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Improvement of Optical Efficiency of a Multi-Concentrator by Means of a New Geometric Configuration

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***Abstract*— This work presents a new design of solar multi-concentrator water heater. The concentration system consists of a CPC associated with three spherical sections at their base, the upper part consists of two parabolic branches, while the lower part is made up of three arc-shaped reflectors arranged in a geometry that allows them to reflect all solar radiation falling on their surfaces toward the absorber.The establishment of thermal balances is carried outthereby determining the hourlyevolution of water temperature profile as well as the thermal and optical efficiency of the studied system.Results show that this geometry has higher optical efficiency compared to the three-branch parabolic concentrator model. Moreover, the thermal efficiency increases by 12 % compared to the old configuration.**

I. INTRODUCTION

Given the promising potential of solar thermal energy, we have developed a new multi-concentrator water heater structure. The old model consists of a non-truncated CPC associated with three arc-shaped reflectors at the bottom [1], which presents a set of disadvantages. The goal, therefore, is to modify this old model to improve its optical and thermal performance while reducing its size. The new configuration consists of multi-concentrators with two parabolic branches. The study shows that we can reduce the size of the system by truncating these two parabolic branches without significant effects on the optical and thermal performance of the device [2]. In other words, a strong truncation reduces the weight and cost of the system since the surface area of the reflectors corresponding to a truncated system is considerably smaller than that of a non-truncated system. This truncated geometry reduces thermal losses and increases the percentage of optical yield captured by the sensor, and it has a much smaller size than the old model, which facilitates handling and installation. The new design is characterized by better optical and thermal performance compared to the old configuration [3]. The results from Ben Rajab et *al.* (2016) showed that the best thermal efficiency achieved is 54% for an inclination angle of 35°, and a significant improvement in optical efficiency results (around 76%) compared to the old configuration (60%). The study by Mohammad and Min (2022) reveals that the concentration ratio of the new configuration is 40 to 60% higher than that of conventional solar concentrators, with significant optical efficiency. Yongcai (2021) adds that the results of the calculations show that the traditional CPC should be replaced by a new design method proposed to solve the problems of non-uniform

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energy flux distribution and optimize optical efficiency. The lack of production and application flexibility of the traditional standard parabolic concentrator (S-CPC) is due to its highly precise curved surface structure. Furthermore, the very uneven distribution of flux on the absorber significantly impacts the stability of the system. An innovative technique to improve the performance of a multi-section parabolic concentrator (M-CPC) has been developed. It turns out that the M-CPC4 is the ideal structure in this design, showing respective improvements of 1.375% and 47% in terms of average optical efficiency and acceptance angle compared to the S-CPC. Additionally, the M-CPC4 could significantly mitigate the high peak energy consumption while promoting an uneven distribution of flux on the absorber. This will allow the operating system to maintain a temperature gradient. Several sectors are leveraging the recent design of the CPC, such as the non-imaging angle detection system that incorporates an optical model using a compound parabolic concentrator (CPC) [7] and to optimize the production and efficiency of photovoltaic systems, several studies have been conducted on different strategies, including the use of compound parabolic concentrators (CPC)[8]. The analysis by Moein Addini and Gandjalikhan Nassab (2024) reveals that the circular solar air heater with rotating air flow, connected to a composite parabolic concentrator, proves to be a very efficient heat exchanger for producing a high-temperature air current, suitable for various uses, The thermal efficiency is rated at 70%, although the outgoing air temperature reaches a high level of 120°C. This means a doubling of the efficiency compared to standard smooth duct solar air heaters[10].

The aim of this study is to optimize the optical efficiency of a parabolic multi-concentrator through a new geometric arrangement. Building on previous experiments, we have proposed a novel model of a two-branch compound parabolic concentrator (CPC) and truncated. Our objective is to design, model and simulate the new parabolic multi-concentrator configuration [11]. The maximum optical efficiency of the studied system is around 0.80, while the thermal efficiency reaches a maximum value of 0.54. The results show that the efficiency of the parabolic concentrator is higher than that of a conventional collector.

II. Materials and Methods

A. *Presentation of new design*

The new model is primarily characterized by its structure, which incorporates a concentration and absorption system. The metal casing completely covering the non-sun-exposed outer surfaces protects the concentrator from external aggressions. An insulating layer of about 5 cm, named for its thermal insulation function, occupies the space between the outer protection and the reflectors. Its objective is to minimize heat loss to the outside as much as possible. The truncated CPC system is associated with two parabolic branches and three arcs of a circle (fig. 1). The reflection system at the base of the concentrator prevents any reflection of the rays outward or their passage through the absorber without being intercepted by it. The section of the absorber passes through the three centers of the three arcs O, F, and E, as illustrated in fig. 2, which constitutes an optimal arrangement for intercepting solar radiation.

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The old model of the three-branch parabolic concentrator system illustrated in Fig. 2 is the subject of a comparative study with the system in description.

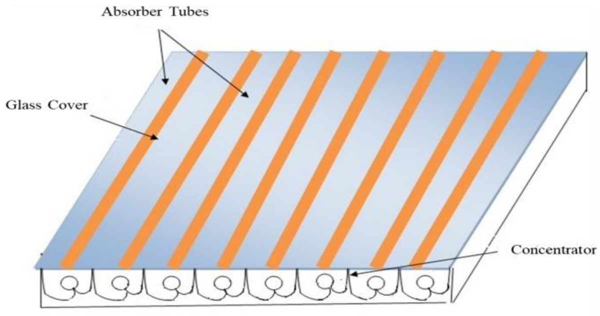

Fig. 1 Multi-concentrator solar water heater

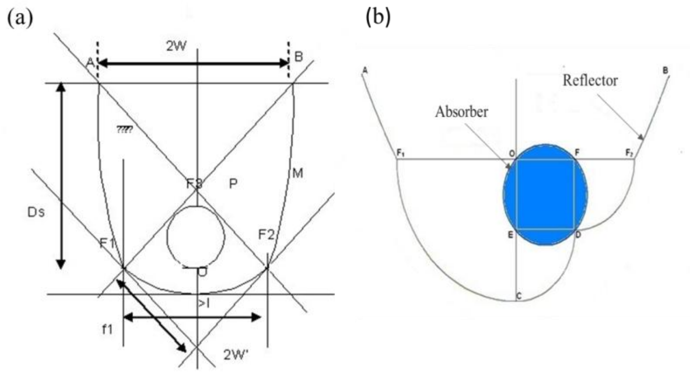

Fig. 2 Concentration Systems (a) Old model [1] (b) New model

Table I presents the characteristics and properties of the new design.

TABLE I : OPTIMAL GEOMETRIC CHARACTERISTICS OF THE SYSTEM.

	Geometric concentration	**Acceptance half-angle (°)**
Value	1	67

Table II presents the characteristics of the multi-concentartor.

TABLE II : CHARACTERISTICS OF THE MULTI-CONCENTRATOR

	Tubes number	α_{ab}	ε_{ab}	λ_{ab} **(W/m.°C)**	ρ_{ab} **(kg /m^3)**	L_{ab} **(m)**	D_1**(m)**	D_2 **(m)**	C_{pab}(j / kg.C°)	m_{ab} **(kg)**
Value	10	0.85	0.15	386	8954	1	18×10^{-3}	20×10^{-3}	383	0.785

B. Mathematical modelling

The differential equation that describes the variation of window temperature as a function of time is as follows:

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$$\frac{m_v \times C_{pv}}{S_v} \times \frac{dT_v}{dt} = \alpha_v \times I + N_{ab} \times (q_{rabsv} + q_{cabsv}) - q_{rva} - q_{cva} \quad (1)$$

I is the intensity of solar radiation, the heat transfer by convection from the absorber to the glass is given by:

$$q_{cabv} = h_{ab,v} \times (T_{ab} - T_v) \quad (2)$$

Or $h_{ab,v} = 3.3$ W/m^2. K

With N_ab is the number of absorber tubes.

Similarly, the heat flux by radiation is expressed by the following equation:

$$q_{rabv} = \sigma \times \varepsilon_{sys} \times (T_{ab}^4 - T_v^4) \quad (3)$$

ε_sys is the apparent emissivity of the system, ε_ab, ε_v represent the emissivity of the absorber and the glass respectively.

$$\varepsilon_{sys} = \frac{1}{(\frac{1}{\varepsilon_{ab}} + \frac{1}{\varepsilon_v} - 1)} \quad (4)$$

Heat losses by radiation and convection from the window to the outside are given by:

$$q_{rva} = \sigma \times \varepsilon_{v,a} \times (T_v^4 - T_a^4) \quad (5)$$

$$q_{cva} = h_{v,a} \times (T_v - T_a) \quad (6)$$

The convection coefficient between the window and the ambient air is estimated by:

$$h_{v,a} = 5.7 + 3.8 \times V_{wind} \quad (7)$$

The heat balance of the absorber is given by:

$$\frac{m_{ab} \times C_{pab}}{S_{ab}} \times \frac{dT_{ab}}{dt} = C \times \rho_r^N \times \tau \times \alpha_{ab} \times \gamma \times I - q_{cabw} - q_{rabsv} - q_{cabsv} \quad (8)$$

C,τ,α, ρr, N and γ represent the radiation concentration, transmittance, absorbance, reflectivity, number of reflections and interception factor, respectively.

The intercept factor is written as follows:

$$\gamma = 0.8 + 0.2 \times C^{-1} \quad (9)$$

The heat transferred by convection from the absorber to the water is given by the following equations (10):

$$q_{cbw} = h_{cbw} \times (T_b - T_w) \quad (10)$$

The convective transfer coefficient is estimated by:

$$h_{cbw} = \frac{Nu \times \lambda_f}{D_2} \quad (11)$$

λ_f and D_2 are the thermal conductivity of water and the inner diameter of the absorber tube, respectively.

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The Nusselt number is estimated as a function of the Reynolds number:

$$Nu = 3.66\,, Re < 2000$$

$$Nu = 0.023Re^{0,8}Pr^{0,4}, Re > 2000$$

The Reynolds number for flow in a circular tube is given by:

$$\mathrm{Re} = \frac{2\,\rho_f \dot{V}}{\pi R1\mu} \tag{12}$$

$\dot{V}$ is the volume flow rate,

The Prandtl number is given by:

$$\mathrm{Pr} = \frac{\mu_f \times C_{pf}}{\lambda_f} \tag{13}$$

The dynamic viscosity of water is given by the following relationship:

$$\mu_f = 2.414e^{\left(\frac{247.8}{(T_f+273.15)^2}\right)} \tag{14}$$

The thermal conductivity of water as a function of temperature is given by:

$$\lambda_f = -9{,}87 \times 10^{-6}\mathrm{T}^2 + 2.238 \times 10^{-3} \times \mathrm{T} + 0.5536 \tag{15}$$

The variation of the density of water inside the absorber tube as a function of temperature is expressed by (16):

$$\rho_f = -0.0038 \times (T_f + 273.15)^2 + 2.0243 \times (T_f + 273.15) + 733.1763 \tag{16}$$

The equation that translates the thermal balance relative to the water inside the absorber is as follows:

$$\frac{m_f \times C_{pf}}{S_f} \times \frac{dT_{f1}}{dt} = q_{cabw} - q_{cw1w2} \tag{17}$$

The thermal power carried by the water to the storage tank is given by:

$$q_{cw1w2} = \dot{m}_{fe} \times C_{pf} \times (T_{f1} - T_{f2}) \tag{18}$$

$\dot{m}_{fe}$ is the mass flow rate of water carried to the reservoir due to the density difference and is given by the following equation :

$$\dot{m}_{fe} = C \times A \times \sqrt{2g.H\frac{\Delta\rho}{\rho_{moy}}} \tag{19}$$

A is the cross-sectional area of the absorber tube

H is the difference in height between the high and low points of the circuit

C is the flow coefficient, taking into account pressure losses.

T_f2 is the temperature of the water carried to the reservoir

The temperature profile of the water carried to the reservoir is determined by the following equation:

$$\frac{m_f \times C_{pf}}{S_f} \times \frac{dT_{f2}}{dt} = N_{ab} \times q_{cw1w2} - q_{losses} \tag{20}$$

$$\mathrm{Q_{losses}} = \mathrm{U_{lr}} \times (\mathrm{T_{f2}} - \mathrm{T_a}) \tag{21}$$

The overall coefficient of heat losses from the lateral surface of the tank to the outside is expressed by :

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$$U_{lr} = \frac{1}{(\frac{L_r}{\lambda_r}+\frac{L_i}{\lambda_i}+\frac{1}{h})} \quad (22)$$

L_r, L_i, λ_r , λ_i represent the thickness of the tank and the thermal insulation, and the thermal conductivity, respectively. h is the convection heat transfer coefficient between the external surface of the tank and the ambient air.

The thermal efficiency of the system is given by

$$\eta = \frac{\dot{m}_{fe}\times C_{pf}\times(T_{f1}-T_{f2})}{C\times\rho_r^N\times\tau\times\alpha_{ab}\times\gamma\times I} \quad (23)$$

The optical efficiency is written

$$\eta_0 = \rho_r^N \times \tau \times \alpha_{ab} \times \gamma \quad (24)$$

III. DISCUSSION

C. Variation in water temperature in the multi-concentrator

For a multi-concentrator with a concentration C of 1.15, the following results are obtained regarding the evolution of the temperature on various components of the system over time. According to Fig. 3, a gradual increase in temperature over time is observed. During the period of sunlight, the water temperature in the multi-concentrator reachs a maximum of 65°C at 4 PM.

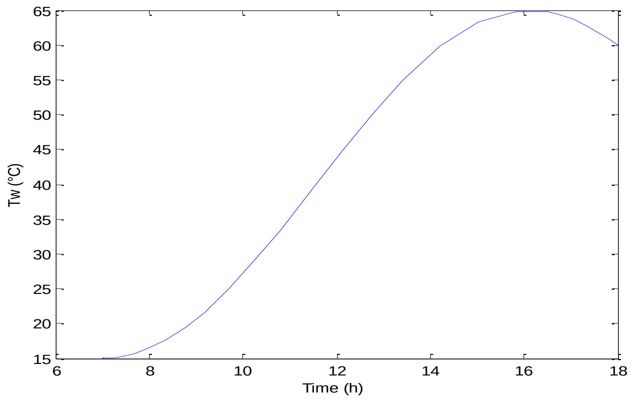

Fig. 3 Evolution of water temperature in the solar water heater during sunshine hours

D. Variation in Global solar flux

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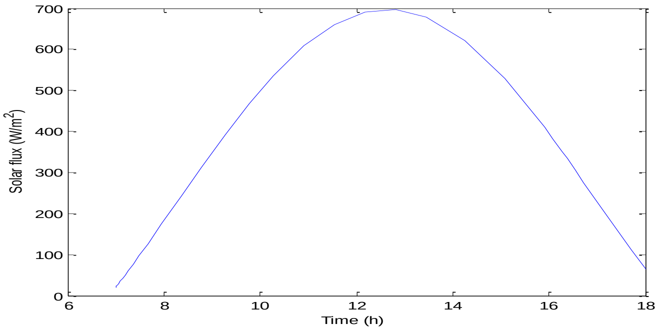

Fig. 4 Global solar flux for a typical February day

Fig. 4 illustrates the variation of global solar flux received by an inclined surface over time. The collected flux is continuously enhanced by the CPC, with the highest increase occurring around 1:00 PM. This improvement results from the capability of the two-branch parabolic concentrator to focus direct solar energy, thereby increasing the flux. The results demonstrate the efficiency with which the multi-concentrator maximizes solar energy collection during peak hours.

E. variation of optical efficiency

Fig. 5 shows the variation in optical yield for the two systems as a function of time. The results indicate that the new design provides a significant improvement in optical yield compared to the old configuration.

Optical yield is one of the characteristic parameters of a solar collector and depends on the properties of the materials used, the arrangement of the absorber in the focal plane, and the angularerrors of the reflective surfaces. The first design studied by [1] presents significant optical losses throughout the day during water heating. A more or less significant fraction of solar radiation is reflecte dout ward after entering through the top opening of the CPC. The parabolic branch located at the bottom is responsible for this loss of solar radiation. The third parabolic branch has been replaced by the current reflection system to enhance optical and thermal performance.

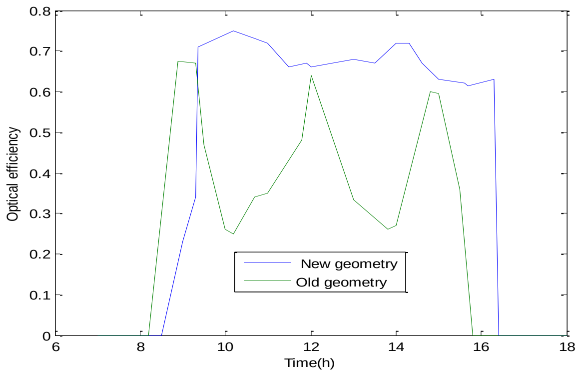

Fig. 5 Temporal variation of optical efficiency for the two configurations

F. variation of Thermal efficiency

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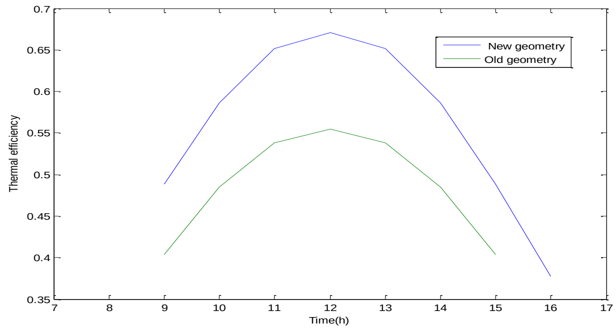

Fig. 6 Thermal efficiency as a function of time for both configurations

Optical losses result in a reduction of the power received by the absorber, leading to a lower temperature and relatively low thermal yield. Fig. 6 shows that the maximum thermal yield of the new configuration is around 67% at noon, while it does not exceed 55% for the old model. Geometric concentration is an important parameter that allows for simplified, characterization of the concentrator and determines its performance. It is defined as the ratio of the capturing area to the receiving area or absorber.

G. Effect of varying geometric concentration on the thermal yield

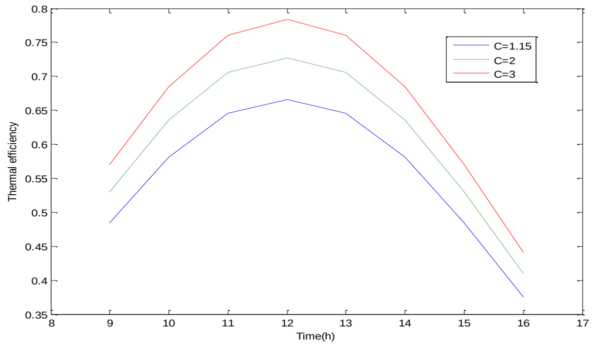

Fig. 7 effect of varying geometric concentration on the thermal yield of the system

Fig. 7 illustrates the effect of varying geometric concentration on the thermal yield of the system. Simulation results show that thermal yield increases progressively with concentration and reaches a maximum value of around 78% for a geometric concentration equal to 3.

IV. Conclusions

This work aims to improve the optical and thermal performance of an older model of solar concentrator by introducing a new configuration composed of two parabolic branches and three circular arcs at its base. A

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mathematical model was developed, accompanied by a comparative study between the two concentration systems. Simulation results indicate that the maximum optical efficiency of the studied system reaches approximately 77%, while the maximum thermal efficiency reaches 67%. Furthermore, the thermal efficiency is improved by 12% compared to the previous configuration.

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