfrac{d_f}{d_p}\right)^{-1.11}$ $c_f=0.00212(1-\varepsilon)^{-0.132}\left(\dfrac{d_f}{d_p}\right)^{-1.63}/\sqrt{K}$	Calmidi [28]

Where: G: Geometric function, χ: Tortuosity of the porous matrix, Ct: Tortuosity factor

Effective Thermal Conductivity (k_{eff})

Thermal conductivity of the porous media explains the medium's ability to transmit heat. Porous media thermal conductivity is influenced by the complex relation between pore spaces structure and geometry and the solid matrix [29]. Boomsma and Poulikakos utilized Fourier's law to calculate the thermal conductivity depending on heat conduction during a four-level series [21]:

$$k_{eff}=\frac{\sqrt{2}}{2(R_A+R_B+R_C+R_D)}$$

Where: R_A, R_B, R_C, R_D: are the simplification quantity (W/m K) for the unit cell subsection.

Metal foams' effective thermal conductivity was reported experimentally and analytically by Calmidi and Mahajan [30].

$$k_{eff}=\varepsilon k_f+A(1-\varepsilon)^n k_s$$

To derive effective thermal conductivity analytically, Calmidi and Mahajan assumed the heat conduction in one dimension, as shown in Fig (2)

$$k_{eff}=\left[\left(\frac{2}{\sqrt{3}}\right)\left(\frac{r\left(\frac{b}{L}\right)}{k_f+\left(1+\frac{b}{L}\right)\frac{(k_s-k_f)}{3}}+\frac{(1-r)\left(\frac{b}{L}\right)}{k_f+\frac{2}{3}\left(\frac{b}{L}\right)(k_s-k_f)}+\frac{\frac{\sqrt{3}}{2}-\frac{b}{L}}{k_f+\frac{4r}{3\sqrt{3}}\left(\frac{b}{L}\right)(k_s-k_f)}\right)\right]^{-1}$$

$$\frac{b}{L}=\frac{-r+\sqrt{r^2+\frac{2}{\sqrt{3}}(1-\varepsilon)\left(2-r\left(1+\frac{4}{\sqrt{3}}\right)\right)}}{\frac{2}{3}\left(2-r\left(1+\frac{4}{\sqrt{3}}\right)\right)}$$

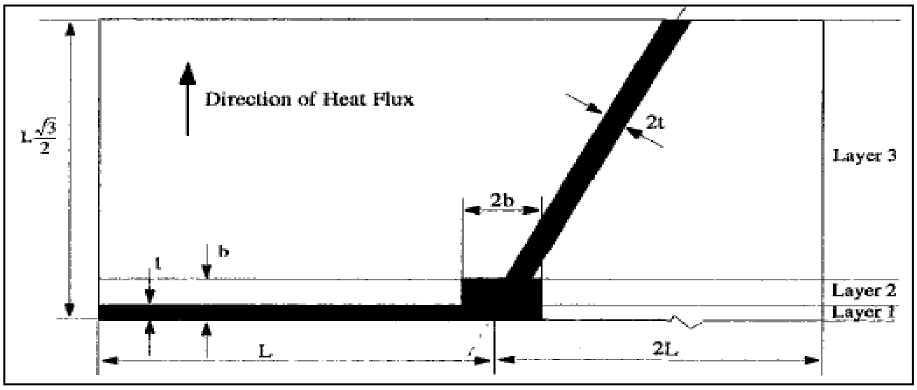


Figure 2: Unit-cell representation of hexagonal structure [30]

Calmidi and Mahajan [30] analysis was adjusted by Bhattacharya et al. [27] to improve a model with a circular intersection.

$$k_{eff} = \left[\left(\frac{2}{\sqrt{3}}\right)\left(\frac{t/L}{k_f+\frac{(k_s-k_f)}{3}} + \frac{\frac{\sqrt{3}}{2}-\left(\frac{t}{L}\right)}{k_f}\right)\right]^{-1}$$

$$\frac{t}{L} = \frac{-\sqrt{3}-\sqrt{3+(1-\varepsilon)(\sqrt{3}-5)}}{1+\frac{1}{\sqrt{3}}-\frac{8}{3}}$$

There are other formulations developed in order to compute the effective thermal conductivity listed by Raed et al. (2015) [10]. Some of these formulations are listed in Table (2).

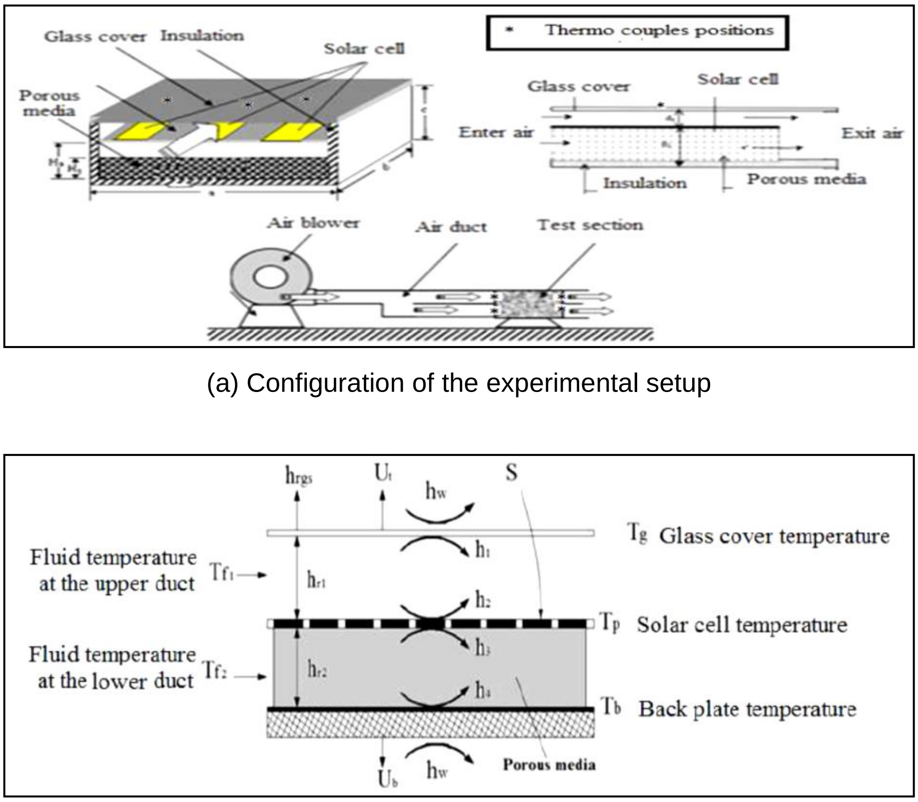
Table 2 Formulations developed to compute the effective thermal conductivity**.**

Relation	Reference
$k_{eff} = k_f\left(\left(1-\sqrt{1-\varepsilon}\right) + \frac{2\sqrt{1-\varepsilon}}{1-\sigma B}\left[\frac{(1-\sigma)B}{(1-\sigma B)^2} ln\left(\frac{1}{\sigma B}\right) - \frac{B+1}{2} - \frac{B-1}{1-\sigma B}\right]\right)$	Jiang and Lu [25]
$k_{eff} = thermal\ dispersion\ conductivity + stagnant\ thermal\ conductivity$	Hadim and North [31]
$k_{eff} = \frac{\left[M\left(\varepsilon k_f + (1-\varepsilon)k_s\right) + (1-M)\right]}{\left(\frac{\varepsilon}{k_f} + \frac{1-\varepsilon}{k_s}\right)}$	Bhattacharya et al. [27]
$(k_{eff})_x = \varepsilon k_f + (1-\varepsilon)k_s + 0.5\,\mathrm{Pr}\,Re_d\left(\frac{u}{u_m}\right)k_f$ $(k_{eff})_y = \varepsilon k_f + (1-\varepsilon)k_s + 0.1\,\mathrm{Pr}\,Re_d\left(\frac{u}{u_m}\right)k_f$	Wakao and Kaguei [32]

Porous Media-Based PV/T System

Many researchers applied the porous media in the PV/T system to enhance the system's performance.

Ahmed et al. (2017) studied experimentally the impact of porous media (glass spheres) on the performance of the PV/T system, see Fig (3). The findings indicate that the utilization of porous media led to an expansion of the heat transfer area, consequently enhancing the thermal efficiency [33].



(a) Configuration of the experimental setup

(b) Mechanism of heat transfer

Figure 3: Sketch of the hybrid collector with porous media [33]

Mousavi et al. (2018) investigated numerically the thermal performance of the PV/T system combined with Phase Change Materials (PCMs) in the porous medium, see Fig (4). The metal foam was used like a porous medium, also the performance of five various PCMs organic and inorganic was studied. The results showed that when using storage material of Paraffin C22 and a mass flow rate of 0.02 kg/s, the system's thermal efficiency would be 83%. Furthermore, add the porous medium result in the best distribution of the temperature, and higher thermal performance has resulted in the porosity of 0.8. Also, they find out that the exergy efficiency was 16.7% for the PV/T module with PCM-filled metal foam [34].

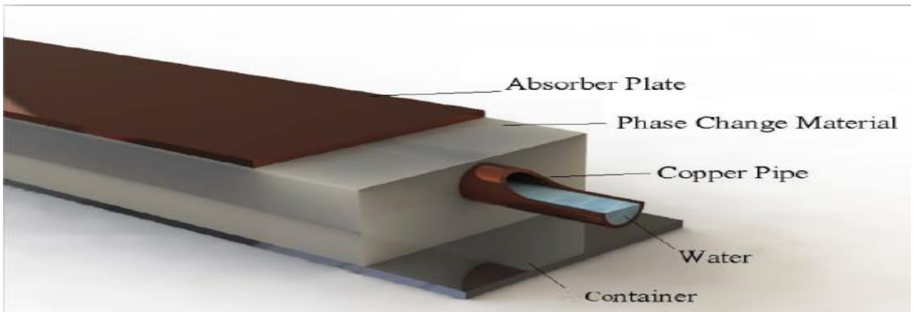


Figure 4: Schematic of the simulation model [34]

Rad et al. (2020) studied experimentally integration of two methods which are the porous media and the PCMs to improve a PV/T system's performance, see Fig (5). They developed the porous media utilizing aluminum shavings, to increment the thermal conductivity of PCM. Their findings were that the PV unit, combined with PCM and porous media possessed high cooling efficiency by decreasing a PV panel's average temperature. A reduction of 24°C would increase the electrical efficiency by about 2.5% in contrast with the single PV. In addition, it was found that the melting time of the PCM had reduced by almost 19%-25% by utilizing the porous medium. By using this way, the max energy efficiency enhancement would be 4.34% [35].

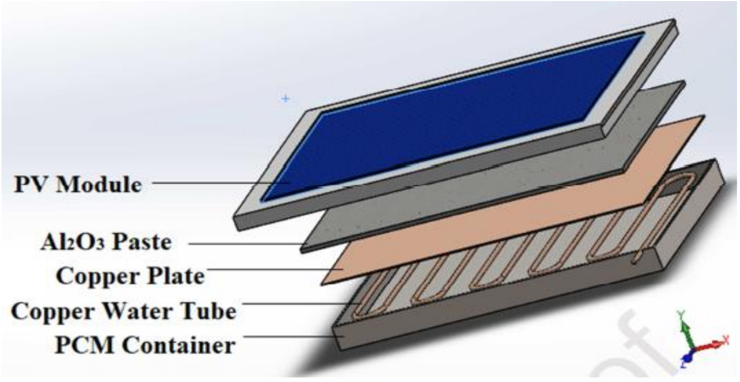


Figure 5: A schematic of the component arrangement for the experimental PV/T setup construction [35]

Essa et al. (2021) investigated experimentally the impact of combined use phase change material of Paraffin and porous media of Stainless-Steel Wool (SSW) to decline the temperature and utilize the thermal energy of the PV/T system, see Fig (6). Comparisons were made using two alternative systems, one has SSW with paraffin whereas the other contains paraffin alone. Water was employed as a heat transfer fluid at three various flow rates of: 0.0033, 0.005, and 0.0067 Letters/Second. The outcomes revealed that the system with a porous metallic media was found to have a low surface temperature, greater electrical efficiency, and improved total efficiency for all of the flow rates examined. The PV cell's temperature dropped from 5 to 25°C. Overall efficiency increased from 10% to 28%, while electrical efficiency increased from 1% to 4% [36].

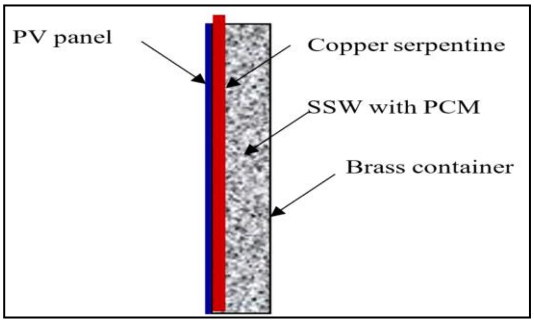


Figure 6: The internal components of the PV/T system [36]

Abed et al. (2021) investigated experimentally the influence of using porous media of glass spheres upon PV/T system's performance, see Fig (7). The research findings revealed that the utilization of porous media enhances the thermal and electrical efficiency of the hybrid PV/T system. The inclusion of porous media resulted in an 11.36% improvement in the system's overall efficiency. Additionally, the electrical efficiency increased by 2.2%, and the overall thermal efficiency rate improved by 10.51% [37].

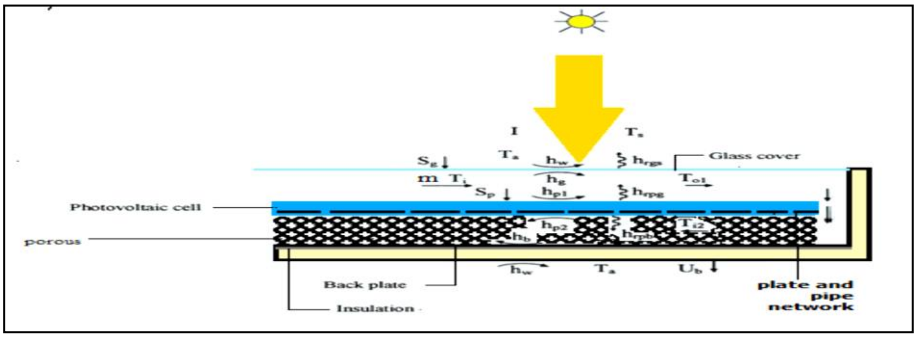


Figure 7: Schematic of hybrid PVT system with porous medium and heat transfer coefficients [37]

Tahmasbi et al. (2021) investigated numerically utilizing porous media of metal foams to improve the thermal and electrical efficiency of photovoltaic thermal/air system (PV/T/air), see Fig (8). The influence of different parameters on such efficiencies, porous layer thickness, Reynolds number, and solar heat flow, were studied as well. Their findings demonstrated that the use of porous media would improve both electrical and thermal efficiency, albeit resulting in a pressure loss ranging from 3 to 4 percent for electrical efficiency and 10 to 40 percent for thermal efficiency. However, it also exerts a negative effect in cases where the thickness surpasses half of a channel height [38].

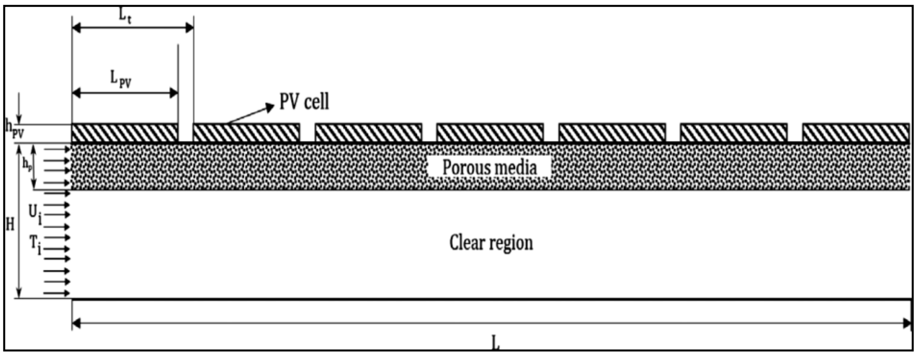


Figure 8: PV/T air system [38]

Conclusion

Porous media with photovoltaic/thermal systems have been the subject of numerous studies. The current review provides an in-depth examination of recent advances and applications of porous media to improve heat transfer performance in PV/T systems. In conclusion, our investigation yielded the following findings:

- Due to its effective thermal conductivity, the porous media has a high convection heat transfer.
- The exergy efficiency increases for the PV/T module by using metal foam filled with Phase Change Materials PCMs.
- The PV unit, combined with PCM and porous media has high-performance cooling by decreasing average temperature of the PV panel.
- Using porous media with the PV/T systems possess a lower surface temperature and hence improves the total electrical and thermal efficiency of the systems.

References

[1] NT Ibraheem, HH Hussain, OL Khaleed 2021, Modelling Heat Transfer in Solar Distiller with Additional Condenser Studying. Al-Mustansiriyah Journal of Science 32, 25-32.

[2] OA Kreem, HH Hussain 2021, Performance of Elliptical Solar Cooker Suitable for Baghdad Environment. Al-Mustansiriyah Journal of Science 32, 1-5.

[3] AR Salih 2023, Seasonal Optimum Tilt Angle of Solar Panels for 100 Cities in the World. Al-Mustansiriyah Journal of Science 34, 104-110.

[4] NK Kasim, HH Hussain, AN Abed 2021, Enhancement of some electrical parameters of grid-connected PV solar system using planer concentrators. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-13.

[5] SB Riffat, E Cuce 2011, A review on hybrid photovoltaic/thermal collectors and systems. International Journal of Low-Carbon Technologies 6, 212-241.

[6] S Misha, AL Abdullah, N Tamaldin, M Rosli, F Sachit 2020, Simulation CFD and experimental investigation of PVT water system under natural Malaysian weather conditions. Energy Reports 6, 28-44.

[7] R Kourav, P Baredar, P Malviya, N Sharma 2015, A review on advancements and application of nanotechnology in solar PV/T system. Int. J. of Adv. Res. in Electrical, Electronics and Inst. Engg 4, 2226-2230.

[8] M Shojaeefard, N Sakran, M Sharfabadi, N Davoudi 2021, in IOP Conference Series: Materials Science and Engineering. IOP Publishing 1067, 012099.

[9] MH Alktranee 2017, A review of performance hybrid photovoltaic/thermal system for general-applications. Hungarian Agricultural Engineering 32, 5-15.

[10] RA Mahdi, H Mohammed, K Munisamy, N Saeid 2015, Review of convection heat transfer and fluid flow in porous media with nanofluid. Renewable and Sustainable Energy Reviews 41, 715-734.

[11] DA Nield, A Bejan 2006, Convection in porous media. Springer 3.

[12] RA Mahdi, H Mohammed, K Munisamy, N Saeid 2015, Experimental and numerical investigation of combined convection heat transfer and fluid flow around circular cylinder through rectangular and trapezoidal Open-Cell aluminum foams. Chemical Engineering Communications 202, 674-693.
[13] RA. Mahdi, H Mohammed, K Munisamy 2013, Improvement of convection heat transfer by using porous media and nanofluid. Int. J. Sci. Res. 2, 2319-7064.
[14] RW Zimmerman, 2017. World Scientific.
[15] L Xue, X Guo, H Chen 2021, Fluid Flow in Porous Media: Fundamentals and Applications. World Scientific.
[16] R Chand 2017, Nanofluid technologies and thermal convection techniques. IGI Global.
[17] Y Su, JH Davidson 2015, Modeling approaches to natural convection in porous media. Springer.
[18] Z Heinemann, G Mittermeir 2013, Fluid flow in porous media.
[19] PX Jiang, M Li, TJ Lu, L Yu, ZP Ren 2004, Experimental research on convection heat transfer in sintered porous plate channels. International Journal of Heat and Mass Transfer 47, 2085-2096.
[20] WS Fu, HC Huang, WY Liou 1996, Thermal enhancement in laminar channel flow with a porous block. International Journal of Heat and Mass Transfer 39, 2165-2175.
[21] K Boomsma, D Poulikakos 2001, On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam. International Journal of Heat and Mass Transfer 44, 827-836.
[22] K Boomsma, D Poulikakos, F Zwick 2003, Metal foams as compact high performance heat exchangers. Mechanics of materials 35, 1161-1176.
[23] A Toth, E Bobok 2016, Flow and heat transfer in geothermal systems: basic equations for describing and modeling geothermal phenomena and technologies. Elsevier.
[24] G Belforte, T Raparelli, V Viktorov, A Trivella 2007, Permeability and inertial coefficients of porous media for air bearing feeding systems. Journal of Tribology 129
[25] PX Jiang, XC Lu 2006, Numerical simulation of fluid flow and convection heat transfer in sintered porous plate channels. International Journal of Heat and Mass Transfer 49, 1685-1695.
[26] R Nebbali, K Bouhadef 2011, Non-Newtonian fluid flow in plane channels: Heat transfer enhancement using porous blocks. International journal of thermal sciences 50, 1984-1995.
[27] A Bhattacharya, VV Calmidi, RL Mahajan 2002, Thermophysical properties of high porosity metal foams. International journal of heat and mass transfer 45, 1017-1031.
[28] VV Calmidi 1998, Transport phenomena in high porosity fibrous metal foams. University of Colorado at Boulder.
[29] B Ghanbarian, H Daigle 2016, Thermal conductivity in porous media: Percolation-based effective-medium approximation. Water Resources Research 52, 295-314.
[30] V Calmidi, R Mahajan 1999, The effective thermal conductivity of high porosity fibrous metal foams.
[31] H Hadim, M North 2005, Forced convection in a sintered porous channel with inlet and outlet slots. International journal of thermal sciences 44, 33-42.
[32] N.Wakao, S Kagei 1982, Heat and mass transfer in packed beds. Taylor & Francis 1.
[33] OK Ahmed, ZA Mohammed 2017, Influence of porous media on the performance of hybrid PV/Thermal collector. Renewable Energy 112, 378-387.
[34] S Mousavi, A Kasaeian, MB Shafii, MH Jahangir 2018, Numerical investigation of the effects of a copper foam filled with phase change materials in a water-cooled photovoltaic/thermal system. Energy Conversion and Management 163, 187-195.
[35] MAV Rad, A Kasaeian, S Mousavi, F Rajaee, A Kouravand 2021, Empirical investigation of a photovoltaic-thermal system with phase change materials and aluminum shavings porous media. Renewable Energy 167, 662-675.
[36] MA Essa, A Amer, MT Mostafa, M Farahat 2021, Enhancing the Power Conversion of Photovoltaic Systems with Metallic Porous Media and Phase Change Material. Egyptian Journal for Engineering Sciences and Technology 36, 72-80.
[37] FM. Abed, AH Jassim, MA Mohamed 2021, Design, Development and Performance investigation of a double-pass hybrid solar heater using porous media. Advances in Mechanics 9, 1121-1140.
[38] M Tahmasbi, M Siavashi, AM Norouzi, MH Doranehgard 2021, Thermal and electrical efficiencies enhancement of a solar photovoltaic-thermal/air system PVT/air using metal foams. Journal of the Taiwan Institute of Chemical Engineers 124, 276-289.