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Enhancement of a solar-tracking concentrator system with multiple conversion mechanisms based on the energy chain principle

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Abstract— *This article presents the improvement of a construction system adapted to solar tracking. The system integrates multiple energy conversion mechanisms in accordance with the energy chain principle and it is based on high-temperature energy capture. Therefore, it enables the deployment of a field of collectors or storage units that use a heat transfer fluid to perform the functions of energy concentration, heating, storage, and distribution. From a forward-looking perspective, these concentrator systems contribute to enhancing solar energy utilization through the application of advanced signal-based simulation and modeling methods for solar systems.*

Keywords— ***Solar concentrator, Thermal collector, Linear Fresnel field, Form factor, Energy of tomorrow.***

I. INTRODUCTION

The use of solar energy represents an alternative based on the implementation of various energy conversion mechanisms, [1]. These mechanisms are classified into two categories of collection, which are conventional solar collection and high-temperature solar collection, [2]. In this context, the study of solar concentration focuses on the application of adaptive technological systems centered around a thermal focal point. This work aims to develop models of active solar systems. Specifically, it seeks not only to establish a field of collectors or thermal storage units using a heat transfer fluid such as water, but also to integrate linear Fresnel collector technology.

The objectives of this article are as follows:

- To determine the shape factor using Gauss approximation and Hottel's string method [3]. This analysis helps evaluate the system's efficiency in terms of economy, ecology, and environmental impact, based on the country's geographical conditions.
- To study the application of a solar concentration system in two and three dimensions. This involves designing a technological model using thermal and dynamic simulations with software such as MATLAB, EnergyPlus, or RetScreen. The goal is to adapt the system's performance to the selected technology, whether cylindrical-parabolic or parabolic.

II. SYSTEM DESIGN AND INSTALLATION TECHNIQUE

2.1 Two-Dimensional Concentration System

The linear Fresnel field technology is based on the use of cylindrical lenses and adjustable reflective surfaces, [4]. These surfaces are arranged in the form of dihedrals with a semi-open angle at the apex.

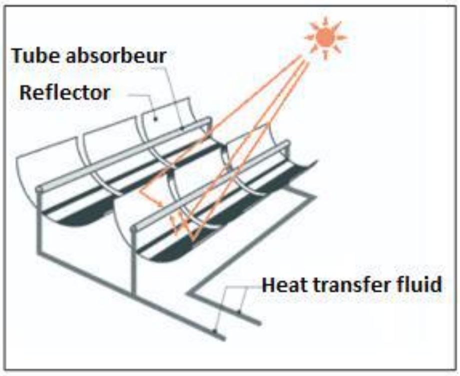

Fig.1 : Two-Dimensional Concentration System

A two-dimensional parabolic flat collector can receive light rays from an entire hemisphere, [5]. The concentrator system used in this study continuously tracks the sun throughout the day. This continuous solar tracking requires a more complex mechanism, and the effective collecting area varies depending on the solar radiation intensity during the day. The two mirrors of the concentrator must be oriented so that their reflected rays intersect at a focal point located at a half-angle at the system's apex. This focal point is equipped with a thermal receiver modeled as a black body, operating at a temperature denoted by T_S.

This configuration can be modeled geometrically. Assuming negligible transient solar shading, the half-angle at the apex is taken as $\Theta_s = 16°$, which allows for an effective distribution of solar radiation within the system. The incoming radiation is captured by a concentrating system with an aperture area A_a, and the absorber is placed on a surface A_C. The absorber is considered a gray body operating at temperature T_C , [6]. During the experiment, it is important to ensure that the space between the source and the aperture remains completely empty.

The maximum geometric concentration is given by the following ratio:

$$C = \frac{A_a}{A_c} \quad (1)$$

The power emitted by the source and absorbed by the receiver can be expressed as:

$$q_{SC} = \mathcal{F}_{SC} A_S \sigma T_S^4 \quad (2)$$

where $\mathcal{F}_{SC} \leq \nu$ represents the fraction of the emitted power that reaches the absorber, either directly or after reflections or refractions.

Similarly, the energy emitted by the absorber and received by the source can be written as:

$$q_{CS} = \mathcal{F}_{CS} A_S \sigma_S T_C^4 \quad (3)$$

According to the second law of thermodynamics, when there is no net heat exchange between two bodies at the same temperature:

If $T_S = T_C$, **then** $q_{SC} = q_{CS}$,

which implies $\mathcal{F}_{SC} A_S = \mathcal{F}_{SC} A_C$ **(4)**

Additionally, we also have:

$$\mathcal{F}_{Sa} A_S = \mathcal{F}_{aS} A_a \quad (5)$$

The geometric concentration ratio is then defined as:

$$C = \frac{A_a}{A_C} = \frac{\mathcal{F}_{Sa} \mathcal{F}_{CS}}{\mathcal{F}_{aS} \mathcal{F}_{SC}} \quad (6)$$

In an ideal concentrator, all radiation entering through the aperture should reach the absorber, which leads to the condition:

$$\mathcal{F}_{Sa} = \mathcal{F}_{SC} \quad (7)$$

Here, $\mathcal{F}_{Sa}$ represents the fraction of power emitted by the aperture that directly reaches the source. Based on radiative transfer theory and geometric modeling, the following relationship holds:

$$C_{[3]} \leq \frac{1}{F_a} \text{ and } \frac{1}{F_a} = \frac{1}{\sin\theta_C} \quad (8)$$

where:

- θ_C is the half-apex angle;
- F_a is the form factor obtained using Hotel's crossed-string method, [7].

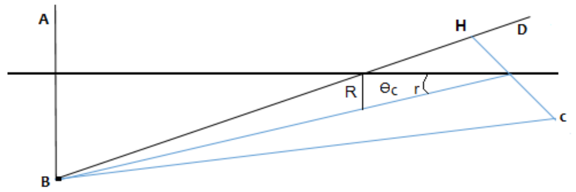

Fig.2 : Configuration of Form Factor Calculations for an Enhanced Two-Dimensional

2.1.1 Calculation of the form factor F_a using a mathematical model

The formula is as follows:

$$F_a = \frac{BD-BC}{CD} \quad (9)$$

When

$CD \ll AB$ *et* $BD - BC \approx HD \approx CD\ \sin\theta_C, F_a = \sin\theta_C$ *, avec* θ_C , it follows that:

$F_a = \sin\theta_C$ *, avec* θ_C

where θ_C is the half-angle at the vertex of a dihedron.

The maximum geometric concentration of an improved two-dimensional system [8] is then expressed as:

$$C_{max} = \frac{1}{\sin\theta_C} = C_{idéal\ 2D} \quad (10)$$

2.2 Three-dimensional concentrator systems

This system is inspired by a compact cylindro-parabolic concentrator used in solar applications. To reach temperatures above 150°C [9], it is necessary to concentrate solar rays using two appropriate sets of reflective elements or lenses.

Solar thermal energy enables the production of domestic hot water in a three-dimensional concentrator configuration. This system offers an effective alternative to electric water heaters (see Figure 3).

The Fresnel linear technology, developed through a thermodynamic concentration approach, is currently considered a promising solution for energy production, [10]. Available thermal storage technologies can ensure energy supply even during periods without sunlight.

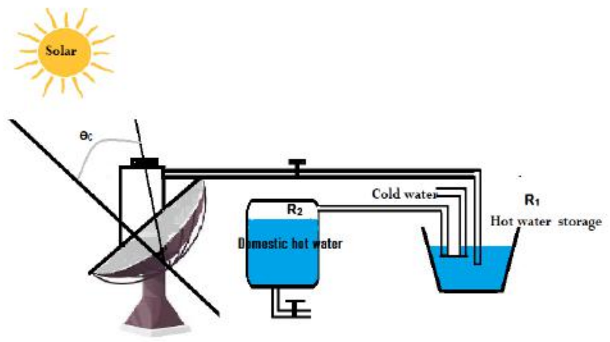

Fig.3: Active three-dimensional (3D) solar system

The flux received by the collector is reflected by the concentrator lenses and then passes through a glazing designed to thermally insulate the focal point, where it is absorbed by a suitable surface (see Figure 3). Reflection, transmission through the glazing, and absorption result in optical losses denoted as $\acute{P}$, which are globally characterized by an energy efficiency.

For the active system shown in Figure 3, only the direct component of solar radiation can be directed to the focal point, as the diffuse component cannot be concentrated.

The main constraint, besides the higher cost compared to flat plate collectors, lies in the need to install a tracking system that follows the sun's movement. In solar cooling applications, this technology is combined with double or triple-effect absorption cycles, which require operating temperatures above 150 °C.

III. THERMAL MODELING OF APPLIED SYSTEMS

For the geometric model, the equation characterizing the steady-state operation per unit surface area of the absorber or receiver is [11]:

$$P_a = P_u + \acute{P} \quad (11)$$

Where:

- P_a is the incident radiation power absorbed per unit area,
- P_u is the useful power of the collector,
- $\acute{P}$ represents thermal losses.

During the system startup phase, thermal inertia cannot be neglected. However, before reaching the collector, the incident radiation may undergo various modifications.

The direction and power of the observed radiation is expressed as [12]:

$$P_a = E.C.\rho.\tau.\alpha \quad (12)$$

where:

- $E = I_{bn}\cos\theta_i$ with θ_i the angle of incidence [°],
- E is the irradiance at the collector level,
- $I_{bn}$is the direct solar radiation,
- C is the geometric concentration ratio of the collector,
- ρ is the reflectivity of reflective surfaces (galvanized sheet in this case),
- τ is the transmissivity of protective glazing,
- α is the absorptivity of absorbing surfaces.

The instantaneous overall efficiency of the collector η is given by:

$$\eta = \frac{P_u}{E.C} \quad \textbf{(14)}$$

At night, the heat transfer fluid (hot water) is stored in a tank that ensures the distribution of unstable power [13]. The energy transported is in the form of sensible heat and the useful power is:

$$P_u = QC_f(\theta_S - \theta_e) \quad \textbf{(15)}$$

where:

- Q is the mass flow rate of the heat transfer fluid per unit surface,

C_f is the specific heat capacity of the fluid [J kg^{-1}°C^{-1}],

- θ_S and $\theta_e$are the fluid temperatures at the outlet and inlet of the collector, respectively.

Thermal losses of the pipe are:

$$\grave{P} = C_p(\theta_{moy} - \theta_a) \quad \textbf{(16)}$$

where:

C_p is the apparent conductance of losses at temperature θ_{moy} [$Wm^{-2\circ}C^{-1}$]

θ_{moy} is the temperature of absorbing surfaces,

θ_a is the ambient temperature.

The instantaneous internal efficiency η_i is:

$$\eta_i = \frac{P_u}{P_a} \quad \textbf{(17)}$$

During the experiment, the following values were used: ρ = 0.80; τ: 0.85 and α : 0.95

IV. RESULTS AND DISCUSSION

A black spherical body with radius R, placed isotropically at a distance R from the aperture, is used in a cooking system in contact with surface R1 (see Figure 3). This surface absorbs heat and transfers it to surface R2. When a relatively low temperature is adopted (such as cold water temperature), the temperature of R1 must be limited to 50 °C to maintain an acceptable performance coefficient.

Distributing a fluid to R2 at low temperature appears to be an effective solution. The combination of R1, R2, R3, and a heat pump creates an active system with three complementary functions: cooking, water heating, and electric energy production.

The ideal maximum concentration for a three-dimensional system is given by:

$F_a = F_S \frac{S_a}{S_C}$, where

$$F_s = \frac{S_a}{4\pi r^2} \quad \textbf{(18)}$$

and

$$R = r\sin\theta_C \quad \textbf{(19)}$$

which leads to

$$F_a = \frac{R^2}{r^2} \ [3] \quad \textbf{(20)}$$

and

$$C_{idéal\ 3D} = \frac{1}{\sin^2\theta_C} \quad \textbf{(21)}$$

The performed models allowed the plotting of the following curves .

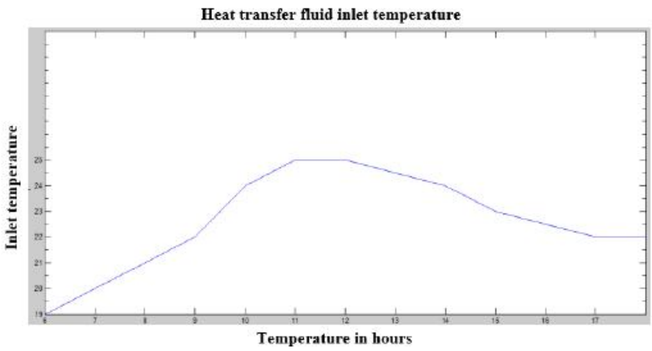

Fig.4 *: Heat transfer fluid inlet temperature in °C*

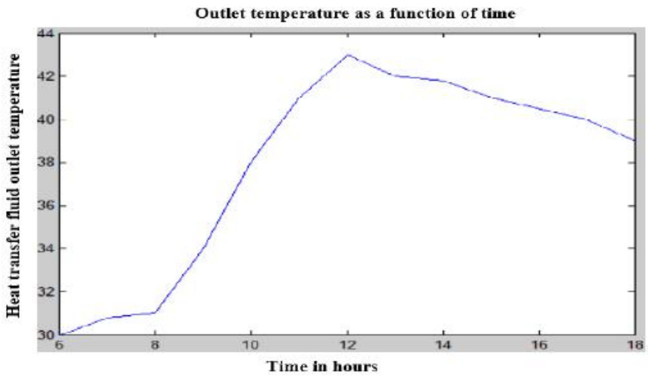

Fig.5 : Outlet fluid temperature in °C

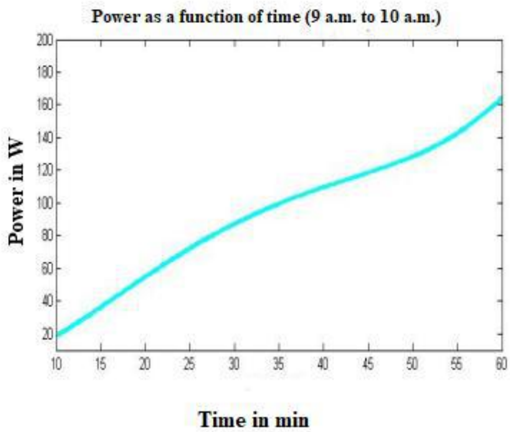

Fig.6 : Overall power received by the sensor between 9 a.m. and 10 a.m

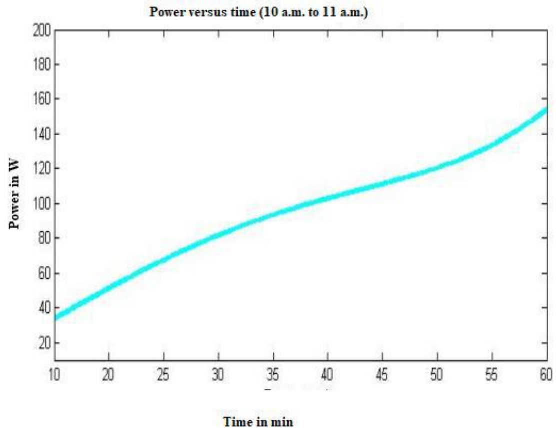

Fig.7 : Overall power received by the sensor between 10 a.m. and 11 a.m.

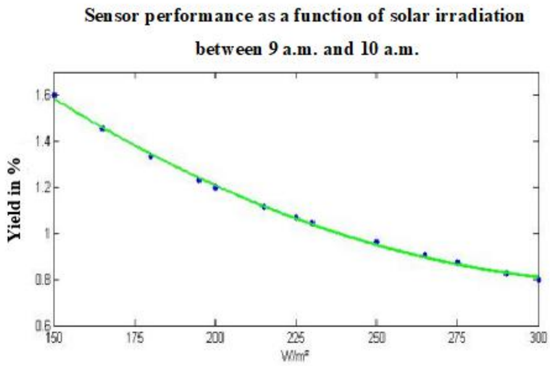

Fig.8 : Overall yield received by the sensor between 9 a.m. and 10 a.m.

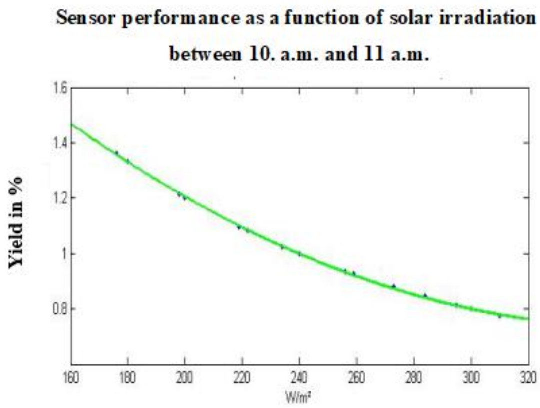

Fig.9 : Overall yield received by the sensor between 10 a.m. and 11 a.m.

These results define the maximum concentration achievable for a given linear field. Using a single-axis concentrator implies that the maximum achievable concentration factor is:

$$C_{max} = \frac{n^2}{\sin^2 \theta_C} \quad (22)$$

Where n is the refractive index and θ_C is the entrance angle of the optical system.

The optical system used is immersed in air, so the refractive index is $n = 1$, and the exit angle is approximately ±90°.

Compound parabolic concentrators were originally developed in high-energy physics to detect Cherenkov radiation, but their usefulness for solar radiation concentration was only recognized recently, notably by Winston in 1974. They are especially efficient in two-dimensional systems, where they achieve ideal concentration.

For example, considering a half-angle at the apex $\theta_C = 16°$, the results are:

- Low concentration: $1 < C = \frac{S_C}{S_r} < 10$ with an operating temperature around 150 °C
- Medium concentration: $10 < C < 100$ with an operating temperature around 300 °C
- High concentration: $C \geq 10$ with an operating temperature above 500 °C

For a 2D low-concentration system, C_{max} =3.7 corresponds to a concentrator temperature close to 150 °C. For a 3D medium-concentration system, C_{max} =13.172corresponds to a concentrator temperature around 300 °C.

V. CONCLUSION

The goal of this work was achieved by significantly improving the solar concentration system using Fresnel technology to refine fixed and targeted orientation of two- and three-dimensional concentrator systems. An East-West axis was selected for the studied location to maximize the power of direct solar energy.

Significant concentrations on the order of 10 were obtained for the systems studied. The increased simplicity of the mechanism reduces maintenance costs over the system's lifetime and allows the design of a lighter solar tracking system. This lightweight design facilitates installation in locations where weight is a critical factor, such as commercial and industrial rooftops.

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