Experimental and Numerical Study of the Performance Improvement of the Solar Dryer Equipped with PVT

Mohamed Fterich
Department of Industrial Engineering, College of Engineering, Northern Border University, Saudi Arabia | Laboratory of Electromechanical Systems (LASEM), University of Sfax, Tunisia
mohamed.fterich@enis.tn (corresponding author)

Ahmed Saadeddine Souissi
Department of Industrial Engineering, College of Engineering, Northern Border University, Saudi Arabia
souissi.ahmed@gmail.com

Ezzeddine Touti
Department of Electrical Engineering, College of Engineering, Northern Border University, Saudi Arabia | Department of Electrical Engineering, Higher Institute of Applied Sciences and Technology of Kasserine, Kairouan University, Tunisia
ezzeddinetouti@gmail.com

Hatem Bentaher
Laboratory of Electromechanical Systems (LASEM), University of Sfax, Tunisia
bentaherh@yahoo.com

Received: 25 February 2024 | Revised: 5 March 2024 | Accepted: 15 March 2024

ABSTRACT

This research addresses the improvement of the performance of a solar dryer equipped with a PVT unit by integrating a heat exchanger into the drying system. The results indicated that introducing a heat exchanger into the drying process had a positive impact on enhancing and raising the drying temperature by harnessing the amount of free energy dissipated after the drying operation. The absorbed energy ranged from 30 J/s to 275 J/s from the hot air emitted throughout the drying process during the day, depending on the drying temperature. This paper also discusses the influence of the drying room design on the thermal balance within the room. Consequently, four different designs for the drying room were developed and studied with the COMSOL software. The findings revealed that the design-4, which optimally places two air inlets (one at the bottom and one at the top) on one side, whereas the opposing side has a centralized air outlet, utilizing a fan to ensure effective air circulation, is the best solution in terms of thermal balance and distribution of the drying air inside the drying chamber.

Keywords-solar dryer; PVT; solar energy; enhanced heat transfer; heat exchanger; 3D CFD simulation

I. INTRODUCTION

Solar drying is an environmentally beneficial and energy-efficient way of preserving agricultural and food goods, that uses solar energy to evaporate moisture from products, increasing their shelf life and preventing rotting [1-2]. In addition, solar dryers have proven to be highly beneficial in regions abundant with sunlight, offering an effective solution for the preparation and preservation of crops, fruits, vegetables, herbs, meat, or fish [3]. As a result, solar dryers emerge as a sustainable post-harvest processing solution, reducing reliance on fossil fuels and traditional power sources. Their efficacy in lowering waste, energy consumption, and post-harvest losses highlights the pivotal role that solar dryers play in enhancing food security, promoting economic development, and advancing environmental sustainability [4]. According to the literature review there are four types of solar dryers: (1) Open, (2) direct, (3) indirect, and (4) mixed solar dryer [5]. Solar dryers have much lower operating costs than conventional drying technologies that need electricity or fossil fuels since they use the free solar energy [6, 7]. Also, solar drying preserves the nutritional value of dried items better than the other procedures because the low drying temperatures prevent vitamin and mineral breakdown [8, 9]. The removal of moisture via solar drying limits the formation of germs, molds, and yeasts, hence extending product shelf life [10]. Solar dryers can be especially useful in areas where the electricity is scarce [11]. Solar dryers are pieces of adaptable drying equipment. They can be customized to meet the individual needs of various materials and climates [12]. Various studies have explored innovative approaches, design modifications, and technological interventions to elevate the overall performance of solar dryers [3, 13-15]. One key area of research involves the integration of photovoltaic/thermal (PVT) air collectors. Using a PVT collector for drying combines the benefits of electricity generation and thermal energy production, making it a highly efficient and sustainable option [16]. Overcoming temperature limitations in PVT collectors for drying involves implementing design and operational strategies to maximize the thermal energy output of the system [17-18]. Furthermore, the benefits of employing renewable energy sources in isolated regions are evident [19].

Despite numerous studies that have investigated the performance of solar dryers and how to ameliorate them, including design modifications, innovative techniques, and experimental evaluations, continuous development is necessary to enhance modern solar dryers [11, 20-22], to meet the evolving requirements of various applications and achieve higher efficiency standards. Therefore, this paper specifically focuses on improving the performance of a solar dryer by integrating a PVT air collector with a heat exchanger in the drying process. By focusing on this integration, the study aims to explore and optimize the potential synergies between solar drying processes using a PVT technology and the heat exchanger. This research also sheds light on the extent of the impact of the drying room design on the efficiency of the dryer and the quality of the dried product by studying the air diffusion and thermal balance of several designs of drying rooms, aiming to enhance the understanding of the importance of effective design when constructing a solar dryer.

II. MATERIALS AND METHODS

A. *Experimental Configuration*

The studied system presented in Figure 1 is a solar dryer with PVT operating under forced convection.

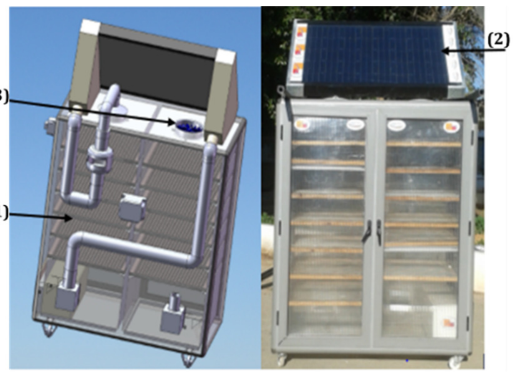

Fig. 1. Experimental solar test bench of the dryer with PVT.

It is a solar drying system with moderate efficiency and without energy storage or recycling of released air. It consists of two elements: (1) A drying chamber for the products to be dried containing racks and (2) a PR/T panel which heats the incoming air through solar radiation and generates a current. Table I provides a comprehensive overview of the dimensions pertaining to the drying chamber housed within the reel test bench. The characteristics of the instrument used in the experimental test to measure the variation of the solar radiation and drying temperature during the drying process are listed in Table II, and their positions are displayed in Figure 2.

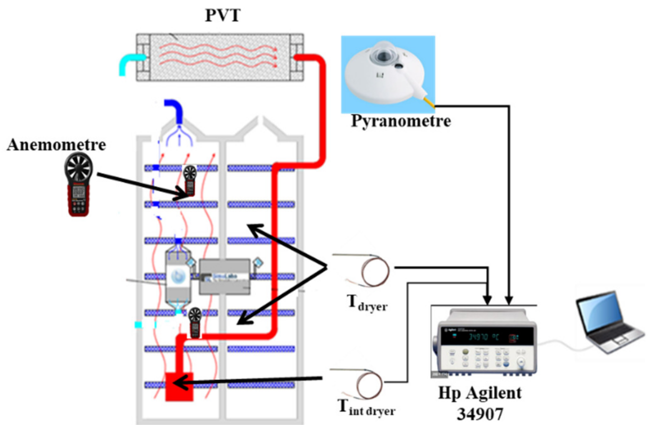

Fig. 2. Experimental test bench with measurement positions.

TABLE I. DRYER SPECIFICATIONS OF THE AT STANDARD ANALYZING PARAMETER

Material	Polycrystalline silicon
Lenth (mm)	810
Width (mm)	750
Hight (mm)	1600

TABLE II. EXPERIMENTAL EQUIPMENT

Sensor/Type	**Reference**	**Application**	**Sensibility/ Accuracy**
Pyranometer	CIMEL CE 1180	Solar radiation	12.29 µV/Wm^2 ±1 W/m^2
Thermocouple type J	N.I.S.T-ITS-90	Temperature	10µV/°C ±0.75 %
Anemometer	KIMO TH 100-AOD	Velocity	m/s ±2%

B. *Numerical Simulations*

To study the new dryer designs, numerical simulations in a temporal state are carried out using the finite element software COMSOL Multiphysics. Equation (1) delineates the fundamental partial differential equations governing continuity, while (2) articulates the corresponding momentum equations within the fluid layer.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

$$\begin{cases} u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}+w\dfrac{\partial u}{\partial z}=\vartheta\dfrac{\partial^2 u}{\partial x^2}-\dfrac{1}{p}\dfrac{\partial p}{\partial x} \\ u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}+w\dfrac{\partial v}{\partial z}=\vartheta\dfrac{\partial^2 v}{\partial y^2}-\dfrac{1}{p}\dfrac{\partial p}{\partial y} \\ u\dfrac{\partial w}{\partial x}+v\dfrac{\partial w}{\partial y}+w\dfrac{\partial w}{\partial z}=\vartheta\dfrac{\partial^2 w}{\partial z^2}+\rho.g \end{cases} \quad (2)$$

As heat transfer physics plays a pivotal role in our model for analyzing temperature distribution, the system of equations (3) has been formulated to depict three-dimensional heat transfer within the drying chamber:

$$\begin{cases} \rho.Cp\dfrac{\partial T}{\partial t}+\rho.Cp.u\dfrac{\partial T}{\partial x}-\lambda\dfrac{\partial^2 T}{\partial x^2}=0 \\ \rho.Cp\dfrac{\partial T}{\partial t}+\rho.Cp.u\dfrac{\partial T}{\partial y}-\lambda\dfrac{\partial^2 T}{\partial y^2}=0 \\ \rho.Cp\dfrac{\partial T}{\partial t}+\rho.Cp.u\dfrac{\partial T}{\partial z}-\lambda\dfrac{\partial^2 T}{\partial z^2}=0 \end{cases} \quad (3)$$

Solid-liquid walls without viscous stress are subject to non-slip conditions. This is described by:

$$\begin{cases} u=0 \\ v=0 \\ w=0 \end{cases} \quad (4)$$

The thermal insulation is described by:

$$-n\left(-K\ \nabla\ T\right)=0 \quad (5)$$

The limit conditions at the outlet of the PVT are defined by:

$$P=P_{atm} \quad (6)$$

In the envisioned dryer designs, the resolution of heat transfer equations and airflow equations is attainable by accounting for the relevant boundary conditions. Specifically, the initial temperature at time t = 0 is set as $T=T_0$ for various components within the drying chamber.

In the proposed drying chamber design, the heat transfer equations and airflow equations can be solved considering the corresponding boundary conditions. Furthermore, at the chamber inlet, the air velocity is equal to 1 m/s, while the temperature varies with time (Figure 3).

A basic mesh model (Figure 4), was created in order to assess its suitability for the designed prototype. Three government equations (energy, radiation, and k-ε) were employed, and the Reynolds-Averaged Navier-Stokes (RANS) method was selected to reduce computational costs by averaging velocity and pressure fields over time. The equation system was implemented in COMSOL Multiphysics, coupling heat transfer and airflow distribution through non-isothermal flow.

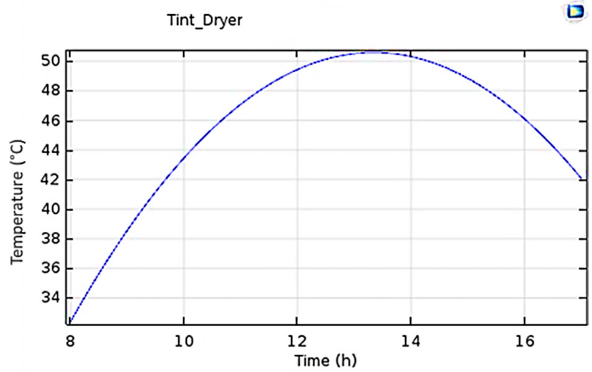

Fig. 3. Inlet temperature of the drying chamber.

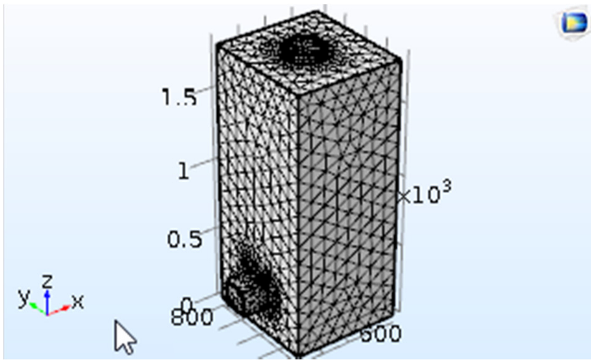

Fig. 4. Mesh of the drying chamber.

III. RESULTS AND DISCUSSION

Building upon this study's experimental investigation as depicted in Figure 5, a notable observation emerges: the outlet temperature of the drying chamber consistently surpasses the inlet temperature of the PVT.

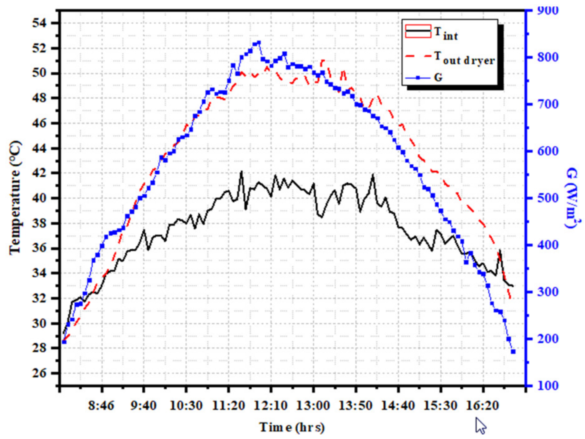

Fig. 5. Temporal variation of the PVT inlet temperature and the drying chamber outlet temperature.

This temperature difference presents an intriguing opportunity for optimizing energy utilization within the system. The surplus energy dissipating the post-drying process represents a potential source for harnessing additional thermal energy. To capitalize on this, the integration of a heat exchanger strategically positioned between the drying chamber and the PVT system (Figure 6) is proposed. This innovative approach aims to recover and channel the excess thermal energy from the higher outlet temperature to the lower inlet temperature, thereby maximizing the overall energy efficiency of the system. By incorporating a heat exchanger into this configuration, it is anticipated not only for energy loss to be mitigated, but also for the overall performance and sustainability of the drying process to be enhanced. This integration aligns with the principles of energy conservation and offers a practical solution to optimize the utilization of thermal energy within the system.

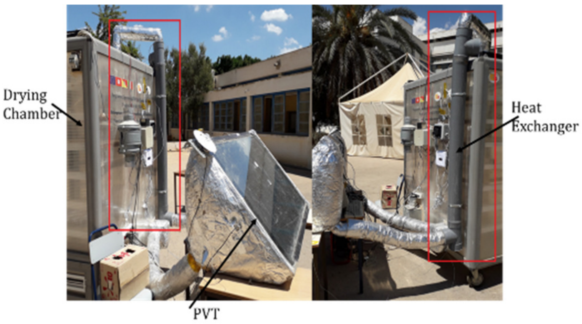

Fig. 6. Solar dryer with PVT and heat exchanger.

A. *Energy Amount obtained from the Installed Heat Exchanger*

Figure 7 depicts the operating principle of the solar dryer with a heat exchanger between the drying chamber and the PVT panel to harness the amount of dissipated energy. This heat exchanger consists of double coaxial tubes, where the outlet of the drying chamber serves as the inlet for the hot fluid and the ambient air acts as the cold fluid. Due to the forced convection between the ambient air and the aluminum duct, the heated air will enter the PVT panel. This results in the preheating of the air before it enters the PVT.

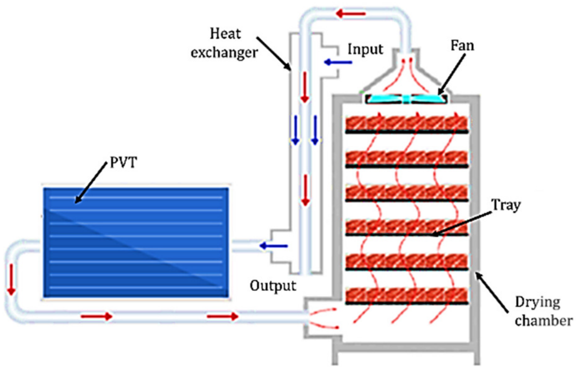

Fig. 7. Operating principle of a solar dryer with a heat exchanger.

Figure 8 illustrates the energy savings achieved through the implementation of the heat exchanger. The findings reveal a dynamic range in the energy absorption by the exchanger, fluctuating between a minimum of 30 J/s and a maximum of 252 J/s. It is worth noting that this energy absorption demonstrates an upward trend corresponding to the increase in solar radiation throughout the day. The experimental data unequivocally support the conclusion that the heat exchanger plays a pivotal role in enhancing the drying process. By effectively harnessing energy that would otherwise be dissipated into the surroundings, the heat exchanger contributes positively to the overall efficiency of the system. This not only underscores the technical prowess of the heat exchanger, but also emphasizes its sustainable impact in mitigating energy wastage during the drying process. Further analysis and optimization of these results could potentially lead to even more efficient and impactful applications in various contexts.

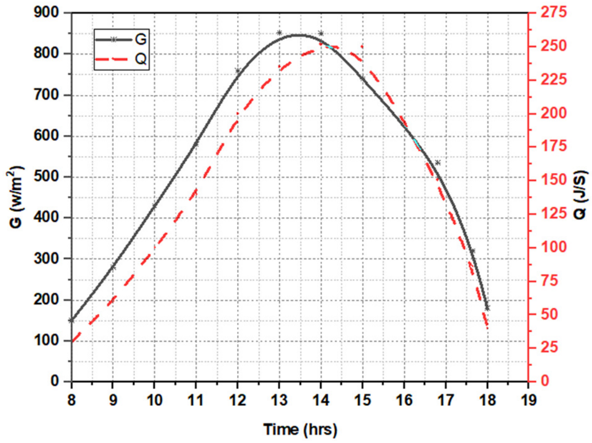

Fig. 8. Temporal variation of the quantity of the energy absorbed by the heat exchanger and the solar radiation during the day.

B. *Temperature Evolution in the Dryer before and after the Addition of the Heat Exchanger*

An experimental study was undertaken to scrutinize the impact of the incorporation of the heat exchanger on the drying temperature. Accordingly, Figures 9 and 10 depict the variations in key drying parameters, including G (W/m^2), T_a (°C), $T_{int\text{-}dryer}$ (°C), and T_{dryer} (°C), for both systems with and without the heat exchanger. The investigation encompassed a comparative analysis of the dryer's efficiency before and after the introduction of the heat exchanger into the drying process. The results revealed a significant difference in drying temperatures within the dryer throughout the day, indicating a gradual increase in the drying temperature with the rising solar radiation. This trend reflects the growing impact of sunlight on the performance of the drying process. Figure 11 presents the evolving drying temperature within the drying chamber for the integrated dryer and without a heat exchanger. The results offer valuable insights into the thermal behavior of the system. Particularly noteworthy is the distinct thermal trajectory observed when the heat exchanger is integrated into the drying process. The data unequivocally point to a significant positive influence on the drying process. Also, the results show a rise in the drying temperature from 48 °C for the dryer without an exchanger to a peak of 53 °C for the dryer with an exchanger, clearly demonstrating the enhanced thermal efficiency achieved through the incorporation of the heat exchanger. This rise in temperature suggests improved heat transfer and more effective moisture removal, emphasizing the tangible benefits of this technological addition to the drying system. The nuanced understanding provided by Figure 8 lays the groundwork for informed adjustments and optimizations in drying operations, paving the way for heightened performance and enhanced overall efficiency.

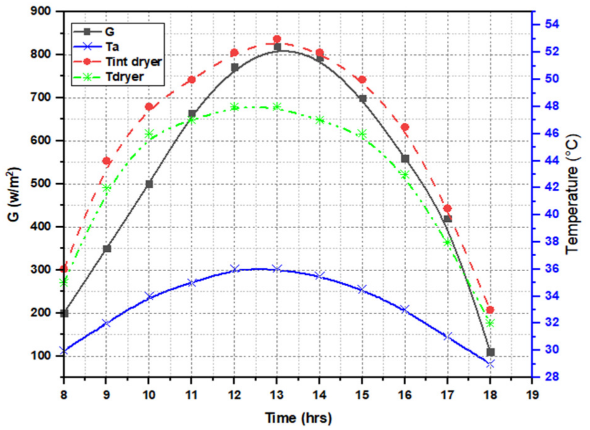

Fig. 9. Temperature evolution inside the dryer without the heat exchanger.

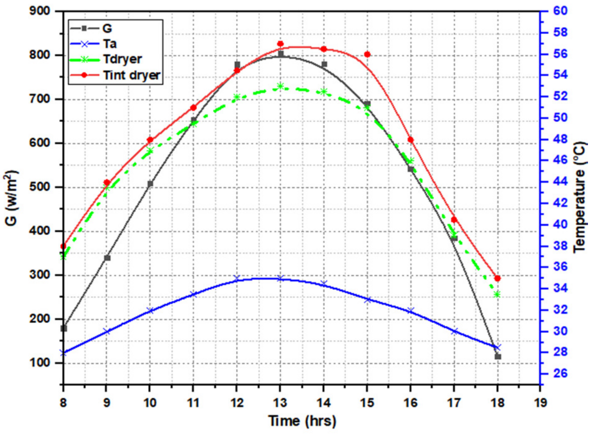

Fig. 10. Temperature evolution inside the dryer with the heat exchanger.

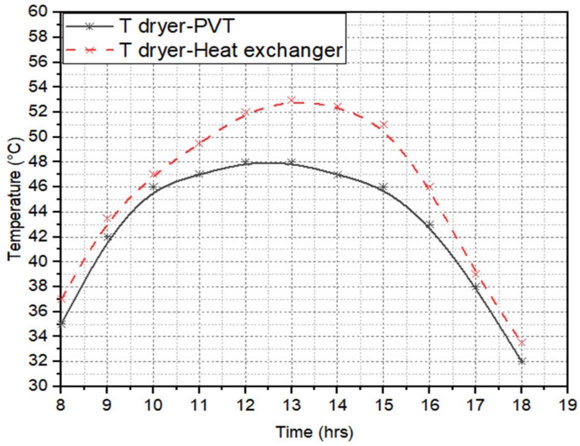

Fig. 11. Evolution of the temperature of the dryer with and without the exchanger.

C. Numerical Study of the Effect of the Solar Dryer Design on Temperature and Airflow Distributions

An experimental validation for the developed numerical simulation was carried out by comparing the temperature evolution in the chamber during experimentation with the numerical predictions. The results presented in Figure 12 indicate that the simulation aligns well with the experimental data. Therefore, it is highly reliable for studying the impact of room design on thermal balance during the drying process.

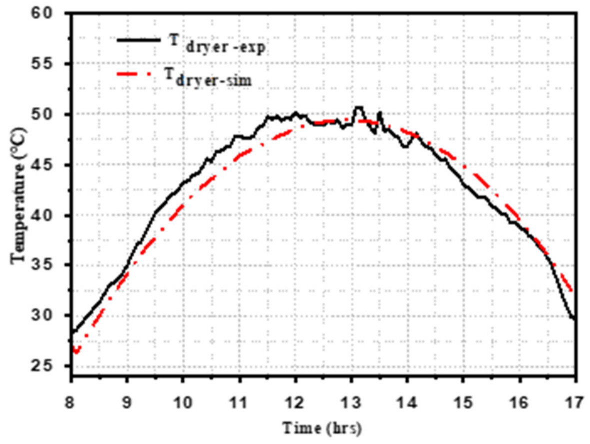

Fig. 12. Temperature evolution inside the drying chamber.

Given the critical role the design of the drying chamber plays in directly influencing the efficiency of the dryer, it becomes imperative to thoroughly investigate the impact of diverse designs on air circulation and drying heat through numerical analysis. To achieve this, the capabilities of Computational Fluid Dynamics (CFD) in COMSOL Multiphysics are utilized in order to understand the effect of the dryer design on the airflow distribution and drying temperature distribution inside the chamber. To comprehend this approach, we executed an assessment of four distinct drying chamber designs (see Figure 13).

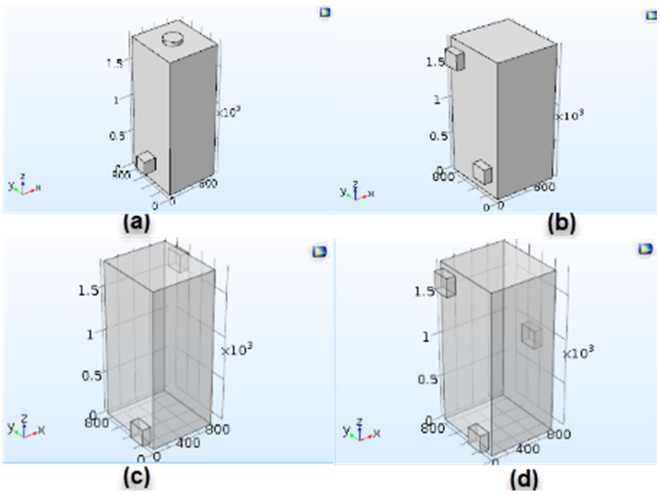

Fig. 13. Proposed designs of the drying chamber: (a) design-1, (b) design-2, (c) design-3, and (d) design-4.

Figure 14 presents a comprehensive representation of the four considered designs, showcasing their intricacies. Emphasis is specifically directed towards elucidating the nuanced configurations of the air inlet and outlet within the confines of the drying chamber. This visual aid serves as a crucial reference point for understanding the structural intricacies and airflow dynamics integral to each proposed design, contributing to a deeper comprehension of the overall drying process.

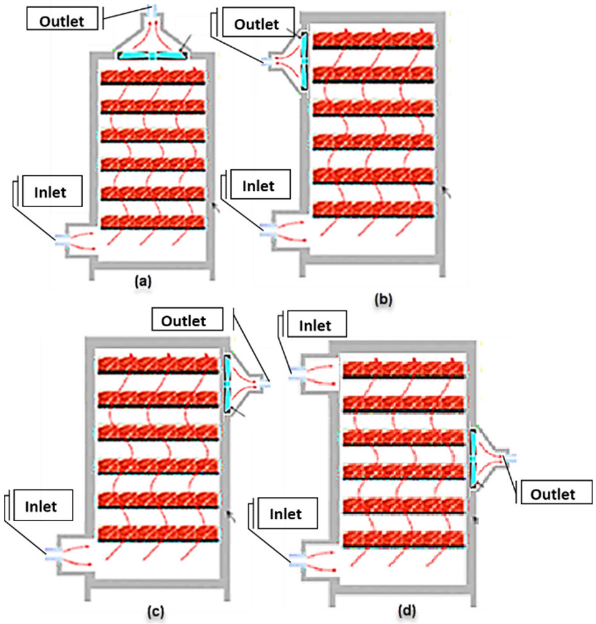

Fig. 14. Principle of operation of the proposed drying chambers: (a) design-1, (b) design-2, (c) design-3, and (d) design-4.

1) Temperature Evolution inside the Proposed Drying Chamber Designs

To assess the impact of drying chamber designs on temperature variations within the proposed configurations, a comprehensive numerical simulation of heat transfer distribution was executed for each of the four designs.

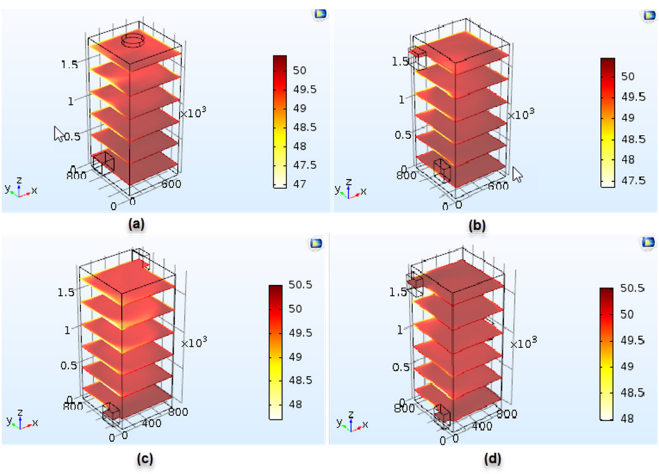

Fig. 15. 3D temperature distribution inside the proposed drying chambers: (a) design-1, (b) design-(2), (c) design-3, and (d) design-4.

The outcomes underscored the substantial influence of design choices on thermal uniformity within the chamber. Notably, the selection of airflow characteristics and the strategic placement of air inlet and outlet points emerged as pivotal factors shaping the thermal performance of the drying system. According to the results, design-4 performed best because it has a good thermal equilibrium along the drying chamber, in which, the difference between the highest (50.5 °C) and the lowest temperature (48 °C) was recorded inside the room. Also, the numerical simulations demonstrated that in a vertical flow solar dryer, optimal temperature distribution is achieved when the air inlet and outlet are positioned on the sides. This strategic placement enhances heat distribution and promotes more uniform drying throughout the chamber. The lateral configuration of the inlet and outlet facilitates efficient airflow, mitigating the risk of temperature variations and ensuring a consistently favorable drying environment. These findings underscore the importance of thoughtful design considerations in enhancing the overall effectiveness of solar drying systems.

2) Air distribution inside the Proposed Drying Chamber Designs

Figure 16 illustrates the airflow patterns within the drying chamber of the proposed designs. The findings derived from the numerical simulations accentuate the significant impact of the drying room's design on the intricate dynamics of air diffusion throughout the drying process. This discovery underscores the vital importance of careful consideration during the design phase to facilitate the safe and uniform flow of the dry air into and out of the room. The simulations bring attention to the critical need for strategic planning to ensure that the heated air reaches all surfaces within the drying chamber in a uniform manner. This meticulous approach not only enhances the overall efficiency of the drying process, but also plays a pivotal role in achieving comprehensive and consistent drying across all surfaces. Consequently, it must be emphasized that an effective design is essential for optimizing the performance of the dryer and additionally ensuring the quality and uniformity of the dried product.

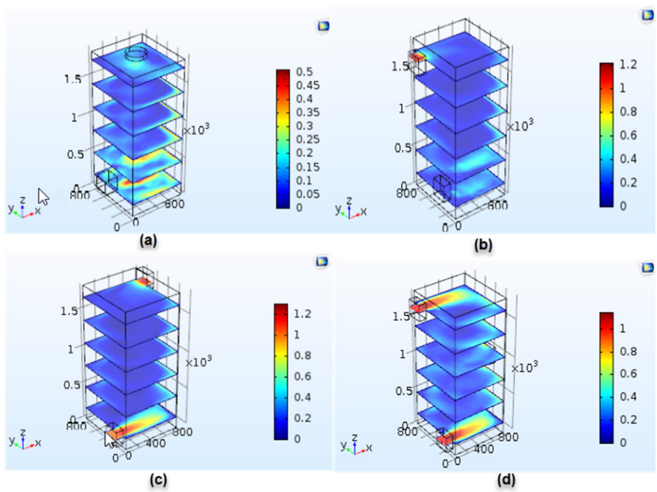

Fig. 16. 3D air flow distribution inside the proposed drying chambers: (a) design-1, (b) design-(2) (c), design-3 and (d) design-4.

IV. CONCLUSION

This research contributes to the theoretical advancements in solar drying, whereas it also provides pragmatic solutions to overcome challenges related to energy consumption, drying duration, and adaptability. The pressing global demand for sustainable and energy-efficient technologies underscores the significance of enhancing solar dryer performance as a key element in fostering eco-friendly alternatives across various drying applications, particularly in agriculture and other material processing sectors. The investigation delved into two distinct drying systems: one involving a solar dryer integrated with a photovoltaic/thermal (PVT) unit, and the other incorporating a solar dryer with a heat exchanger unit. A noteworthy finding was the positive impact observed when the heat exchanger was introduced into the drying process, resulting in an improvement in the drying temperature. This improvement subsequently translates into heightened dryer efficiency and an enhanced quality of the dried product. Moreover, the study extended its scope to analyze the influence of the design of the drying chamber on heat distribution and air circulation within the chamber. The conducted numerical simulations highlighted that the configuration of the drying chamber significantly affects the dryer's efficiency by influencing the thermal balance within the chamber. Furthermore, the pivotal role of chamber design in facilitating effective air circulation within the drying trays, a factor crucial for achieving optimal drying conditions, was showcased. This research contributes to the academic understanding of solar drying and also provides practical insights that can be instrumental in advancing sustainable and efficient drying technologies for real-world applications. Future research can conduct a techno-economic study of the solar drying unit, potentially uncovering new ways to enhance energy utilization in drying applications.

NOMENCLATURE

PVT:	Photovoltaic thermal panel
G:	Solar radiation (W/m^2)
λ	Thermal conductivity of air (W/m.K)
Cp	Specific heat capacity of air (J/kg.K)
T_a:	Ambient temperature (°C)
T_0:	Initial temperature (°C)
Q:	Quantity of energy absorbed by the heat exchanger (W)
ρ:	Air density (kg/m^3)
T_{dryer}:	Temperature inside the drying chamber (°C)
$T_{int\ dryer}$:	Inlet temperature of the drying chamber (°C)
$T_{dryer\text{-}PVT}$:	Temperature of the drying chamber with PVT (°C)
$T_{dryer\text{-heat exchanger}}$:	Temperature of the drying chamber with PVT and heat exchanger (°C)
u:	Air velocity component along axis x
v:	Air velocity component along axis y
w:	Air velocity component along axis z
exp:	Experimental
sim:	Simulation

ACKNOWLEDGMENT

The authors gratefully acknowledge the approval and the support of this research study by the grant no. ENGA-2023-12-2221 from the Deanship of Scientific Research, Northern Border University, Arar, K.S.A.

REFERENCES

[1] V. R. Mugi, P. Das, R. Balijepalli, and C. Vp, "A review of natural energy storage materials used in solar dryers for food drying applications," *Journal of Energy Storage*, vol. 49, May 2022, Art. no. 104198, https://doi.org/10.1016/j.est.2022.104198.

[2] N. B. Khedher, R. Ramzi, and I. A. Alatawi, "Numerical Comparison of Triangular and Sinusoidal External Vibration Effects on the 3D Porous Drying Process," *Engineering, Technology & Applied Science Research*, vol. 10, no. 2, pp. 5554–5560, Apr. 2020, https://doi.org/10.48084/etasr.3486.

[3] M. Fterich, H. Chouikhi, H. Bentaher, and A. Maalej, "Experimental parametric study of a mixed-mode forced convection solar dryer equipped with a PV/T air collector," *Solar Energy*, vol. 171, pp. 751–760, Sep. 2018, https://doi.org/10.1016/j.solener.2018.06.051.

[4] A. Fudholi, K. Sopian, M. H. Ruslan, M. A. Alghoul, and M. Y. Sulaiman, "Review of solar dryers for agricultural and marine products," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 1–30, Jan. 2010, https://doi.org/10.1016/j.rser.2009.07.032.

[5] L. Fernandes and P. B. Tavares, "A Review on Solar Drying Devices: Heat Transfer, Air Movement and Type of Chambers," *Solar*, vol. 4, no. 1, pp. 15–42, Mar. 2024, https://doi.org/10.3390/solar4010002.

[6] R. K. Saini *et al.*, "Technological development in solar dryers from 2016 to 2021-A review," *Renewable and Sustainable Energy Reviews*, vol. 188, Dec. 2023, Art. no. 113855, https://doi.org/10.1016/j.rser.2023.113855.

[7] A. Shahsavari and M. Akbari, "Potential of solar energy in developing countries for reducing energy-related emissions," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 275–291, Jul. 2018, https://doi.org/10.1016/j.rser.2018.03.065.

[8] Z. Deng, M. Li, T. Xing, J. Zhang, Y. Wang, and Y. Zhang, "A literature research on the drying quality of agricultural products with using solar drying technologies," *Solar Energy*, vol. 229, pp. 69–83, Nov. 2021, https://doi.org/10.1016/j.solener.2021.07.041.

[9] A. K. Babu, G. Kumaresan, V. A. A. Raj, and R. Velraj, "Review of leaf drying: Mechanism and influencing parameters, drying methods, nutrient preservation, and mathematical models," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 536–556, Jul. 2018, https://doi.org/10.1016/j.rser.2018.04.002.

[10] J. P. Ekka and D. Kumar, "A review of industrial food processing using solar dryers with heat storage systems," *Journal of Stored Products Research*, vol. 101, Mar. 2023, Art. no. 102090, https://doi.org/10.1016/j.jspr.2023.102090.

[11] M. Ssemwanga, E. Makule, and S. I. Kayondo, "Performance analysis of an improved solar dryer integrated with multiple metallic solar concentrators for drying fruits," *Solar Energy*, vol. 204, pp. 419–428, Jul. 2020, https://doi.org/10.1016/j.solener.2020.04.065.

[12] Y. Mohana, R. Mohanapriya, T. Anukiruthika, K. S. Yoha, J. A. Moses, and C. Anandharamakrishnan, "Solar dryers for food applications: Concepts, designs, and recent advances," *Solar Energy*, vol. 208, pp. 321–344, Sep. 2020, https://doi.org/10.1016/j.solener.2020.07.098.

[13] F. Hussain, I. Akhtar, G. Murtaza, U. Haider, L. Rukh, and M. Awais, "Simulation and Performance Evaluation of Solar Tunnel Dryer for Apricot Drying in Northern Pakistan," *International Journal of Engineering and Applied Sciences*, vol. 9, no. 1, pp. 1–5, Mar. 2021.

[14] S. H. Bandaru, V. Becerra, S. Khanna, J. Radulovic, D. Hutchinson, and R. Khusainov, "A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications: Performance Indicators, Progress, and Opportunities," *Energies*, vol. 14, no. 13, Jan. 2021, Art. no. 3853, https://doi.org/10.3390/en14133853.

[15] P. Kumar and D. Singh, "Advanced technologies and performance investigations of solar dryers: A review," *Renewable Energy Focus*, vol. 35, pp. 148–158, Dec. 2020, https://doi.org/10.1016/j.ref.2020.10.003.

[16] H. A. Kazem, A. H. A. Al-Waeli, M. T. Chaichan, K. Sopian, A. S. Al Busaidi, and A. Gholami, "Photovoltaic-thermal systems applications as dryer for agriculture sector: A review," *Case Studies in Thermal Engineering*, vol. 47, Jul. 2023, Art. no. 103047, https://doi.org/10.1016/j.csite.2023.103047.

[17] P. Mani, P. K. Nataraj, S. Gopi, and V. S. Ponnappan, "A review on environmental effect of various designs and types of drying methods," *Environmental Quality Management*, https://doi.org/10.1002/tqem.22019.

[18] C. L. Oria and E. V. Palconit, "Performance Investigation of an Inflatable Solar Dryer with Steel-Can Solar Air Heater for Drying Coffee and Corn," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8707–8711, Jun. 2022, https://doi.org/10.48084/etasr.4966.

[19] E. A. Al-Ammar, N. H. Malik, and M. Usman, "Application of using Hybrid Renewable Energy in Saudi Arabia," *Engineering, Technology & Applied Science Research*, vol. 1, no. 4, pp. 84–89, Aug. 2011, https://doi.org/10.48084/etasr.33.

[20] A. B. Lingayat, V. P. Chandramohan, V. R. K. Raju, and V. Meda, "A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights," *Applied Energy*, vol. 258, Jan. 2020, Art. no. 114005, https://doi.org/10.1016/j.apenergy.2019.114005.

[21] W. Wang, M. Li, R. H. E. Hassanien, Y. Wang, and L. Yang, "Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango," *Applied Thermal Engineering*, vol. 134, pp. 310–321, Apr. 2018, https://doi.org/10.1016/j.applthermaleng.2018.01.115.

[22] A. Khanlari, A. Sözen, C. Şirin, A. D. Tuncer, and A. Gungor, "Performance enhancement of a greenhouse dryer: Analysis of a cost-effective alternative solar air heater," *Journal of Cleaner Production*, vol. 251, Apr. 2020, https://doi.org/10.1016/j.jclepro.2019.119672, Art. no. 119672.