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Experimental Study of Polyethylene Fusion by Scheffler Solar Concentrator

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Authors' contributions

This article is the result of a team effort by all authors. Author DD designed the study, wrote the protocol and drafted the first version of the manuscript. Authors SO and ALO managed the analyses of the study. Authors TSMK and BK managed the literature search and made major corrections. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The present work is the use of Scheffler technology to melt plastic waste to produce composite materials using an oven type receiver. The composite material in this study contains polyethylene as a matrix and sand as reinforcement.
Study Design: The fusion temperature of polyethylene is about 200°C and is obtained by solar concentration. The experimental plastic melting unit in Saaba (latitude 12.38° N; longitude -1.43° E), Burkina Faso, uses two 8 m² Scheffler concentrators sharing a cubic receiver. Three types of mirrors with a reflectivity of at least 90% are used as reflecting facets to equip the Scheffler dishes at the site.
Methodology: The thermal behavior of the receiver is analyzed experimentally. Temperatures are measured on the inner and outer walls as well as the internal air temperature with 5 K-type thermocouples. When the fusion temperature is reached on the inside, we introduce the plastic waste which has been previously washed, crushed, dried and weighed.
Results: The installed model obtained an average energy of 1.80 kW at the receiver and an

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average internal temperature of 251.15°C for an average irradiance of 623 W/m² during the no-load test. During the load test, an average energy of 1.34 kW and an internal temperature of 206.4°C were reached for an average irradiance of 473 W/m² and an optical efficiency of 56%. This test led to the production of two pavers of the composite material matrix with 2.2 kg of plastic waste.

Conclusion: These results show that the profiles of the primary reflector, tracking system, and tilt axis are accurate and the maximum concentrated solar flux converges on the absorbing surfaces of the receiver. The tempered panes of the absorbing surfaces is more transparent and less emissive. Thus our device contributes to the valorization of plastic waste by using a non-polluting energy source.

Keywords: Scheffler concentrator; fusion; solar energy; valorization; plastic waste.

1. INTRODUCTION

The management of household solid waste in general and plastic waste in particular is a major concern for municipalities in developing countries. The cities of Burkina Faso, faced with an increase in the volume of plastic waste, mainly packaging plastic, are no exception to this reality. Many researches explained this phenomenon. According to Beede et al. [1], this increase is linked to population growth. Indeed, an African city like Ouagadougou, the capital of Burkina Faso has experienced a 1.66% population growth in the last 10 years. Faced with the problem of plastic waste, the government of Burkina Faso promotes scientific research oriented toward waste management and valorization. Several solutions have been implemented, including transforming plastic waste into construction materials. The manufacture of composite materials using thermoplastic polymers as matrix and sand as reinforcement is a process of treatment of plastic waste commonly used in developing countries. This recovery route requires the melting of polymers at high temperatures. However, the fusion is energy intensive and often carried out with fossil energy, making the composite materials non-competitive compared to cement-based materials.

In the study we use solar energy to solve this problem. Solar thermal applications are nowadays financially viable and can substitute for fossil fuels. Solar energy, abundant, environmentally friendly and free of energy costs is a huge renewable resource on earth. Yet, the radiated solar energy is very strongly attenuated as it passes through the earth's atmosphere [2]. To increase yield, there are two types of technologies of energy capture. Those using the global radiation and those using only the direct component [3]. Optical concentrators allow to increase the density of flux arriving on a receiver and contribute to solve the problems posed by the low energy density of the incident solar radiation [4]. In this work, we focus on the solar concentrator, specifically the Scheffler solar collector, invented in 1986 by Wolfgang Scheffler. The Scheffler concentrator is a reflective concentrator. Thanks to a tracking system following the solar azimuth and declination, the point of concentration of the solar radiation is at the same place throughout the day [5]. Scheffler concentrators with movable reflectors and fixed focus are mainly used for direct cooking or steaming applications and are capable of increasing the receiver temperature up to 200°C [6]. An average cooking power of 2.2 kW was obtained with an 8 m² reflector equipped with single mirrors for a solar irradiance of 700W/m² and an optical efficiency of 75% [7]. The technology is used for various domestic and industrial applications. Concentrators with 0.5 to 2.7 m² of reflective surface are suitable for home use. Sizes of 7 m²; 8 m²; 9.7 m²; 12.6 m² and 16 m² are commonly used for school canteen and industrial applications [6]. The technology has evolved significantly with 16 m² to 50 m² reflectors installed mostly in India [8]. Most of the improvements have been in the form of added functionality, either in the size or shape of the reflectors or in the receivers or tracking mechanisms [6]. The literature review shows that the applications of the technology are quite diverse, including power generation, steam generation, heat storage, distillation, and desalination [9]. The Scheffler technology is an efficient renewable energy technology application and is therefore an alternative to the high cost of fossil fuel.

Chandak, (2012), documented the construction of a 1 MW power plant in Rajasthan through the use of 60 m² square shaped reflectors. Munir, (2010), with an average insolation of 800 W/m², and an 8 m² reflector, experimentally obtained an estimated 1555 W (1.5 KW) of energy available at the receiver. Munir et al. (2010a) conducted an efficiency study on a concentrating device using only a primary reflector and another using a primary and secondary reflector. The efficiencies of 49.9% and 40% show that the use of a secondary reflector results in a loss of efficiency of about 9-10% and therefore its use should depend on the type of cooking. Ayub et al. 2018 [10], designed and developed, a solar bakery unit comprising a 10 m^2 Scheffler primary reflector and a secondary reflector. The results indicate that the receiver temperature is between 300 and 400°C with a calculated maximum available solar energy of 3.46 kW, an average efficiency of 63%. The energy available in the cooking chamber, 3.29 kW, and the temperatures at the entrance of the cooking chamber (200 to 230°C), allow most products cooking. Bhambare et al. [11], installed and experimented in Oman a decentralized autonomous pilot desalination unit operating with a pair of 16 m^2 Scheffler concentrators. The reflectors are all directed towards the North Pole and each one has its own receiver. The output of 60 and 65 liters per day during the summer period was obtained with a pilot plant designed to produce 100kg/day of fresh water.

The work of Dib et al. [12] improved the design of receivers used in Scheffler concentrators to avoid energy losses at the absorber inlet. And those of Habeebullah et al. in [8], show that the heat losses from the receiver by conduction, convection and radiation from the inner mass are significantly reduced by using furnace-type receivers protected by a greenhouse. Another improvement to Scheffer's technology consisted to replace the daily tracking mechanism originally equipped with a pendulum clock by a DC wiper motor. The motor is powered by batteries connected to photovoltaic panels. To this system, Chandak, [8], added a controller to the wiper motor placed after the timer, thus achieving a rotation speed accuracy of 15° per hour.

The objective of the present work is the use of Scheffler's technology to melt plastic waste and produce composite materials using an oven type receiver. The experimental study will be conducted according to the equipment configuration given by the layout diagram in Fig. 1 of the melting unit located at Saaba, in Burkina Faso.

2. MATERIALS AND METHODS

2.1 Realization and Description of the Prototype

The basic components of the Saaba fusion unit device are schematically shown in Fig. 1. The fusion unit consists of two mobile reflectors of 8 m^2 and a fixed receiver. The cube-shaped receiver is 1.10 m above the ground, between the two reflectors and inclined at 12.38°, which is the latitude of the site.

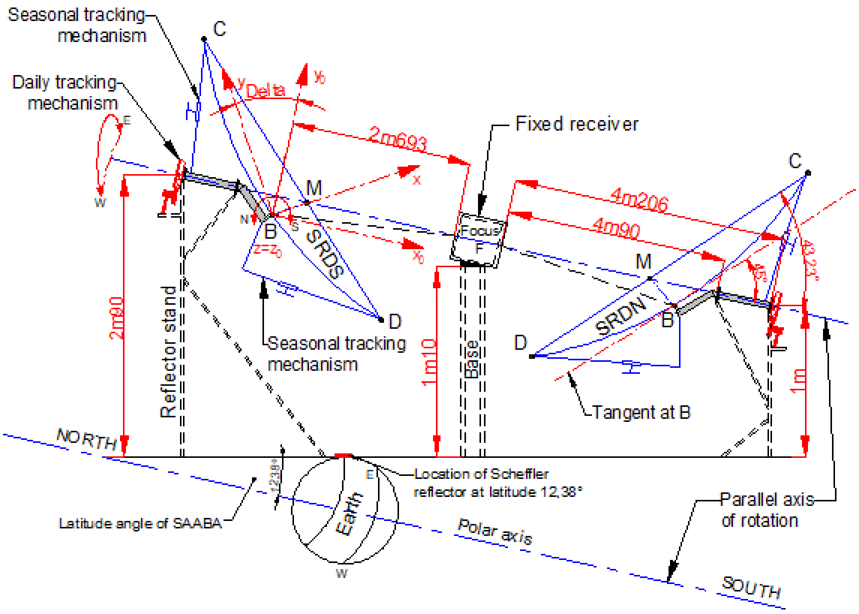

Fig. 1. Configuration of the plastic waste (PW) melting unit with a pair of Scheffler reflectors facing each other. Scheffler reflector directed to the south (SRDS) and Scheffler reflector directed to the north (SRDN)

The surface of the primary reflector is the lateral section of a paraboloid. Each reflector has a surface of 8 m², one directed to the south (SRDS) and the other to the north (SRDN) (Fig. 1). The reflector's frame is deformable. The deformation is done manually at intervals of 3 to 4 days using telescopic levers [8] (Fig. 1) and modifies the effective aperture area so that it remains perpendicular to the sun rays on any day of the year.

The secondary reflector reflects the light from the SRDS and SRDN onto the absorbing surfaces of the receiver which transfers the heat to the plastic waste. In the present study, the secondary reflector is composed of 4 trapezoidal shaped reflective facets, forming a total surface of 0.784 m². The reflective facets are made of self-adhesive mirror-effect film (SAMEF) of the brand D-C Fix. They are glued to 0.3 mm thick aluminum sheets (ISO 9001: 2000 17-3F1997-2-F-1030-6-B1F 2016) before being riveted to the shower tray (Fig. 2).

2.1.1 Receiver

The receiver is made of 2 mm thick black steel sheet. It is cubic in shape, 0.35 m on each side, and has a hole on one side to admit the plastic waste (Fig. 3b). The tray is insulated all around with 20 cm of rock wool and 5 cm of glass wool (Fig. 3). A black paint (TOPLAC) is applied on the absorbent surfaces (0.0784 m²) (Fig. 2b). Before the application of the paint, the absorbent surfaces are roughened with emery paper to maximize adhesion. Also, on each absorbent surface, we placed tempered panes of 0.28 m x 0.28 m in size and 3 mm thick.

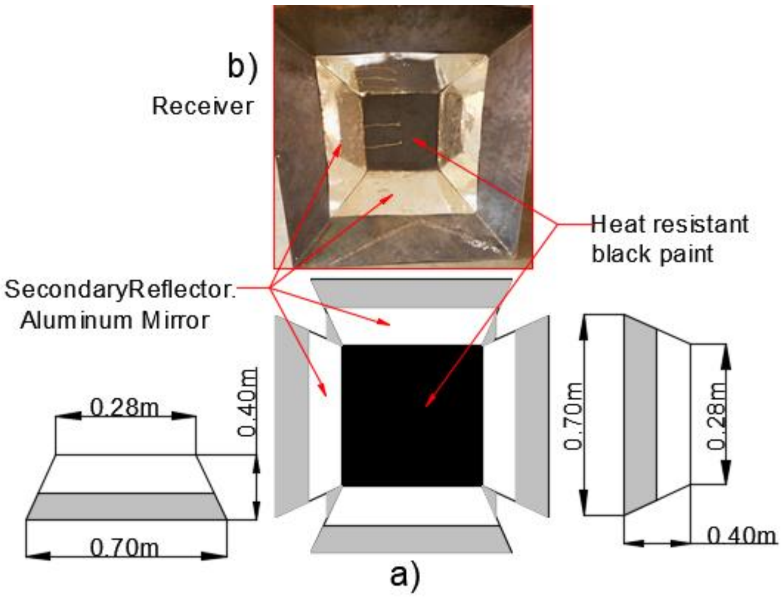

Fig. 2. a) Diagram of the secondary reflector. b) Photo of the secondary reflector

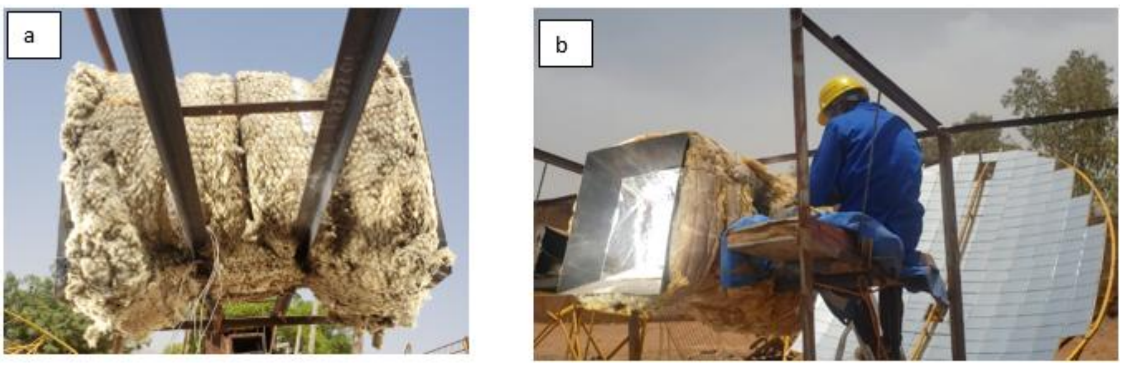

Fig. 3. a) Insulation of the perimeter of the receiver with rock wool. b) Inlet opening of the plastic waste in the receiver

2.2 Reflective Facets

Reflectors are designed with mirrors that are usually curved so that all the light reflects at the focal point, no matter where it strikes the surface of the concentrator. Glass mirrors (e.g., low iron) are generally used to reflect the incident radiation. They have a transmissivity of up to 98%. However, glass mirrors (GM) can be replaced either by a self-adhesive mirror-effect film (SAMEF) or by aluminum mirrors (AM). Aluminum has a weighted reflectivity of 88-91%, Fend et al.,2000, in [13]. In the present study, the three types of mirrors with a reflectivity of at least 90% are used as reflecting facets to equip the Scheffler dishes of the Saaba site (Fig. 4).

Fig. 4 shows the Scheffler reflector directed to the north (SRDN) reflecting incident radiation to the north and the Scheffler reflector directed to the south (SRDS) reflecting incident radiation to the south.

The rotating drum, the telescopic levers and the reflector and receiver supports are made of rectangular, circular and L-shaped steel sections. All metal surfaces of the concentrator elements were painted with anti-rust paint before the application of the yellow paint to protect them from corrosion and other natural hazards.

The telescopic levers allowing to obtain the desired parabola shape by deformation of the reflector frame are fixed on the upper and lower parts of the reflector frame. The rotating drum used for daily tracking is direct pivot connection with the support at two points without using bearings or sliding bearings.

2.2.1 Glass mirror (GM)

The 5 mm thick glass mirror is cut into facets of 120 mm x 200 mm (Fig. 5). The mirror pieces are then assembled on 14 flat iron rails using copper wire with the reflector frame on the rotating support in situ at Saaba. A total of 290 glass mirror facets provided the 8 m^2 SRDN (Fig. 4). By comparison, Ramachandran et al. [14], used glass mirrors with 92% reflectivity in their work

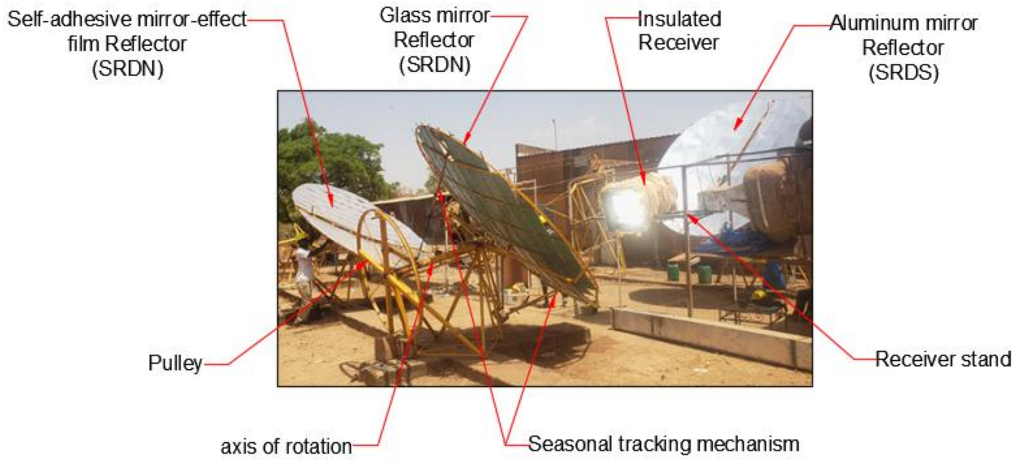

Fig. 4. The reflection elements of the plastic waste melting unit at Saaba (Latitude 12.38°; Longitude -1.43°)

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Fig. 5. a) Pieces of glass mirror and Iron strips. b) Self-adhesive mirror-effect film. c) Aluminum Mirror

The mirrors, whatever their size or thickness, are cut into facets so that they not only fit the curved shape of the dish frame during assembly but also do not put any strain on the frame. We use a plastic film to protect the reflective surfaces while cutting the facets to size, assembling them on the rails, and mounting the rotating drum with the dish on the support.

2.2.2 Self-adhesive mirror-effect film (SAMEF)

The SAMEF is from the brand D-C Fix. It includes a reflective side and an adhesive side. The film is 0.1 mm thick and comes in the form of a 1.5 m x 90 cm roll (Fig. 5b). It is cut into reflective facets of 90 cm x 20 cm. The facets are first glued to 0.3 mm thick aluminum sheets. The whole is then assembled on the rails of the frame of the reflector with soft wire, without the rotating support off site, in the workshop of Lycée Technique National Aboubacar Sangoulé LAMIZANA of Ouagadougou. The reflecting surface is protected by a plastic film that is removed at the end of the assembly.

2.2.3 Aluminum mirror (AM)

The mirrors are made of 0.3 mm thick aluminum foil in the format 1.2 m x 1.5 m (Fig. 5c). The reflective side of the foil is protected by a plastic film. The foil is cut into facets of 90 cm x 20 cm. The facets are then assembled on the reflector frame rails with soft wire, without the rotating support in a private workshop off site. In Fig. 4, the 8 m^2 SRDS is made of aluminum mirror. The aluminum mirror from the Alcan company in Germany has a reflectivity of over 87% [13].

2.3 Tracking System

The tracking system mechanism includes a single gearbox for daily tracking, and telescopic levers for seasonal tracking. The daily tracking mechanism consists of a motor, a pair of spur gears, a clutch, a sprocket and chain system, and a sun position sensor (Fig. 6a).

The motor uses DC and is powered by a solar module, through a box equipped with a control board (microcontroller). It starts when the motion detector sensor intercepts sunlight and stops as soon as the sensor is in the shade. The gear pair is straight-toothed and has a 12 teeth sprocket ($Z_{Sprocket}$=12) and a 120 teeth wheel (Z_{Wheel}=120). The transmission ratio K is determined by equation 1.

$$K = \mathrm{k}_1 \mathrm{k}_2 \tag{1}$$

$$\mathrm{k}_1 = \frac{\mathrm{Zpignon}}{\mathrm{Z_{roue}}} \tag{2}$$

$$\mathrm{k}_2 = \frac{\mathrm{R_{pignon}}}{\mathrm{R_{poulie}}} \tag{3}$$

R represents the radius of the sprocket or pulley.

Solving equations 1, 2 and 3 gives a transmission ratio K= 0.0021. The driving torque is transmitted to the sprocket-chain system via a clutch. The sprocket-chain system transmits the motion to the driven pulley in fixed connection with the parabola of the Scheffer concentrator.

The clutch is disengaged in case of resistant torque. The characteristics of the sprocket are the number of teeth Z=8; the pitch, p = 12.70; the original diameter, d = P/sinα = 38.1866 mm; and the angle at the center is defined by the relation 2α = (360°) /Z hence α = 22.5°. The 152 cm diameter receiving pulley is in fixed, removable and adjustable connection with the chain.

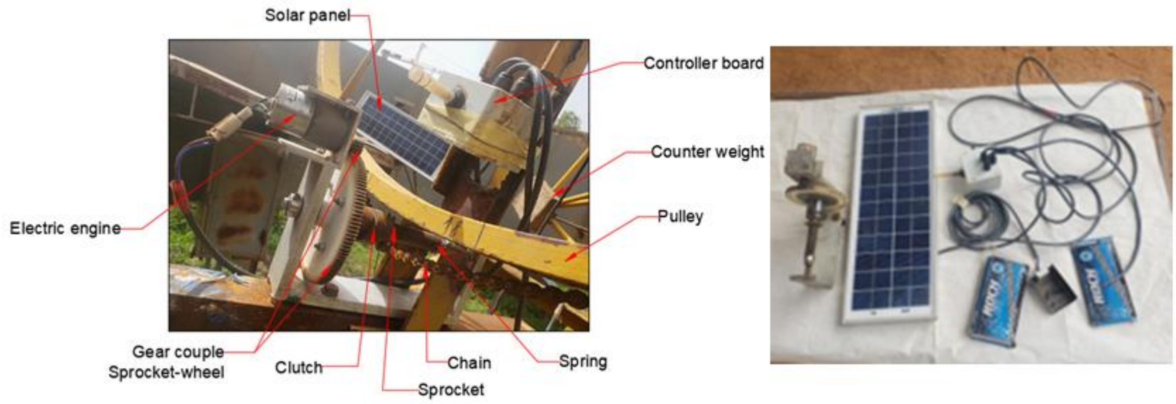


Fig. 6. a) Daily tracking mechanism mounted on the SRDS at Saaba (latitude 12.38°; longitude -1.43°). b) Overview of the equipment used

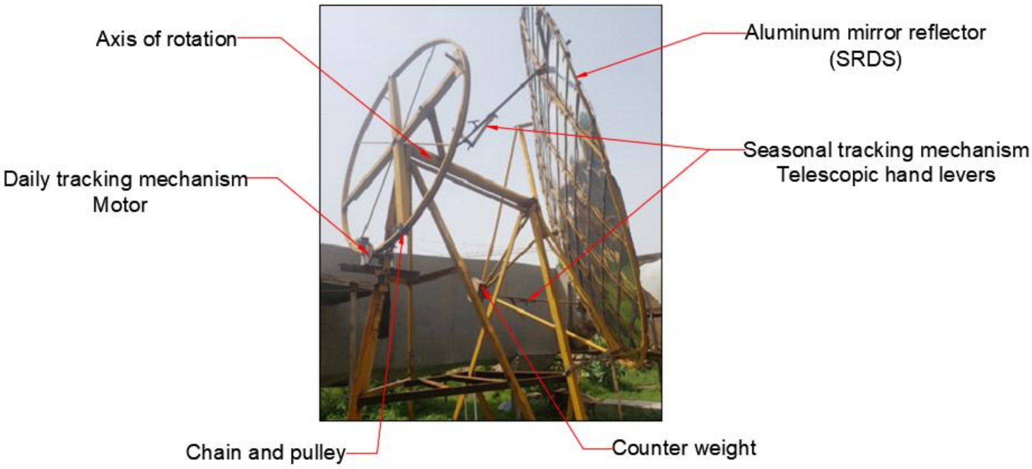
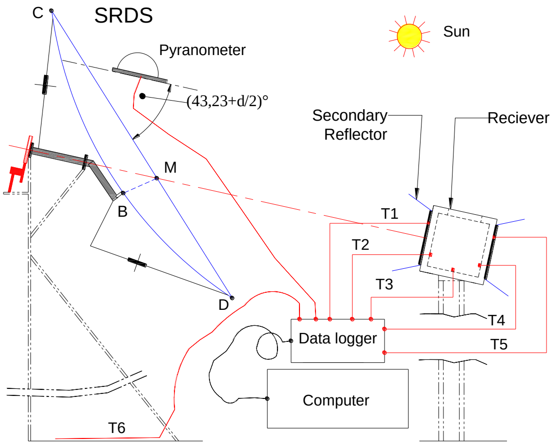


Fig. 7. Seasonal tracking mechanism using the telescopic levers of the SRDS. Saaba website



Temperature measuring points on receiver		
T1	North wall outside temperature	NWOT
T2	North wall inside temperature	NWIT
T3	Inside temperature	IT
T4	South wall inside temperature	SWIT
T5	South wall outside temperature	SWOT
T6	Ambient temperature	AT

Fig. 8. Configuration diagram of the measurement equipment at Saaba.

Table 1. List of material used for measurement

	Data logger GRAPHTEC Midi LOGGER GL 220	K type Thermocouples	Pyranometer direct radiation
Specification range	10 Channel handy-type logger	-100 to 1370°C	0 to 2000 W/m^2
Accuracy	0.1% of F.S.	±(0.05% of reading + 1.0°C)	± 15 W/m^2

The seasonal tracking mechanism allows the seasonal adjustment of the dish. The adjustment is done every 3 or 4 days using telescopic bars as shown in Fig. 7 of the SRDS of the Saaba site.

2.4 Experimental Protocol

The experiment consisted in measuring the temperatures inside and on the walls of the receiver with thermocouples. When the interior temperature reached the melting temperature, we introduce the plastic which has been previously washed, shredded, dried and weighed. The experiment took place in two stages in Saaba (Latitude 12.38° N; longitude -1.43° E) where the plastic waste fusion unit is located. The unit is located on the site of solar bread oven in the premises of Gabriel TABORIN School (EGT). The first stage consisted in an experiment without load which took place from April 06 to 27, 2021. The second stage, where we loaded the oven, which took place on April 29 and 30, 2021. For this purpose, the equipment used and their connections are illustrated in Fig. 8. Table 1. lists the equipment used.

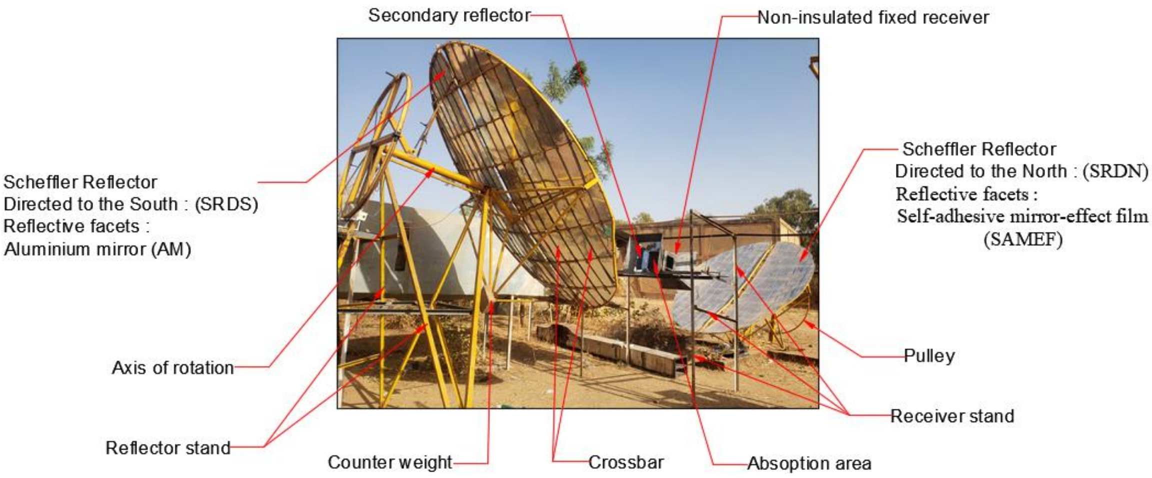


Fig. 9. Figure of the plastic waste melting unit at Saaba.

The first stage of the experiment included a series without load with the 3 types of mirrors in the reflectors. From April 06 to 24, we recorded the energy output of an SRDS in aluminum mirror and that of an SRDN in self-adhesive mirror-effect film (Fig. 9). From April 27 to 30, we recorded the energy output of an SRDS in aluminum mirror and that of an SRDN in glass mirror. The reflective facets of the primary and secondary reflectors were washed with water and allowed to dry for some time. Non-tempered panes 5 mm thick were placed on the absorbing surfaces of the receiver.

In the second step, shown in Fig. 4, the energy available at the absorber is provided by a SRDS in aluminum mirror and by an SRDN in glass mirror.

3. RESULTS AND DISCUSSION

3.1 No-load Test

The first stage of the tests verified the quality and reliability of the reflective facets, the focusing panes, and the black paint (TOPLAC) applied to the absorbing surfaces. The ordinary untreated 5 mm thick glass panes broke under the effect of heat (Fig. 10a). The black paint applied to the absorbing surfaces melted (Fig. 10c). We concluded that the paint was of poor quality or that the surface was not properly prepared before applying the paint. The secondary reflector, made of self-adhesive mirror-effect film of the brand D-C fix, was badly damaged. Also the sealant (silicone sealant, Asmaco 2500) did not hold (Fig. 10c).

The windows limit the effect of the wind on the absorber. Tempered panes are harder to break than non-tempered panes.

The experiments continued with the replacement of the broken panes with the tempered ones (Fig. 10b) without changing the damaged facets (in SAMEF) of the secondary reflector with aluminum mirror facets nor the paint. An average absorbed energy of 1.80 kW over a 10-hour period and an average internal temperature of 251.15°C (Fig. 12) at the receiver were obtained on 4/24/2021 for an average irradiance of 623 W/m² (Fig. 11). The energy was

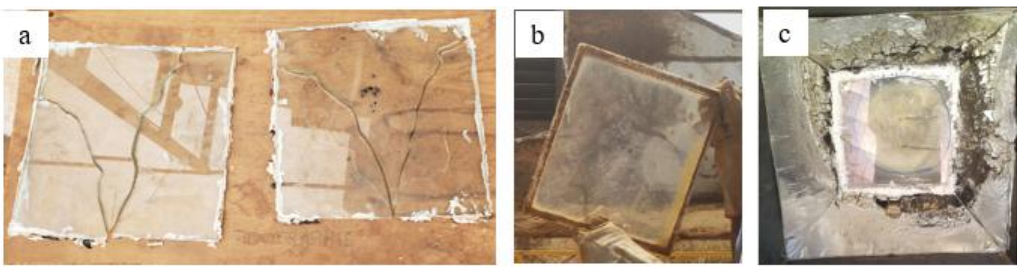


Fig. 10. a) Broken ordinary panes (5 mm thick). b) Tempered panes of 3 mm thickness and 0.28 m side. c) Damaged secondary reflector made of self-adhesive mirror-effect film and wall-panes seal provided by silicone

provided by the pair of an SRDS in aluminum mirror and an SRDN in self-adhesive mirror-effect film whose opening surface is 5.17 m² in the northern hemisphere. For the same reflectivity of the mirrors, the NWIT remain almost higher than the SWIT and are respectively carried by the energy provided by the SRDS in aluminum mirror and the SRDN in self-adhesive film with mirror effect (Fig. 12b). The same is true for the NWOT and SWIT (Fig. 12a). The motorization of the SRDS would explain this performance of the aluminum mirror.

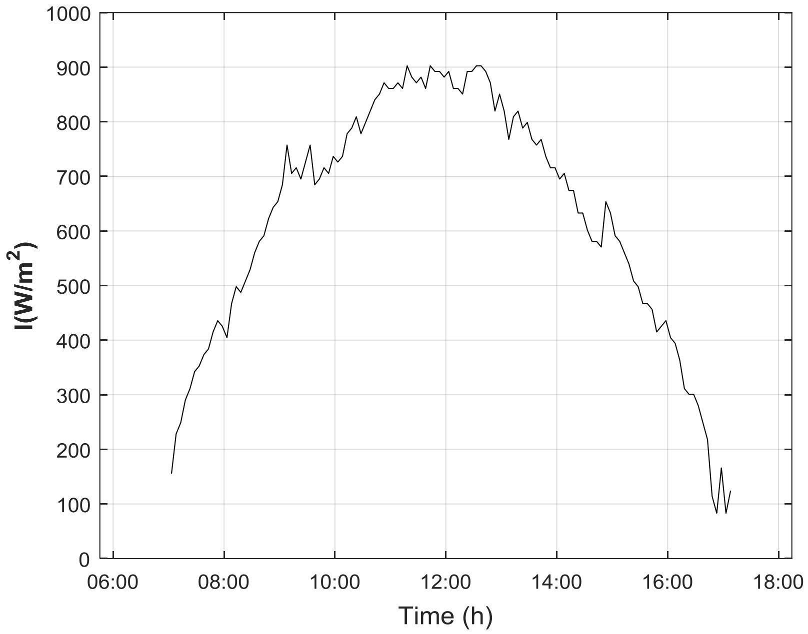


Fig. 11. Irradiance on April 24, 2021.

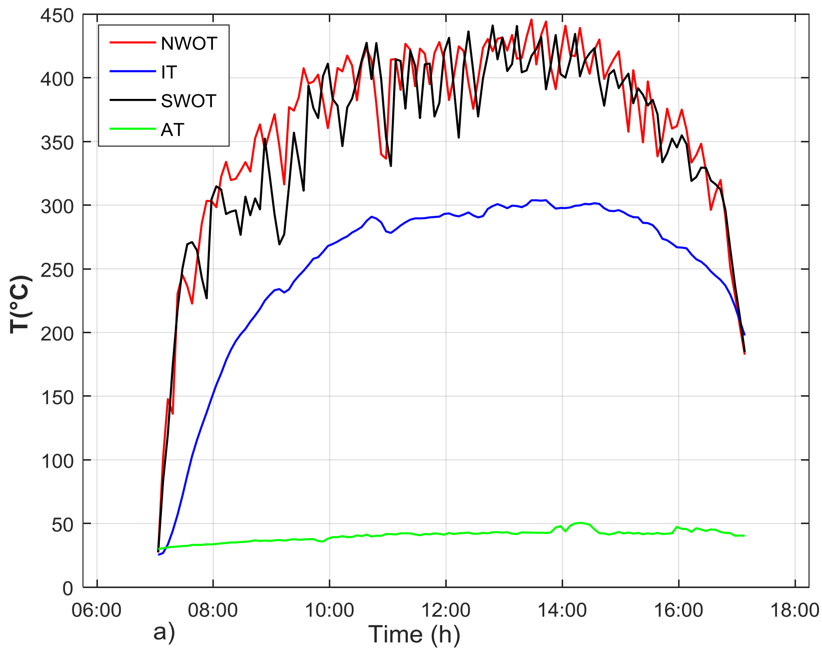


Fig. 12. a) Temporal evolution of temperature NWOT, IT, SWOT, AT at the measurement points on April 24, 2021

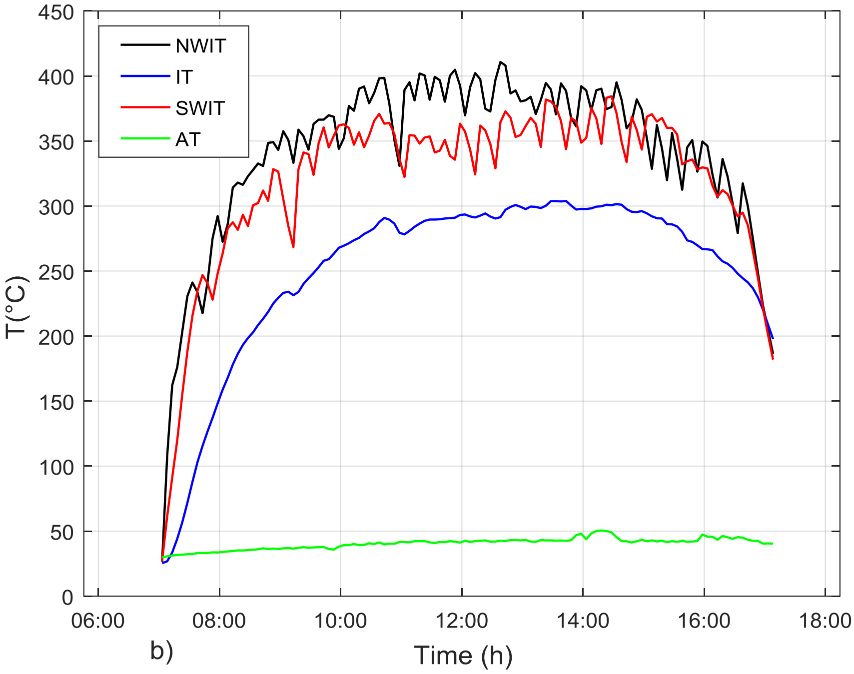


Fig. 12. b) Temporal evolution of NWIT, IT, SWIT, AT temperature at measurement points on April 24, 2021

Fig. 13. Pavers of the matrix of the composite material produced with molds of different shape on April 30, 2021

3.2 Load Test

The experiment under load started on 4/30/2021 at 10.24 am. At about 11.00 am, the internal temperature was above the melting temperature (208.9°C) for an irradiance of 850 W/m². Temperature drop occurred at 11.15 am, after we opened the orifice to load the oven with plastic waste (Fig. 3b). The introduction of 2.2kg of plastic occurred at 11.37 am, contributing to a further drop in temperature. After the introduction of the plastic waste, the closing of the orifice and the installation of the insulation, the temperature rose again to reach the melting temperature (200.8°C) at 12.39 pm. Casting occurred at 3.40 pm, approximately 5 hours after the test was started. Two pavers of the composite material matrix (Polyethylene) were produced (Fig. 13). The average energy and average internal temperature recorded during this period are 1.34 kW and 206.4°C respectively for an average irradiance of 473 W/m² and an optical efficiency of 56%.

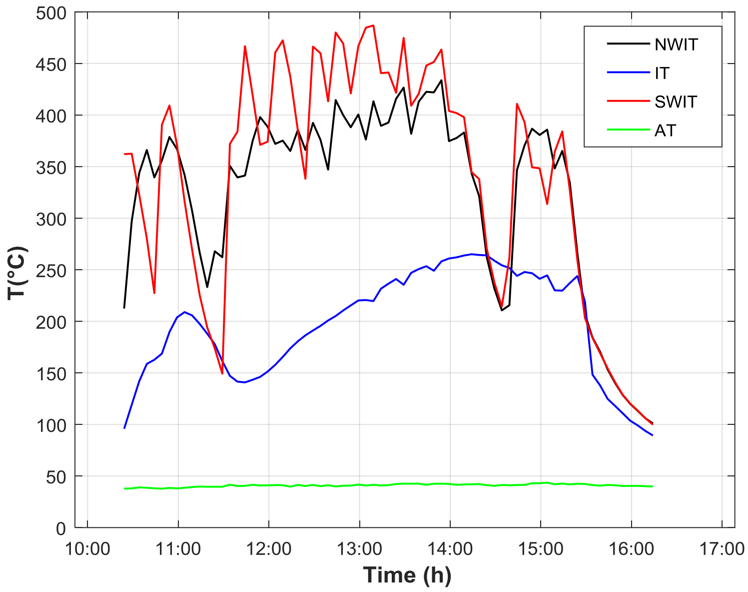


Fig. 14. Temporal evolution of the indoor temperature on April 30, 2021

From 11.34 am to 3.14 pm, the SWIT was higher than the NWIT (Fig. 14). As the SRDN is not motorized, we deduce that the performance of the glass mirrors is much higher than that of the aluminum mirrors which equip the motorized SRDS. We also observe on Fig. 14 that the SWIT are lower than the NWIT between 10.34 am and 11.39 am. This was due to a bad synchronization of the rotation of the SRDN with that of the sun.

4. CONCLUSION

The polyethylene (PE) melting unit of Saaba, equipped with a pair of 8 m² Scheffler concentrators with a single receiver produces the heat necessary to melt PE (HDPE and LDPE). On 4/30/2021 with an average irradiance of 473 W/m² and an average available energy of 1.34 kW, two pavers were produced without reinforcement (Fig. 13). An average temperature of 196.5°C inside the receiver was recorded during the loaded experimental day. The late start of the experiment (at 10.00 am), which induces a very short time of preheating of the receiver combined with a low average irradiance may explain the average energy of 1.34 kW obtained on 4/30/2021. An average absorbed energy at the receiver of 1.80 kW for an average irradiance of 623 W/m² and an average temperature of 251.15°C were recorded on 4/24/2021. Our results show that the profiles of the primary reflector, the tracking system and the tilt of the rotation axis are accurate and the solar radiation converges on the absorbing surfaces of the receiver. The absorbed power on any day of the year can be improved by removing the secondary reflector, applying black paint (Matt Black, RAL 9011) to the absorbing surfaces, placing the reflector facets on the reflector frame in situ, using motorized tracking systems.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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