Comparative Numerical Analysis of Middle-Temperature and High Temperature versions of High-Vacuum Flat-Plate Collectors: Assessing Performance in the Field.

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Abstract

High Vacuum Flat Plate Collectors (HVFPCs) stand as a highly promising solution for renewable thermal energy generation. At present, TVP-Solar exclusively manufactures HVFPCs tailored for middle-temperature (MT) applications, with a maximum operating temperature of 200 °C. Recent advancements have yielded optimized absorbers designed for HVFPCs, enabling them to attain elevated temperatures (HT) up to 300 °C via optimization of optical parameters, thus effectively ameliorating the prevailing radiative losses affecting HVFPCs. This study employs dynamic simulation to analyze the daily performance of an HVFPCs test field. Our primary objective is to compare the performance of MT and HT HVFPCs configurations within the field, operating at temperatures of 150, 200 and 250 °C. The results of the numerical analysis not only highlight the advantage of the optimized technology but also serve as a robust cornerstone for future undertakings, particularly in the formulation of advanced control strategies tailored for HT HVFPC-equipped fields.

Keywords: Solar Energy, Solar Thermal Collectors Field, High-Vacuum Flat-Plate Collectors, dynamic solar field simulations, Solar Field Performances

1. Introduction

The utilization of solar energy represents a straightforward and sustainable approach for producing thermal energy, catering to both domestic and industrial needs. Amongst the various solar energy technologies, Flat plate solar collectors (FPSCs) are the most established technology being the first FPC with a separate storage tank patented by William J. Bailey in 1910 (Schobert, 2014). FPCs consist of a dark absorber plate, typically made of metal or coated with a selective surface, enclosed within an insulated casing. The absorbed solar radiation heats the absorber plate, which in turn transfers the thermal energy to a circulating fluid, such as water or air (Benz and Beikircher, 1999). FPCs have emerged as structurally simple systems with low manufacturing costs (Karki et al., 2019) and minimal maintenance requirements, ensuring long-lasting operation. Another key advantage is their versatility, as they can be integrated into various building designs, both for new constructions and retrofitting existing structures (Al-Joboory, 2019). Their adaptability allows

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for seamless incorporation into roofs, walls, or ground-mounted systems, enabling homeowners and building owners to harness solar energy without significantly altering the architectural aesthetics.

Despite their numerous advantages, FPCs have some drawbacks compared to other solar thermal technologies. They heave lower thermal efficiency compared to evacuated tube collectors and concentrating solar thermal (CST) devices because of the substantial convective heat losses that limit their maximum achievable delivery temperature for domestic applications (60-90 °C) (Kalogirou, 2004).

Evacuated tube collectors, which utilize a vacuum to minimize heat loss, can achieve higher operating temperatures and better thermal efficiency, particularly in colder climates.

A promising advancement in flat collector technology is the introduction of high vacuum flat plate collectors (HVFPCs) by TVPSolar (“TVP Solar, (2023)). These collectors feature a flat design where the space between the absorber, glass cover, and collector case is evacuated, effectively eliminating convective thermal losses. This reduction in convective losses, along with minimized conductive losses due to architectural enhancements, results in significantly higher efficiency compared to conventional FPSCs operating at middle temperatures. A recent study by (Gao et al., 2022), demonstrated that an efficiently optimized HVFPC field achieved a stable annual average thermal efficiency of up to 50% at 123 °C. These results are remarkable for renewable thermal energy generation at middle temperatures.

Researchers have been actively investigating further improvements in HVFPC technology in recent years, focusing particularly on the selective solar absorber (SSA), the critical component of HVFPCs responsible for capturing solar irradiation. The fundamental characteristic of SSAs is that exhibit high solar absorptance in the solar spectrum range and minimal thermal emittance in the infrared region but, for flat collectors operating at temperatures above 123°C, (Cao et al., 2014), demonstrated that thermal emittance assumes greater importance than solar absorptance in terms of SSA efficiency. However, the current Middle Temperature (MT) commercial version of HVFPCs, MT Power, employs a commercial SSA with optical properties optimized for operation at 100 °C.

(De Maio et al., 2022) have developed low-emissive SSAs specifically designed for HVFPCs, optimized to operate at higher temperatures, thereby paving the way for the development of HVFPCs for High Temperatures (HT) applications. The HT version of TVPSolar HVFPC considered in this study maintains the same structural characteristics while adopting an SSA developed, designed, and optimized to work at 300°C.

A comprehensive performance comparison between the MT and HT versions of TVPSolar HVFPCs was conducted using a dynamic simulation model of a TVPSolar test field, implemented in Simulink. After validating the model with experimental data, the simulation was utilized to evaluate the performance of the field equipped with HT and MT panels at various operating temperatures (150°C, 200°C, 250°C). The simulation employed hourly meteorological data from Cairo for the year 2019. The validated simulation model facilitated a thorough assessment of the comparative performance of the HT and MT solar panels under different operating conditions. By analyzing the system behavior at 150°C, 200°C, and 250°C, the study provided a detailed understanding of the energy output and efficiency of both panel types across a range of operating temperatures.

2. Experimental system and Model Description

The solar plant model (Fig. 1) replicates an existing test field located on the rooftop of TVP-Solar headquarters in Avellino, Italy. This test field comprises 25 arrays, each consisting of 7 MT panels mounted with a tilt angle (β) of 15° and an azimuth angle (γ) of 0°. The collectors in each array are connected in series using hose connectors and are interlinked through supply and return pipelines, while the arrays are connected in parallel. Additionally, there is a third pipe that functions as a pressure equalizer, balancing the pressure between the two main pipes to prevent flow reversal in certain rows due to pressure differentials. A vent valve is also incorporated into the system to release excess pressure when necessary. The solar field follows a single-side module format, with the pipelines running laterally through the field.

At ground level, the thermal block consists of two subsystems. Subsystem 1 primarily includes a pressurization pump, an expansion vessel, and a buffer tank. These components work together to adjust the flow rate and maintain the system pressure within the desired range of 0.6-1.0 MPa. Since the facility currently lacks a designated application, Subsystem 2 becomes crucial when the heat transfer fluid (HTF) reaches its target temperature. In this case, the HTF is channeled for cooling. This subsystem is equipped with a dry cooler and an electromagnetic three-way valve. When the HTF's temperature at the field outlet surpasses the set threshold, the valve redirects it to the dry cooler for cooling before recirculation.

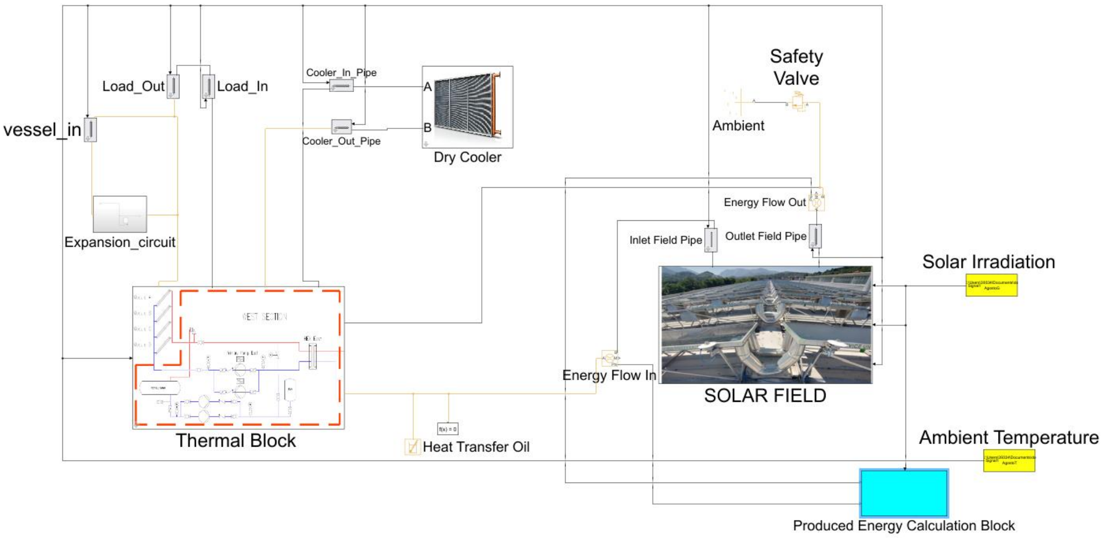

Figure 1 Simulink model of the HVFPCs Solar plant.

2.1 Mathematical Model of MT and HT HVFPCs

In this study, the instantaneous thermal power converted by each solar thermal collector and transferred to the heat transfer fluid (HTF) is modeled using the basic equation for solar thermal collector performance:

$$Q_c = \eta * A_c * G \tag{1}$$

This equation states that the power output (Q_c in Watts) is equal to the product of the collector efficiency (η), the collector surface area (A_c), and the incident solar irradiation (G) on the collector surface. The efficiency (η) of an HVFPC collector can be expressed as a function of the solar absorber optical properties, as shown in the following formula (Gaudino et al., 2023):

$$\eta_{th} = \alpha\tau f * IAM_\theta - \left\{\frac{\varepsilon_e(T_m)*\sigma\left[(T_m+273.15)^4-(T_{amb}+273.15)^4\right]}{G} * \frac{A_{abs}}{A_c} + \frac{k(T_m-T_{amb})^z}{G}\right\} \tag{2}$$

In this expression: α is the solar absorptance of the absorber surface, τ is the glass cover transmittance, *f* is the collector efficiency factor, which accounts for the difference between the HTF temperature and the average absorber temperature, *IAM* is the incidence angle modifier function, which describes the optical efficiency for a certain radiation incidence angle normalized by the optical efficiency at perpendicular irradiation (Lv et al., 2018), ε_e is the effective emittance of the absorber surface, T_m is the mean HTF temperature between field inlet and outlet, T_{amb} is the ambient temperature, A_{abs} is the absorber surface area, A_C is the collector surface area while *k* and *z* are constants related to the heat transfer characteristics of the collector. This comprehensive model captures the key factors that influence the thermal efficiency of the solar thermal collector, including optical, thermal, and geometrical parameters, allowing for a detailed performance analysis and optimization of the system.

For an HVFPC with the TVPSolar MT Power collector architecture, *k* and *z* were determined by a mathematical fit of experimental data (Gaudino et al., 2023) and equation (2) becomes:

$$\eta_{th} = \alpha\tau f * IAM_\theta - \left\{\frac{\varepsilon_e(T_m)*\sigma\left[(T_m+273.15)^4-(T_{amb}+273.15)^4\right]}{G} * \frac{A_{abs}}{A_c} + \frac{0.258(T_m-T_{amb})}{G}\right\} \tag{3}$$

The efficiency formula for the MT and HT versions of TVPSolar HVFPC, considered in this work, differs due to the optical properties of the solar absorbers adopted by each version. The coefficient of solar absorptance and the effective emittance of the commercial selective absorber used in the MT version of TVPSolar HVFPC were obtained experimentally by calorimetric measurements taken under Sun and LED light (D'Alessandro et al., 2022). The coefficient of solar absorptance in the solar spectrum of the absorber adopted by the HT version of TVPSolar HVFPC was obtained through the integration of the spectral absorptivity, determined by applying Fresnel laws once the refractive index of the materials composing the multilayer stack was experimentally characterized using a Horiba Jobin Yvon - UVISEL spectroscopic ellipsometer ("Spectroscopic Ellipsometry - HORIBA). The simulated values closely matched the absorptance obtained by reflectance measurements using an integrating sphere.

Unlike the commercial absorber, which has an aluminum substrate, the SSA of the HT HVFPC is a multilayer deposited on a copper substrate with very low thermal emittance. Measuring the thermal emittance of the HT absorber required a highly precise methodology. The effective emittance of the HT absorber was determined using an improved calorimetric procedure, as detailed by (Gaudino et al., 2024b). The coefficients of solar absorptance for the MT and HT absorbers are listed in Table 1, while the effective emittances as a function of absorber temperature are shown in Fig. 2(a). Substituting the optical properties of the absorbers into equation (3), the efficiencies of the MT and HT versions of the TVPSolar HVFCs were obtained and are illustrated in Fig. 3(b).

Table 1 Solar absorptance values for MT and HT absorbers.

SSA	α
MT	0.95
HT	0.89

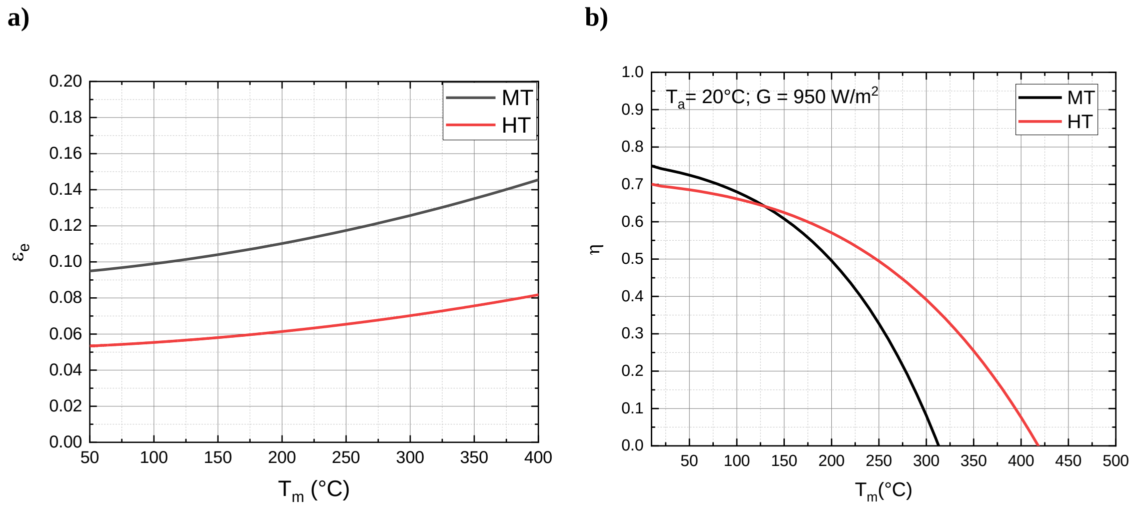

Figure 2 a) Effective thermal emittance as a function of absorber temperature for both MT and HT absorbers. b) Thermal efficiency curves of MT and HT HVFPCs as a function of absorber temperature, with an ambient temperature mantained at 20°C and solar irradiation of 950 W/m².

The efficiency of the HVFPC serves as the mathematical representation of a collector's performance within the Simulink model of the solar plant employed in this study.

As shown in Figure 2 b), the MT absorber exhibits higher thermal efficiency at lower temperatures compared to the HT absorber, which is more favorable at higher temperatures. Additionally, the HT absorber demonstrates a higher stagnation temperature, representing the maximum attainable absorber temperature (the equilibrium temperature between the absorbed and emitted power).

After formulating the mathematical representation of HVFPCs within the dynamic model, it was validated through experimental daily performance measurements.

2.2 Dynamic Solar HVFPCs field model validation

The performance measurements for validating the dynamic HVFPCs simulation model were carried out using the TVPSolar test field located in Avellino. It should be noted that the architectural constraints of the building roof influenced the structure of the installation.

The field is divided into two sections, each forming a 6° angle with the horizontal plane. Each set comprises seven panels: four on the east-facing surface and three on the west-facing surface. A comprehensive evaluation of plant performance must account for the varying orientations of the collectors within the arrays. The objective of the performance measurements was to monitor the solar field's daily productivity and efficiency. Water was the selected Heat Transfer Fluid (HTF), and the set-point temperature for each measurement day was determined accordingly.

To assess the field's performance, several parameters were measured, including HTF temperatures at the inlet and outlet of the solar field and dry cooler, HTF flow rates at the inlet of the solar field and dry cooler, solar irradiation, and ambient temperature. Solar irradiation was monitored separately on each side of the building roof using two pyranometers to capture localized variations in solar irradiation across the roof. The flow rate regulation took into account the average value of irradiation measured by the two pyranometers. The measurements were conducted when the solar irradiation (G) was greater than or equal to 150 W/m^2 to cover the full range of solar illumination.

Figure 3 (Gaudino et al., 2024a) displays the results obtained on July 9, 2023. The set-point temperature was maintained at 100 °C. The solar irradiation measurements were recorded from the east-facing pyranometer (G_{est}) and the west-facing pyranometer (G_{west}). The HTF flow rate (depicted in Figure 3 a)) is regulated to maintain the set-point temperature while providing a specific cooling power for the dry cooler. In Figure 3 b), P_{inc} represents the sum of solar power on the collectors positioned on the east-facing side of the roof (G_{est} * A_c * N_{C_est}) and the solar power incident on the collectors mounted on the west-facing side of the roof (G_{west} * A_c * N_{C_west}), where N_{C_est} and N_{C_west} are the number of collectors mounted on the east and west facing side of the roof, respectively. P_{conv} (W) represents the amount of power converted by the solar field while maintaining the set-point temperature. It is computed using the formula (4):

$$P_{conv} = \dot{m} * c_p * \Delta T \qquad (4)$$

The simulation takes into account various input parameters, including the HTF mass flow rate, solar irradiation, ambient temperature, set-point temperature, and dry cooler air flow rate for controlling the cooling power. To maintain consistency with the actual case, water was used as the circulating HTF with the same flow rate.

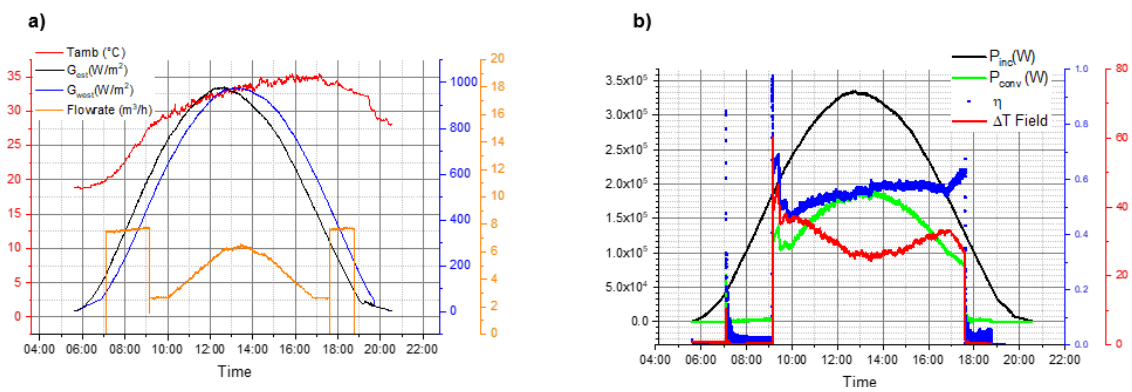

Figure 3 a)Acquired weather data, and flow rate b) Measured field performance parameters with a set point temperature equal to 100 °C.

Figure 4 provides a comparison between the daily experimental and numerical results of the HTF ΔT and average temperature T_m between the inlet and outlet of the solar field over time. The simulation accurately replicates the behaviour of the solar field, as the differences between the numerical and experimental measurements are within a 4% margin during operational hours. These small deviations can be attributed to measurement uncertainties. Therefore, the comparison depicted in Fig. 4 demonstrates the fidelity of the numerical model in reproducing the performance of the analysed solar field.

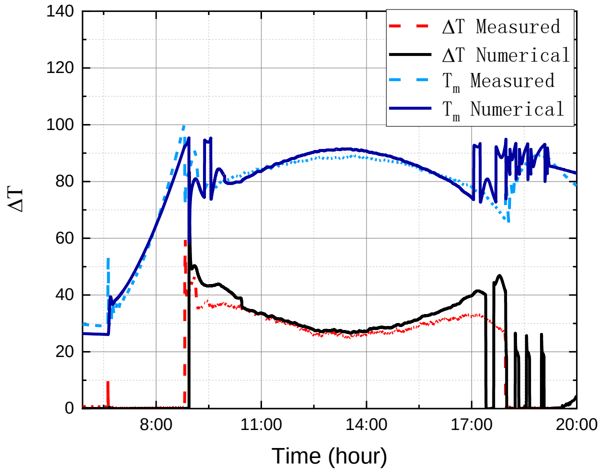

Figure 4 Comparison between experimental & numerical results: Measured ΔT (red dashed line) and the Tm (light blue dashed line) and comparison with simulation results (black and dark blue continuous line respectively)

3. Results & Discussion

Figure 5 presents a comparison of the monthly energy production between a medium temperature (MT) and a high temperature (HT) high-vacuum flat plate collector (HVFPC), operating at three different temperatures (Tm = 150, 200, and 250 °C). The data used in this comparison were the hourly irradiation and ambient temperature measurements from Cairo in 2019.

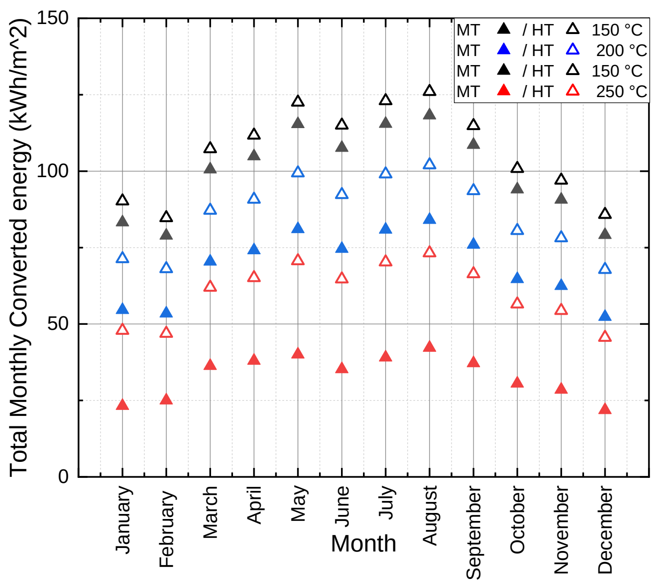

Figure 5 Comparison between monthly energy production of MT and HT version of a TVPSolar HVFPC

The difference in the projected annual energy production between the HT and MT HVFPCs varies depending on the operating temperature, as evident from the efficiency curves in Fig. 2 b). The maximum difference is observed at 250 °C, where the annual production of the HT collector is 724 kWh/m^2 compared to 397 kWh/m^2 for the MT HVFPC, resulting in an 82% increase in energy output.

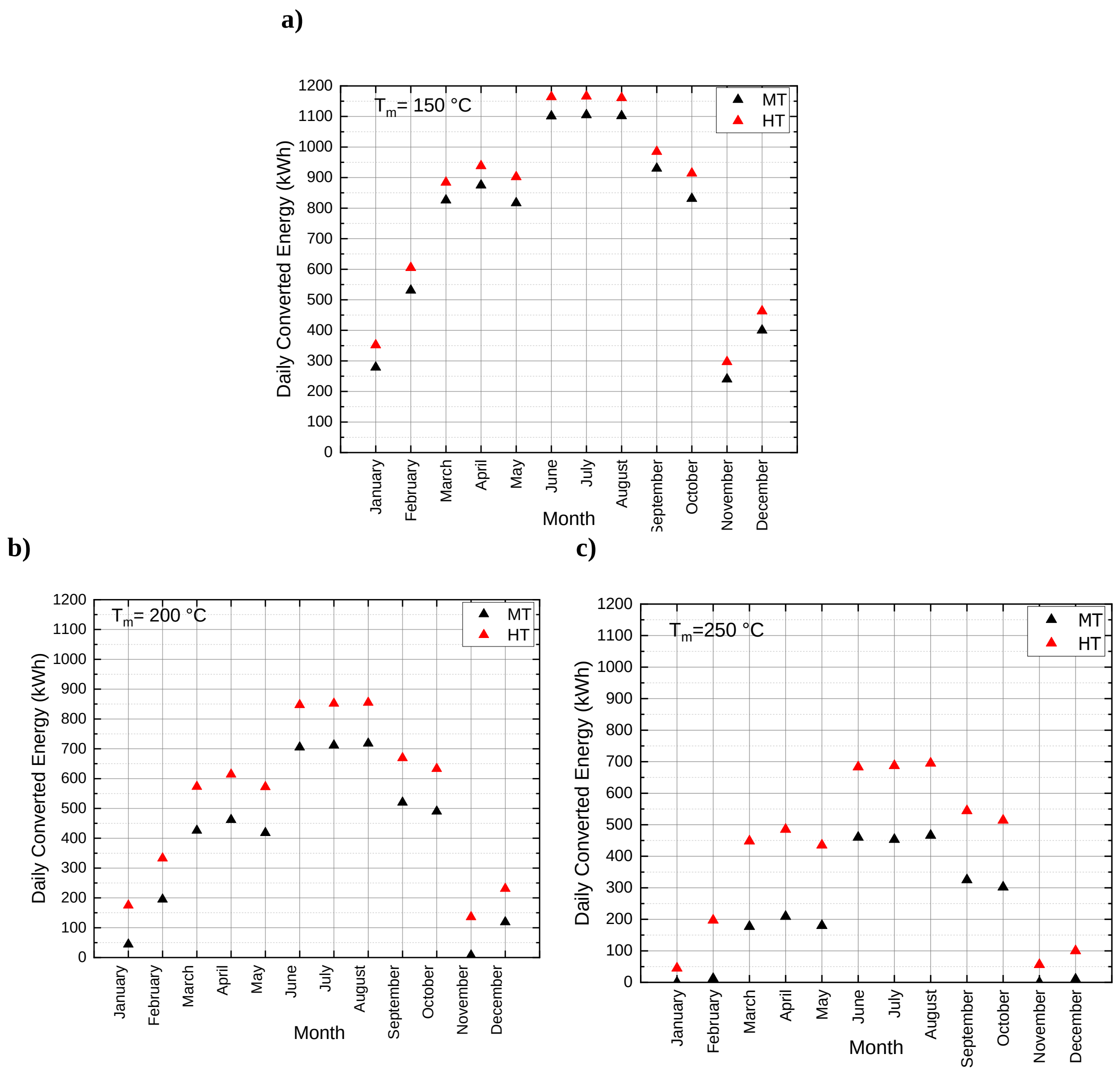

Figure 6 Numerical comparison between average daily energy production per month of MT and HT field for an operating temperature of a) 150 °C b) 200 °C and c) 250 °C

To further investigate the solar field performance, simulations were conducted to compare the daily energy production of MT and HT HVFPC fields, using diathermic oil (Xceltherm 500) as the heat transfer fluid and operating temperatures of 150, 200, and 250 °C. The input data for these simulations were the same irradiation and ambient temperature measurements from Cairo in 2019. The hourly data were averaged on a daily basis and then aggregated monthly to simulate the field performance through the monthly average day, as shown in Fig. 6.

It is important to note that using the monthly average day to represent the daily energy production is a conservative, pessimistic approximation of the field's performance. This approach underestimates the actual irradiation that could be obtained in a given month, as the monthly average day does not capture the full variability of the solar resource.

4. Conclusions

High-vacuum flat plate collectors represent the state-of-the-art technology for middle-temperature thermal energy generation. This technology can be further improved through the optimization of the solar absorber's spectral selectivity. In this paper, a numerical performance comparison between a solar field equipped with commercial (MT) and optimized (HT) HVFPCs is presented.

The key difference between the MT and HT HVFPCs lies in the optical properties of the solar absorber. The numerical performance comparison was carried out using a dynamic simulation model implemented in Simulink and validated through daily experimental measurements conducted with a TVPSolar test field.

The comparison of the daily energy production per month, as shown in Fig. 6, demonstrates that by improving the solar absorber properties (HT version), the collector's performance can be significantly enhanced. At an operating temperature of 250 °C, the HT HVFPC can achieve the same energy output as the MT HVFPC operating at 200 °C.

Having an accurate simulation model of the solar field, particularly for HVFPCs with optimized absorbers, is advantageous for future advancements. The TVPSolar company plans to replace the MT HVFPCs in the test field with the optimized HT version and configure the system to achieve even higher temperatures. The availability of the simulation model will facilitate the assessment and development of these future enhancements.

5. Aknowledgment

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6. References

Al-Joboory, H.N.S., 2019. Comparative experimental investigation of two evacuated tube solar water heaters of different configurations for domestic application of Baghdad- Iraq. Energy and Buildings 203, 109437. https://doi.org/10.1016/j.enbuild.2019.109437

Benz, N., Beikircher, T., 1999. HIGH EFFICIENCY EVACUATED FLAT-PLATE SOLAR COLLECTOR FOR PROCESS STEAM PRODUCTION1Paper presented at the ISES Solar World Congress, Taejon, South Korea, 24–29 August 1997.1. Solar Energy 65, 111–118. https://doi.org/10.1016/S0038-092X(98)00122-4

Cao, F., McEnaney, K., Chen, G., Ren, Z., 2014. A review of cermet-based spectrally selective solar absorbers. Energy Environ. Sci. 7, 1615. https://doi.org/10.1039/c3ee43825b

D’Alessandro, C., De Maio, D., Caldarelli, A., Musto, M., Di Giamberardino, F., Monti, M., Mundo, T., Di Gennaro, E., Russo, R., Palmieri, V.G., 2022. Calorimetric testing of solar thermal absorbers for high vacuum flat panels. Solar Energy 243, 81–90. https://doi.org/10.1016/j.solener.2022.07.039

De Maio, D., D’Alessandro, C., Caldarelli, A., Musto, M., Russo, R., 2022. Solar selective coatings for evacuated flat plate collectors: Optimisation and efficiency robustness analysis. Solar Energy Materials and Solar Cells 242, 111749. https://doi.org/10.1016/j.solmat.2022.111749

Gao, D., Li, J., Ren, X., Hu, T., Pei, G., 2022. A novel direct steam generation system based on the high-vacuum insulated flat plate solar collector. Renewable Energy 197, 966–977. https://doi.org/10.1016/j.renene.2022.07.102

Gaudino, E., Anacreonte, A., Caldarelli, A., Strazzullo, P., Musto, M., Bianco, N., Giamberardino, F., Iameo, R., Palmieri, V., Russo, R., 2024a. Impact of Collector Array Orientation on the Performance of a Flat Collectors Field for Middle-Temperature Applications. https://doi.org/10.46855/energy-proceedings-11166

Gaudino, E., Caldarelli, A., Russo, R., Musto, M., 2023. Formulation of an Efficiency Model Valid for High Vacuum Flat Plate Collectors. Energies. https://doi.org/10.3390/en16227650

Gaudino, E., Farooq, U., Caldarelli, A., Strazzullo, P., De Luca, D., Di Gennaro, E., Musto, M., Russo, R., 2024b. Thermal Emittance Measurement of Very Low-Emissive Materials for Solar Thermal Applications. https://doi.org/10.20944/preprints202405.0717.v1

Kalogirou, S.A., 2004. Solar thermal collectors and applications. Progress in Energy and Combustion Science 30, 231–295. https://doi.org/10.1016/j.pecs.2004.02.001

Karki, S., Haapala, K.R., Fronk, B.M., 2019. Technical and economic feasibility of solar flat-plate collector thermal energy systems for small and medium manufacturers. Applied Energy 254, 113649. https://doi.org/10.1016/j.apenergy.2019.113649

Lv, Y., Si, P., Rong, X., Yan, J., Feng, Y., Zhu, X., 2018. Determination of optimum tilt angle and orientation for solar collectors based on effective solar heat collection. Applied Energy 219, 11–19. https://doi.org/10.1016/j.apenergy.2018.03.014

Schobert, A.H., 2014. Energy and Society: An introduction, Seconda. ed. CRC Press, 600 Broken Sound Parkway,NW, Suite 300.

Spectroscopic Ellipsometry - HORIBA, (n.d.). https://www.horiba.com/en_en/products/scientific/surface-characterization/spectroscopic-ellipsometry/., n.d.