

# Design and experimental investigation of a dryer with two types of combined solar concentrators using two natural heat-transfer fluids

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**Abstract**—In this experimental study, a new solar dryer has been designed and manufactured by combining a concave solar concentrator with a series of convergent lenses whose concentrated radiation are reflected on the same absorber. Our main goal for this combination is to reduce the thermal losses by increasing the receiver bottom temperature. In our dryer, the receiver design uses air and water as the heat transfer fluid; these two fluids are heated and sent a heat exchanger to raise the drying air temperature. Furthermore, in order to improve the thermal performance, our approach is based on some techniques such as; the combination of two types of solar concentrators, simultaneous use of two natural heat transfer fluids, tilting concentrators, the insertion of obstacles at the absorber, and a specific solar tracker for explosive atmosphere. Our dryer has been tested for the first time in gas filling plant in Morocco for drying painted gas cylinders. The experimental results show that compared with flat-plate solar collector, the proposed dryer can significantly improve the performance in terms of air drying temperature. In fact, our solar dryer has reduced the drying time from 420 seconds to just 40 seconds and has improved drying air the temperature from 40 °C to 65 °C. Also, the health risks of workers have been reduced and the number of painted bottles has been increased by more than 43%.

**Keywords** — Solar dryer, Combined solar concentrators, Two naturel heat transfer fluids, Thermal losses, Obstacles

## I. INTRODUCTION

The most important property of the solar energy is a renewable energy resource. The average annual sun exposure in Morocco is about 2500 hours; it receives a daily solar energy of 16.2 to 27MJ/m<sup>2</sup>[1]. The drying consumes about 12 to 25% of the total primary energy demand [2]. The solar energy is an area to study extremely in drying due to they are easily applicable. Therefore, this energy appears to be the energy of the future [3, 4]. One of the advantages of this energy is its aptitude to be transformed into heat. The solar collector constitutes the major component of any solar system [5]. Hot air is obtained from these collectors, and they are used in space heating [6,7], product drying [8,9], greenhouse heating [10] and pre-heating in ventilation systems [11,12].

The parabolic solar concentrator is often used with systems for solar absorption refrigeration that can achieve temperatures over 100°C [13,14]. Thus, the environmental problems related to the emission of greenhouse gases will be reduced [15].

The activity of painting gas cylinders is expanding in Morocco. The company, Salam Gas, recorded an increase in this activity of 1700%. Despite, this important evolution, drying is done naturally and at ambient temperature. However, this traditional drying generates two major drawbacks. First, the customer expectations in terms of time, quality and quantity are not met. Second, in terms of employee health, exposure to high concentrations of solvents can cause loss of medium-term and long-term knowledge, causing behavioral changes, affecting mood and memory [16, 17].

To overcome these drawbacks, in this work and for the first time in this industry, we propose a solar dryer by combining a concave solar concentrator with a series of convergent lenses whose concentrated radiation are reflected on the same absorber. Solar drying systems must be properly designed to meet the drying requirements, such as product quality and drying time. Several researchers have developed simulation models for natural convection and forced convection systems [18]. Solar air collectors are simple devices for air heating by utilizing solar energy for many applications that require low to moderate temperatures below 60°C, such as

drying and space heating. The principal types were classified as one pass, double duct, and two passes [19]. Recently, studies covering different types of collectors have been undertaken by several researchers. Hot air generation and drying applications were examined with their designs [20, 21]. A single-pass solar air collector [22] and a double-pass solar air collector [23, 24] were designed and experimentally analyzed for their performance.

In this paper, we present the experimental studies and design of a new solar dryer by using a combined parabolic solar concentrator with a series of convergent lenses and using a specific solar tracker for explosive atmosphere. Our main goal for this combination is to reduce heat losses at the absorber by adding convergent lenses. The idea is to increase the receiver bottom temperature by the additional thermal energy lenses. The receiver design uses air and water as the heat transfer fluid; these two fluids are heated and sent a heat exchanger to raise the drying air temperature. According to Benghanem [25], both the orientation and tilt angles have significant effects on the magnitude of the solar radiation reaching the surface of a collector through solar tracker and forced convection. Also, to improve thermal performance and achieve air temperature that can ensure rapid drying, we used three techniques, first, we combined parabolic solar concentrator and a series of convergent lenses for the same absorber, we also used two natural heat transfer fluids water and air at the same time, so these two fluids are heated and sent a heat exchanger to raise the drying air temperature. Second, the insertion of the obstacles inside the absorber, in addition while tilting the concentrators according to the latitude angle, and finally, the solar tracker realized is specific to the explosive environment by using a pneumatic motor and a pneumatic control. Several experiments were conducted on a prototype designed and fabricated in a gas filling plant in Oujda (Morocco). The experimental results are provided and are compared with the performance of the dryer with flat collector [26].

## II. MATERIALS AND METHODS

### A. System Design

In this study, we used a solar dryer equipped with a combined parabolic solar concentrator and a series of convergent lenses, forced convection, and specific solar tracking for an explosive atmosphere zone. Maximum power into the solar collector occurs when the surface is normal to the incident solar radiation. However, it is not always possible with fixed solar collector, since the relative position of the earth to the sun varies [27]. This system (Fig.1, Fig.2 and Fig.3) was designed, fabricated and tested in a gas filling plant by the laboratory in the Engineers National School (Mohamed First University Oujda, Morocco). The solar dryer comprised a concave solar concentrator having an area  $6\text{m}^2$  ( $3\text{m} \times 2\text{m}$ ) and 27 convergent lenses for heating the air and water at the same time. The receiver is connected to a drying unit through a centrifugal fan with an airflow rate up to  $2000\text{m}^3/\text{h}$  (Fig.4, Tab.1). The absorber tube was fixed on galvanized sheet metal; obstacles were inserted throughout the absorber tube for improved air heat exchange. The absorber was coated with black paint to absorb the incident solar radiation. The drying system used was the subject of some improvements, in particular, the insertion of obstacles on both sides of the absorber (Fig.5). The air is preheated at the absorber, after its temperature will be increased at the exchanger (steam/air) at the exit of the receiver. The concave solar concentrator was tilted to an angle about  $34^\circ$  horizontally, which is considered an optimum angle for year-round performance of the system at Oujda [1]. When solar rays hit a surface at an oblique angle, the rays are more spread out [28]. The system was oriented to face the east to maximize the incident solar radiation on the collector. The automatic operation of the dryer with the beginning of the painting cycle has led to the reduction of heat loss and improving the dryer thermal performance. A detailed numerical and experimental analysis of such an optical design system with  $3\text{m}$  focal length and  $1.8\text{m}$  effective aperture was performed in a previous study.

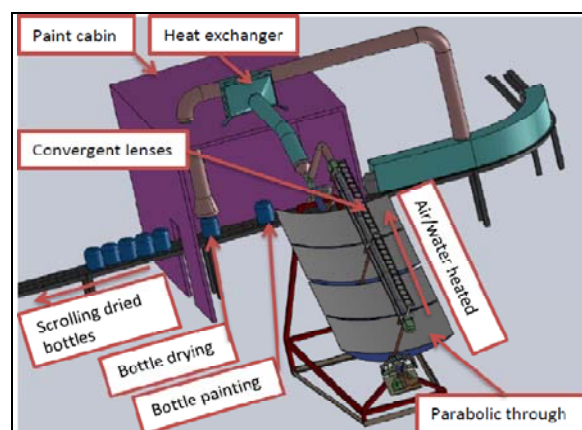


Fig.1. Schematic view of the solar dryer used for painted gas cylinders

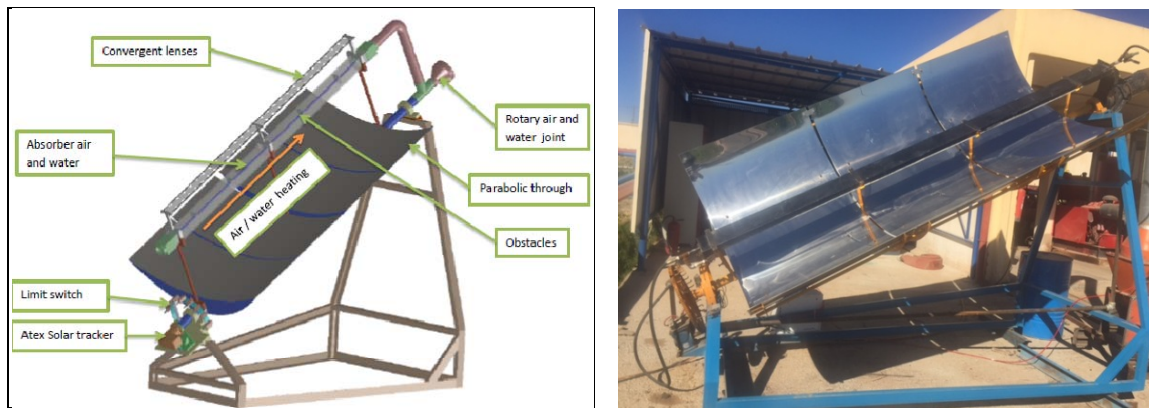


Fig.2. Schematic of the two concentrators combined

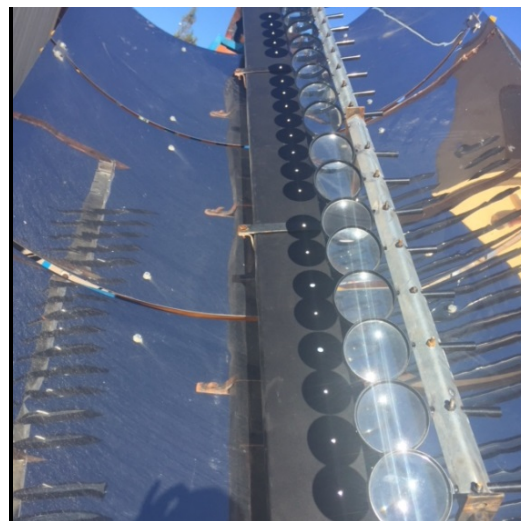


Fig.3. Realization of the combination of parabolic concentrator and convergent lenses

TABLE I. The concentrator's characteristics

Components	Dimensions	Values
Concentrator	length, L	3m
	Width, Lar	1.8m
	Opening area	5.1m <sup>2</sup>
Absorber	Thickness of the glass, e	0.005m
	Height obstacles, h <sub>as</sub>	0.04m
	Distance between obstacles, b	0.1m
	absorber tube diameter, d	0.012m
	absorber tube length, La	9m
Convergent lenses	Diameter number	90mm 27

### B. Hot Air/Water Production Unit

The collector is orientated in a north-south direction and tracking the sun from east to west. The stainless reflector surface of 6 m<sup>2</sup> focuses the sun's radiation on a receiver canal, called a solar absorber, along the focal line of reflector length of 3 m. A series of 27 convergent lenses focus the radiation on the opposite part of the same receiver.

The absorber channel, having a rectangular shape, was made in galvanized sheet on which was fixed the water tube and was inserted crosswise (fig.05) and covered with a layer of black paint. The bottom of the absorbing channel is ordinary glass, allowing passage of the concentrated solar radiation to the focal plane within the channel.

Some modifications have been implemented to the absorber; the thermal oil has been replaced by air and water as HTF (heat transfer fluid), which are free of cost, nonpolluting, and the air has practically no operating temperature limit. The cross-section of the solar air/water receiver is shown schematically (fig.5). The new receiver implements a longitudinal flow design, where the temperature gain is obtained at the passage of air

between obstacles, which circulates hot water. The hot air channel has a dimension of 150mm x 50mm with a face glass.

The air is preheated at the absorber with two concentrators and then it will be sent to the air/water heat exchanger (fig.4) for superheating to a temperature of about 70°C.

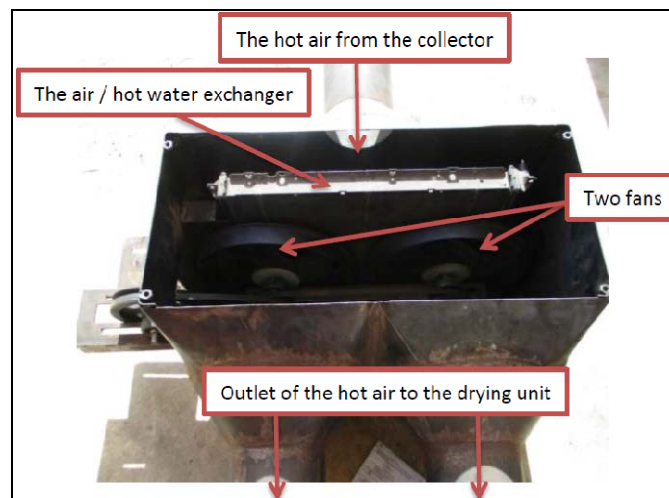


Fig.4. Air / water heat exchanger developed

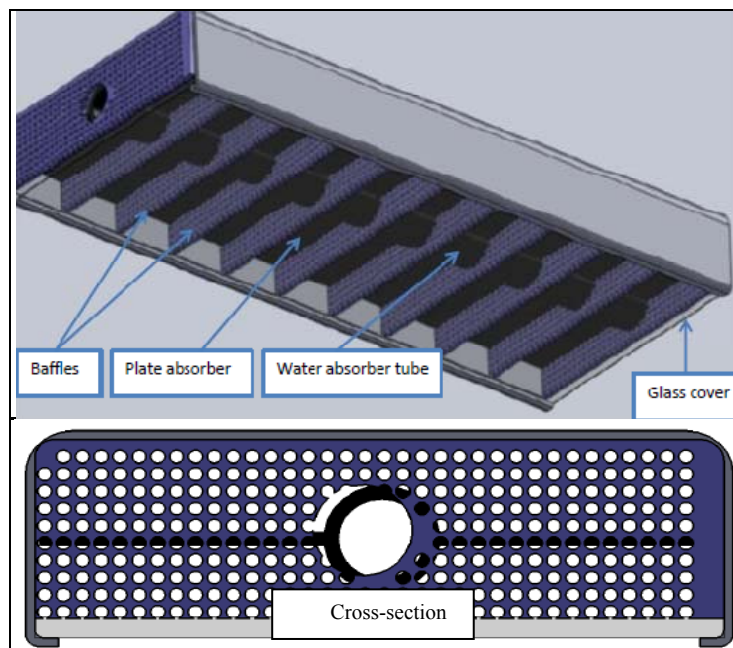


Fig.5. Schematic and cross-section of solar air/water absorber equipped with obstacles

### C. Experimental Procedure

Painted cylinders transported by a motorized chain conveyor enter one by one into the drying unit. The fan is operated automatically with a speed adjusted to the optimum air during the drying experiments (fig.1). The air is preheated the first time during its passage through the obstacles fixed on the planar absorber and the hot water tube, and then these two natural fluids (air and water) will be sent to a heat exchanger to raise the temperature of the drying air up to 70 °C. The air charged with solvents is discharged outside of the working environment using the paint booth extractor (fig.1). Quality paint has been tested manually and with the specific tape.

The hot water then passes through a condenser and circulates in a closed circuit by thermo-siphon-induced flow. The height position of the condenser, relative to the concentrator, ensures free passage of water in the absorber without the need to use a circulation pump rate in the solar receiver. The condenser is equipped with a safety valve, a pressure gauge, and a tap for the makeup water.



The solar tracker used is specific to the explosive medium using a pneumatic motor and a pneumatic control. The control circuit is pneumatic and the limit has been provided at the beginning and end of the work day. Timers are adjustable, depending on the season, with the opportunity to order a manually rotating hub (fig.6).

The timing for drying should be equal or inferior to 40 seconds to obtain the desired result. The solvents content in each cylinder is about 0.01 liter. The measurement of temperatures, solar radiation, and air speed is done every 15 minutes. The drying operation starts at 08:30 and stops at 15:30.

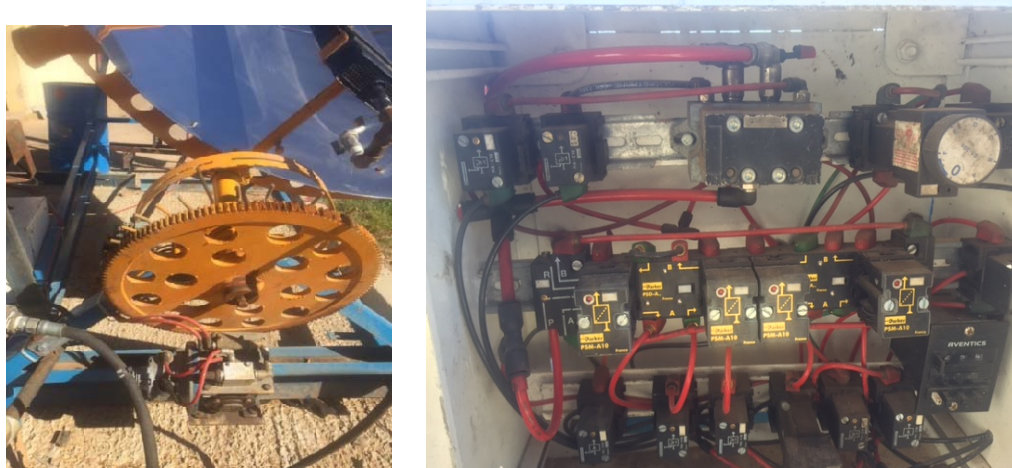


Fig.6.Sun tracking system developed with its pneumatic control box

**D. System Analysis**

The dimensions of the solar concentrator and the energy produced by the solar collector were calculated with the help of the following equations.

Concentration ratio is based on the concept of surface:

$$C_g = \frac{S_c}{S_r} \tag{1}$$

Distance focal line (fig.7)

$$f = \frac{r^2}{(4xh)} \quad r = \frac{AB}{2} \tag{2}$$

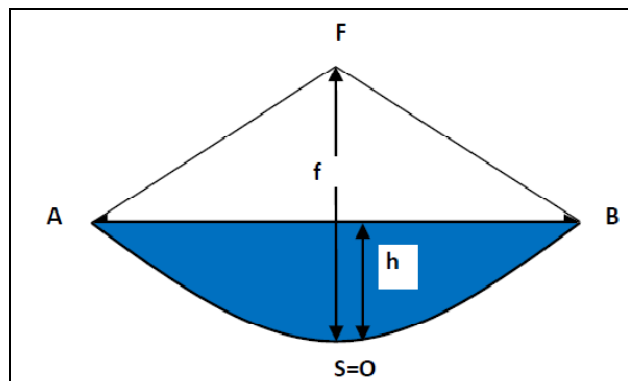


Fig.7.Parabolic cross section of the collector

The power output is the power recovered by the collector at the absorber level; it can be determined by the following expression:

$$Q_u = I_c \cdot \rho \cdot \tau \cdot \alpha \cdot \gamma - U_L \cdot S_r \times (T_e - T_a) \tag{3}$$

$$Q_u = Q_a - Q_p \tag{4}$$

Thermal losses reduce the energy received in the opening of a cylindrical parabolic concentrator; the power consumption is expressed as follows,  $Q_p$ : Power corresponding to thermal losses

$$Q_a = I_c \cdot S_r \cdot \tau \cdot \alpha \cdot \rho \tag{5}$$

The losses  $Q_p$  at the receiver are determined by the expression:

$$Q_p \cdot r = hcv \cdot S_r \cdot (T_r - T_a) \tag{6}$$

These thermal losses are proportional to the surface of the receiver and the temperature difference ( $T_r - T_a$ ) between the absorber surface and the ambient temperature. Our goal is to reduce this difference by adding convergent lenses that send concentrated radiation back to the bottom of the absorber and this to increase  $T_a$ .

For calculating the outlet heat transfer fluid temperature, the following equation was used:

$$T_s = T_e + \frac{Q_u}{C_p \cdot M} \quad (7)$$

Energy production in solar collector can be found by the following equation:

$$E_n = P_n \times t_d \quad (8)$$

$$P_n = \rho_a (h_s - h_a) D_s \quad (9)$$

Calculating the air enthalpy by using the Mollier chart

The energy amount crossing through the sun to the collector is calculated as above with complex formulas or can be momentarily measured with a solar meter [10].

### III. EXPERIMENTAL RESULTS AND DISCUSSION

A solar dryer has been manufactured and tested in a butane gas filling plant (Oujda, Morocco). This dryer will be used for drying gas bottles after washing and after painting in a short time. The bottles pass one by one automatically under the drying unit. The drying air velocity was fixed at 0.9 m/s. The dryer performance was tested in three days; the dryer was tested in an environment with average relative humidity 30% and average ambient temperature 25°C.

#### A. Solar Radiation and Ambient Temperature Values

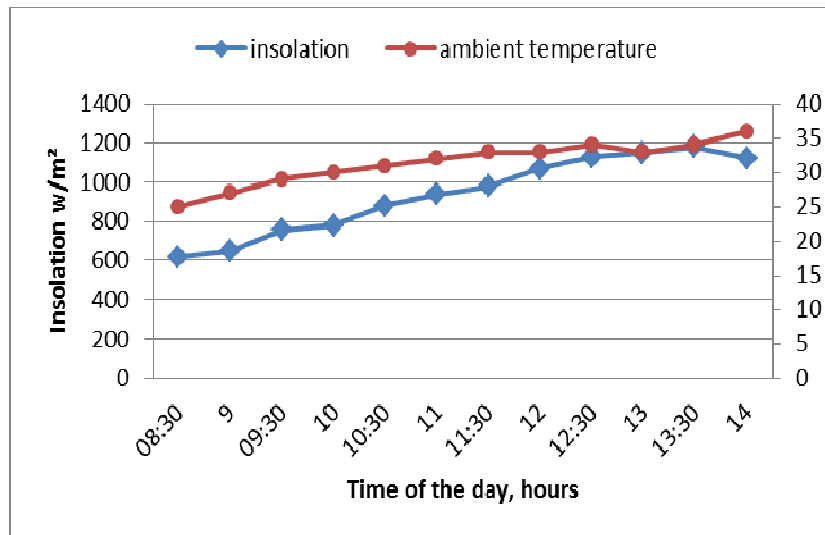


Fig. 8. Variation of the ambient temperature and the insolation during a day in September 2017

The change of solar radiation and ambient temperature on September 2 is shown in Fig. 8. A solar maximum intensity 1200  $W/m^2$  was observed at an ambient temperature of 35°C. It increases from the sun rising to reach a maximum at mid-day before decreasing again until cancelling at night. The use of solar energy is well adapted to the applications for which the needs coincide with the sunniest hours.

*B. The Impact of the Simultaneous Use of Two Natural Heat Transfer Fluids*

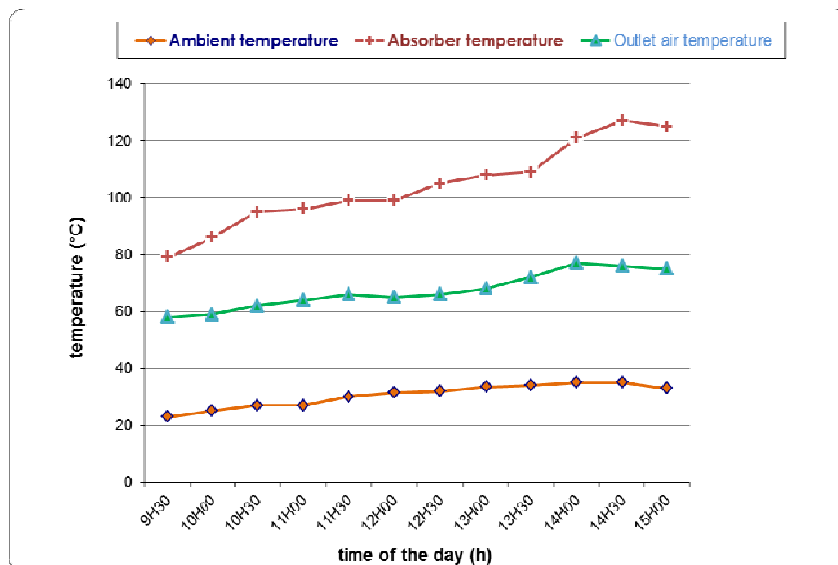


Fig. 9. Drying air temperature.

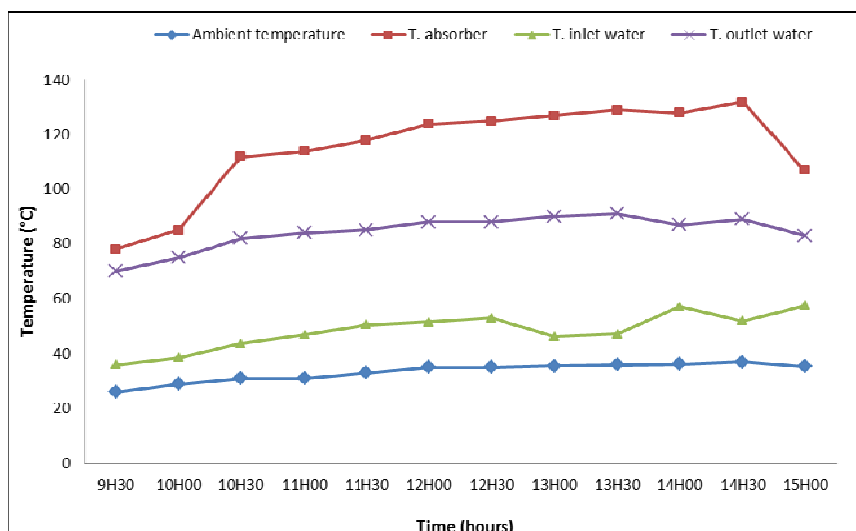


Fig. 10. Inlet-outlet water temperature in absorber.

As seen in Fig.9 and Fig.10, by using exchanger air/water and two heat transfer fluids, the drying air temperature has improved on average by 5°C. However, the use of obstacles throughout the absorber allowed the improvement of the drying air temperature. The maximum temperature of the drying air recorded during hours of peak sunlight was 75°C.

The average drying air temperature recorded was 65°C, the high temperature of the absorber and high convective and radiative heat transfer. The water circulates in a closed circuit and the temperature at the receiver inlet is high in addition to the thermal insulation of the hot water circuit, and this is responsible for the rise in the air temperature.

C. Effect of Convergent Lenses on Rise of Receiver Temperature

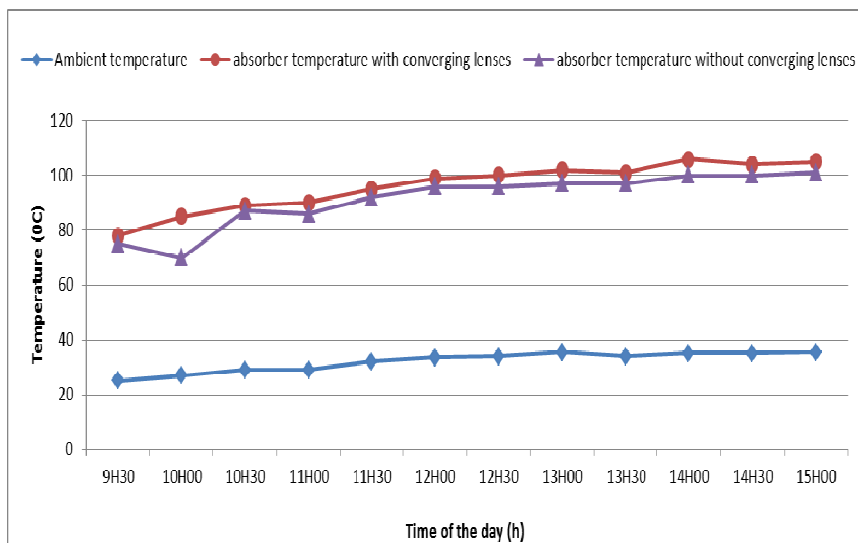


Fig. 11. Lenses impact on the absorber temperature

We find in Figure 11, the improvement of the absorber temperature  $T_a$  by the combination of convergent lenses having only a surface of  $0.79\text{cm}^2$  with the parabolic concentrator. Given these results, it is planned to put Fresnel lenses having a surface area of  $40\text{ cm}^2$  to increase the absorber temperature  $T_a$  and thus reduce heat losses at the receiver.

D. Effect of Drying Air Temperature on Drying Time

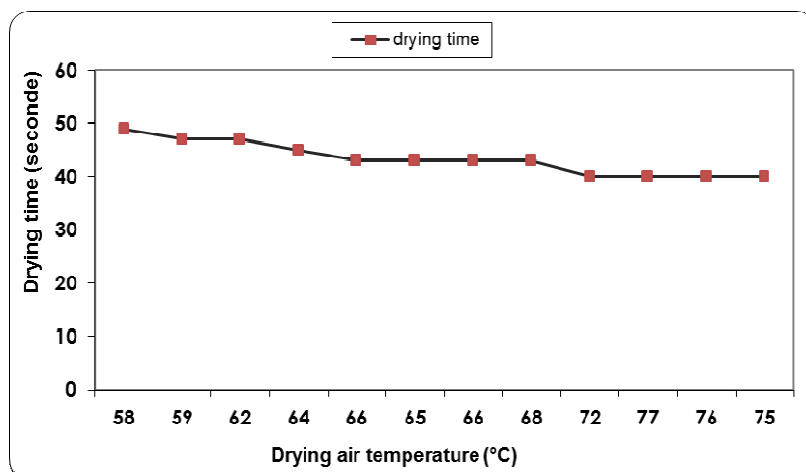


Fig. 12. Drying time with solar dryer.

Fig. 12 represents the temperature variation according to time in the drying unit for an optimum airflow ( $500\text{m}^3/\text{h}$ ). There was a significant reduction in the drying time from 420 seconds natural with drying to about 40 seconds using our solar dryer and without the need to store the painting cylinders on the floor. The performance of the painting activity was increased by over 40%, the number of painted cylinders per day increased from 3000 to 4300, an increase of 43%.

IV. CONCLUSIONS

A forced convection solar dryer using a parabolic concentrator combined with a series of convergent lenses, the whole is tilted at an angle of  $34^\circ$ . This dryer was designed, fabricated, and tested for drying painted gas cylinders. Firstly, our work demonstrates the impact on the dryer performances by the combination of two types of concentrators on a single receiver, and the first use of a solar dryer in the gas cylinder paint industry. Secondly, dryer performances were improved by tracking the sun and by inserting obstacles in the absorber. We also deduce the simultaneous use of two natural heat exchange fluids (air and water) resulted in the improvement of the drying air temperature and reaches  $65^\circ\text{C}$ . The maintenance of a good performance during the day is ensured by the inclination of concentrators at a  $34^\circ$  angle, the sun is tracked by a pneumatic tracker developed by us and which is specific for an explosive environment.



Accordingly, 420 seconds of drying under natural conditions decreased to 40 seconds with the developed dryer. The solar dryer has enabled the drying of painted cylinders on the conveyor and without the need to file them down and go directly to the filling unit. This led to a significant 43% increase in the number of painted bottles per day. On the health and safety side, employees are not exposed to solvents, since the bottles are dried inside the paint booth, which evacuates drying air to the outside. In perspective and given the results obtained, we will increase the Fresnel lens surface from  $0.79\text{cm}^2$  to  $40\text{cm}^2$ .

### ACKNOWLEDGMENT

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### NOMENCLATURE

C: concentration factor	$\beta$ : Angle between the reflected ray of the sun and the center of normal opening
$C_p$ : specific heat (J/kg.K)	$\tau$ : transmission coefficient
$D_s$ : Air flow ( $\text{m}^3/\text{s}$ )	f: focal distance (m)
$f_r$ : Overall fluid-absorber transfer coefficient	$K(\theta)$ : Incidence angle changed
$h_a$ : ambient air enthalpy, (J/kg)	$\gamma$ : Interception factor
$h_s$ : heated air enthalpy, (J/kg)	$\rho$ : Monochromatic reflection coefficient
I: the energy gained from the total radiation striking the collector surface ( $\text{W}/\text{m}^2$ ).	$\alpha$ : Absorption coefficient
L: concentrator length (m)	$\tau$ : transmission coefficient
$Q_u$ : amount of heat generated at the collector (w),	$\sigma$ : Standard deviation of the normal flow
$P_n$ : power required (W)	$\rho_a$ : ambient air density, ( $\rho_a = 1,2 \text{ kg}/\text{m}^3$ )
$S_c$ : concentrator area ( $\text{m}^2$ )	
$S_r$ : Receiver area ( $\text{m}^2$ ),	
$t_d$ : drying time (s)	$U_L$ : Thermal losses coefficient ( $\text{W}/\text{m}^2 \text{ K}$ )
$T_c$ : collector inside temperature, (K)	$T_s$ : collector outside temperature, (K)

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