



A Comparative Study of Experimental Results and Modelling Results for the Melting of Polyethylene using a Scheffler Solar Concentrator

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Abstract: Plastic waste (PW) management remains a major concern in our towns and rural areas. An approach involving the recovery of this waste through the manufacture of composite materials could be a solution to this problem. To this end, an experimental study and a numerical study were proposed. The results of the experimental study showed that the melting of 2 kg 200 g of waste, under an average solar irradiance of 473 W/m^2 and an average internal temperature of 206.4°C , is effective, representing a difference of 6.4°C from the melting point of PE (200°C). Simulation studies have shown that the average internal temperature in the simulation is 216.85°C , which is 16.85°C below the melting point of PE (200°C). From these results, we note that the experimental data show a higher efficiency of 96.89 per cent of the heat required to melt 2kg 200g, compared with the simulation result of 92.22 per cent. Experimental work is more efficient than simulation work.

Keywords: plastic waste, temperature, melting, experimentation, simulation.

INTRODUCTION

The manufacture of composite materials using thermoplastic polymers as a matrix and sand as a reinforcing agent is a method of processing plastic waste (PW) commonly used in developing countries (DC). This recovery process requires the polymers to be melted at high temperatures exceeding 200°C . Using solar thermal energy instead of fossil fuels helps to minimise the costs of plastic waste treatment. Solar energy, which is abundant, environmentally friendly and free of energy costs, according to Munir (2010) [1], is a vast renewable resource on Earth.

Energy harvesting technologies are generally classified into two main categories: those that utilise total radiation and those that utilise only the direct component. The Scheffler reflection concentration sensor, invented by Wolfgang Scheffler, belongs to the second family. Optical concentration sensors increase the flux density reaching a receiver. This is first attenuated as it passes through the Earth's atmosphere. The distinctive characteristic of Scheffler technology is that the focal point of the solar radiation remains in the same place throughout the day, even though the reflector's parabolic dish tracks the sun from morning to evening, enabling cooking to take place in the shade. The focal point of the solar radiation is kept in the same position throughout the day, thanks to a tracking system that follows the sun's azimuth and declination. Parabolic solar concentrators have been in use for nearly 150 years. At that time, they had a rigid structure with a focal point that moved in line with the sun's position, which made the system rather impractical [2]. Solar energy concentration technologies have evolved and are now based on four fundamental components: the concentrator, the receiver, transport and storage, and energy

conversion. This is the case with Scheffler technology, invented in 1986 by Wolfgang Scheffler (Oelher and Scheffler, 1994). This reflective concentrating solar collector is mainly used in developing countries. Scheffler technology has been widely used in India since 1990, where 80 per cent of the world's Scheffler solar concentrators are installed, with reflectors ranging in size from 7 m² to 50 m² [3]. Scheffler reflectors, which belong to the family of solar collectors, capture the direct component of solar radiation and enable heat to be generated at temperatures in excess of 250°C with excellent thermal efficiency (>70%) [4]. A maximum temperature of 1020°C has already been achieved at the focal point, and an average cooking power of 2.2 kW was obtained using an 8 m² reflector equipped with standard glass mirrors (75 per cent reflectivity) and under sunlight intensity of 700 W/m². Scheffler technology has seen its applications expand worldwide to include electricity generation, hot water production, steam generation, heat storage, distillation and desalination [5]. Scheffler technology is an efficient application of renewable energy and offers an alternative to address the high cost of energy, particularly fossil fuels, in developing countries.

Concentration sensors have some drawbacks, however. They can only concentrate direct radiation; in other words, they cannot focus the total radiation. Another major drawback is that they only work in clear skies, which generally requires the use of control systems. Consequently, despite its wide range of applications and commercial availability, the use of Scheffler technology remains largely confined to cooking applications. In our case, Scheffler technology is used to generate heat at a temperature in excess of 200°C in a furnace-type vessel in order to melt flexible plastic waste (PW) for the manufacture of polymer matrix composites.

The objective of this study is to compare the results of the experimental study with those of the numerical simulation. The experimental setup comprises a pair of Scheffler reflectors sharing a single receiver, as shown in Figure 2. The experiment is being carried out using three types of mirror in order to measure their performance. Scheffler reflectors have therefore been equipped with the following reflective elements: glass mirrors (m.e.v); aluminium mirrors (m.e.a); and self-adhesive mirror-effect films (f.a.e.m). For the numerical simulation, a virtual model was designed to provide accurate results through the analytical solution of the equations using the COMSOL Multiphysics software.

The results of the experimental tests and numerical simulations will be compared and discussed with a view to validating or otherwise the model and manufacturing the prototype of the oven-type receiver.

PRESENTATION OF THE RESULTS OF THE EXPERIMENTAL STUDY

In this section of our study, we shall present a summary of the works of the experimental study into the melting of polyethylene using a SCHEFFLER solar concentrator. Figure 1 illustrates the experimental set-up. In this setup, the receiver is positioned between the two parabolic dishes at a height of 1.10 metres above the ground and is inclined at a latitude of 12.38° in a north-south direction. The focal length chosen is 2.69 metres and the calculated focal point is approximately 1.43 metres above the ground on the vertical axis.

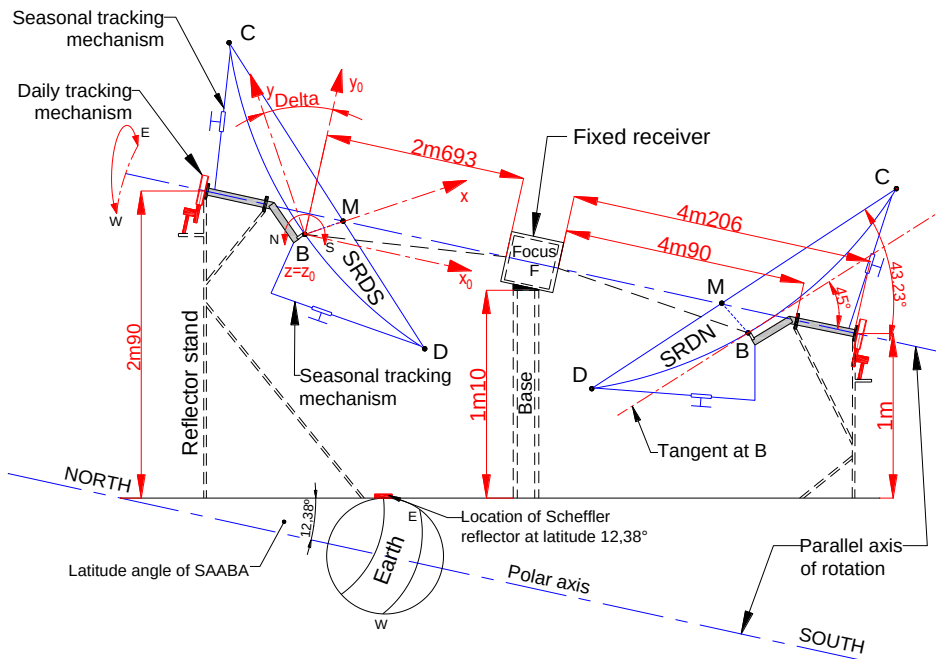


Fig.1: Configuration of the plastic waste (PW) melting unit with a pair of Scheffler reflectors facing each other at SAABA (latitude 12.38° N; longitude -1.43° E). Scheffler reflector directed to the south (SRDS) and Scheffler reflector directed to the north (SRDN).

Experimental Protocol

Experiments on the melting of plastic waste, both under vacuum and under load, were carried out at the Saaba solar bread oven site, located within the Gabriel TABORIN School (EGT). The glass mirrors (m.e.v) were assembled on site. The self-adhesive mirror-effect film (f.a.e.m) and the aluminium mirrors (m.e.a) were assembled in the general mechanics workshop at the Aboubacar Sangoulé LAMIZANA National Technical College (LTN/ASL). Thermocouples connected to a data logger were used to measure, respectively, the ambient air temperature (AT), the temperature in the melting chamber (IT), the temperatures of the outer and inner walls of the receiver on the north side (NWOT and NWIT) and the temperatures of the outer and inner walls of the receiver on the south side (SWOT and SWIT). A pyranometer, also connected to the data logger, was installed in such a way that there were no shadows around it, so as to record direct radiation (G_b). Figure 2 shows an image of the plastic waste melting unit used in this study. It contains a pair of movable Scheffler primary reflectors, one directed to the north and the other to the south. The reflector Scheffler directed to the north (RSDN) reflects incident radiation northwards, and the reflector Scheffler directed to the south (RSDS) reflects incident radiation southwards. They both have a fixed receiver containing secondary reflectors. The heat flux from the primary reflectors is concentrated onto two absorbing surfaces of the receiver, each of which faces a respective primary reflector. The heat accumulated by the hot surfaces is then transferred by conduction to the polymer matrix.

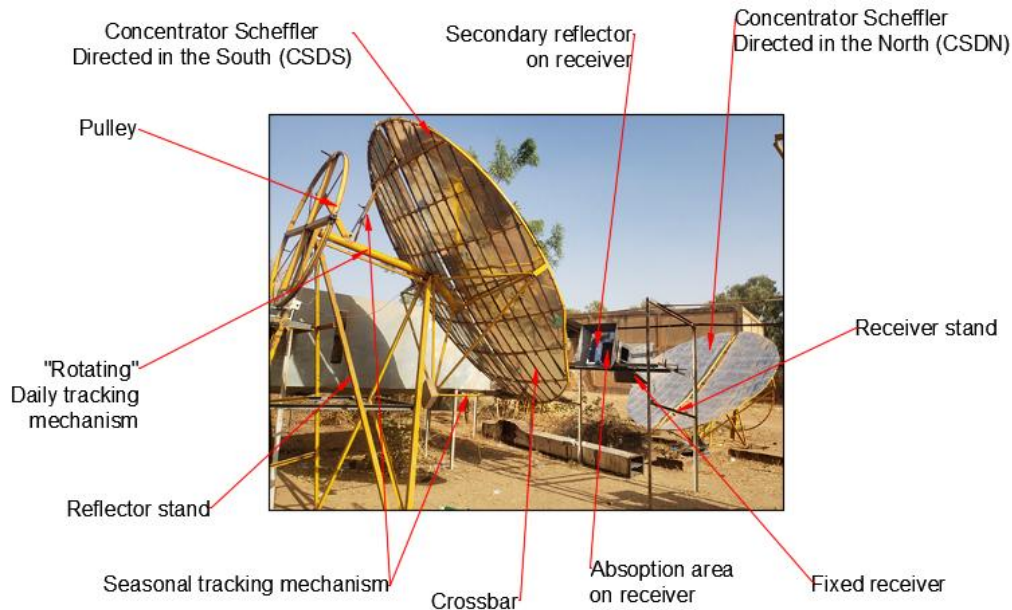


Fig. 2: Figure of the plastic waste melting unit at SAABA.

The equipment used for measurement and data logging in this experiment is described in Table 1. A diagram showing the configuration of the material installation is also provided in Figure 3. For this experiment, it was decided to measure the temperatures every 5 minutes.

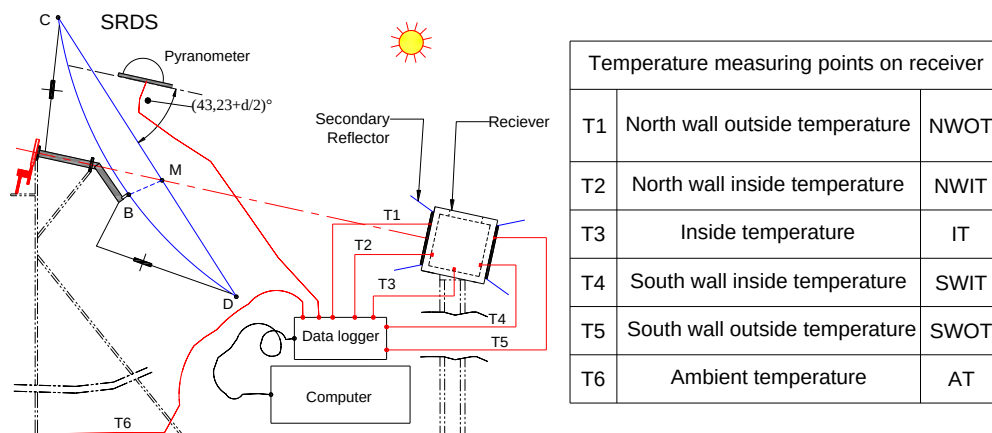


Fig. 3: Configuration diagram of the measurement equipment at SAABA.

Table 1: List of material used for measurement

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

Experimental Results

The load test took place on April 30, 2021 and began at 10.24 am. It is illustrated in Fig. 4. The energy available at the absorber is supplied by an RSDS in m.e.a. and an RSDN in m.e.v. At around 11.00, the temperature was 208.9 °C, with a solar irradiance of 850 W/m². It is higher than the melting point of PE, which is around 200 °C.

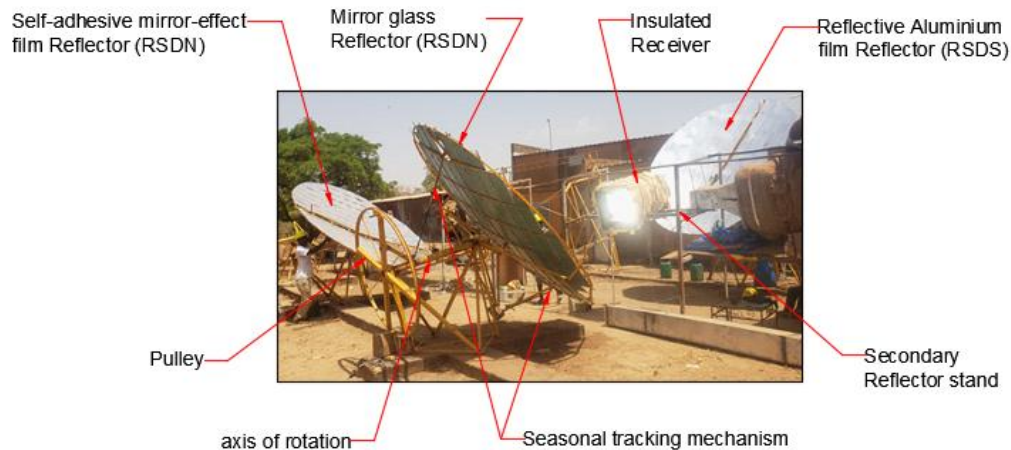


Fig. 4: The reflection elements of the plastic waste melting unit at SAABA (Latitude 12.38°; Longitude -1.43°).

The opening of the orifice for the introduction of 2 kg 200 g of plastic, which had been washed and shredded beforehand, took place at 11.37 am. Five hours after the start of the test, the average power and the internal temperature recorded during this period were 975.6 W and 206.4 °C respectively (exceeding 200 °C = the melting point of the PE) for a solar irradiance of 473 W/m². Two pavers of the polymer matrix of the composite material were thus produced (Fig. 5).



Fig. 5: Pavers of the matrix of the composite material produced with molds of different shape on April 30, 2021.

The temperatures of the south wall inside (SWIT) remain higher than those of the north wall inside (NWIT), driven by the energy supplied by the RSDN in m.e.v and by the

RSDS in m.e.a respectively, from 11:34 am to 15:14 pm (Fig. 6). The RSDN is not motorised; it follows that the efficiency of the m.e.v is significantly better than that of the m.e.a units equipped on the RSDS, which is, however, motorised. A poor synchronisation of the RSDN's motion with that of the Sun would explain why the SWIT values are lower than the NWIT values shown in Fig. 6.

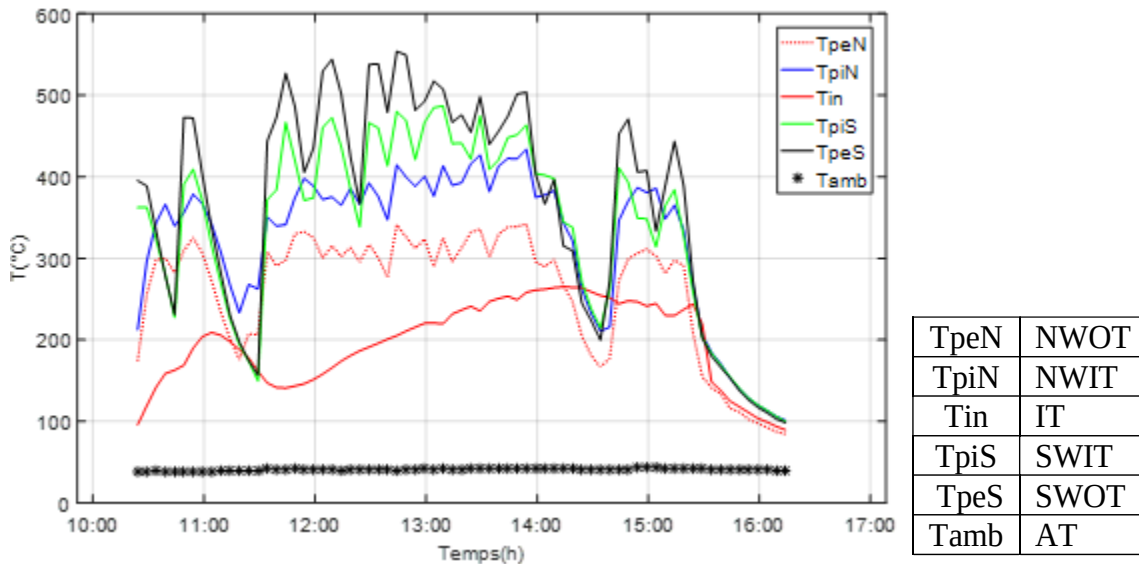


Fig. 6: Temporal evolution of the AT, NWOT, IT, NWIT, SWIT, and SWOT temperatures on April 30, 2021.

PRESENTATION OF MODELING RESULTS

Heat Transfer Equations and Boundary Conditions

By solving equations (1) and (2) using COMSOL Multiphysics and the finite difference method, it is possible to determine, on one hand, the available flux at the absorbing wall and, on other hand, the heat distribution within the receiver.

The equation for heat conduction through uninsulated walls is given below:

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_H \quad (1)$$

In short, the absence of heat dissipation from insulated surfaces means that the receiver's internal environment is adiabatic. This leads to the following boundary conditions : $\vec{n}q=\vec{0}$, from which :

$$\lambda \frac{\partial T}{\partial x} = 0 ; \lambda \frac{\partial T}{\partial y} = 0 ; \lambda \frac{\partial T}{\partial z} = 0$$

With :

- ρ : Density
- C_p : Thermal capacity
- λ : Thermal Conductivity

- $\rho C_p \left(\frac{\partial T}{\partial t} \right)$: Energy stored in the material
- $\lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$: Energy evolution through conduction
- q_H : Internal flow source = Incoming heat flux, $q_H = q_{1H} + q_{2H}$
- q_{1H} : Heat flow : wall 1
- q_{2H} : Heat flow : wall 2

The transfer of the available flow from the walls of the collector to the internal receiver is given by equation (2) below.

$$\rho C_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_H \quad (2)$$

With $q_H = q_{1H} + q_{2H}$

Where q_{1H} is the flux received by the left inlet and q_{2H} is the flux received by the right inlet.

Equation (2), rewritten differently, gives:

$$\left(\frac{\partial T}{\partial t} \right) + \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\lambda}{\rho C_p} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q_H}{\rho C_p}$$

With:

- $\left(\frac{\partial T}{\partial t} \right)$: Temperature gradient
- $\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right)$: Convection term
- u, v, w : Speeds in all three directions
- $\frac{\lambda}{\rho C_p} = \alpha$: Diffusivity
- $\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$: Distribution term
- $\frac{q_H}{\rho C_p}$: Internal flux source, coming from q_{1H} and q_{2H}

Receiver Modeling

A virtual model in the form of a cube with sides measuring 35 cm, representing our oven-type receiver, was created using COMSOL Multiphysics. Simulation enables the search for solutions to complex problems using software by creating a virtual model of the system under investigation (Fig.7).

Vacuum Modelling of the Receiver

Simulation provides accurate results through the analytical solution of heat equations. Equations (1) and (2) will be solved using the COMSOL Multiphysics software.

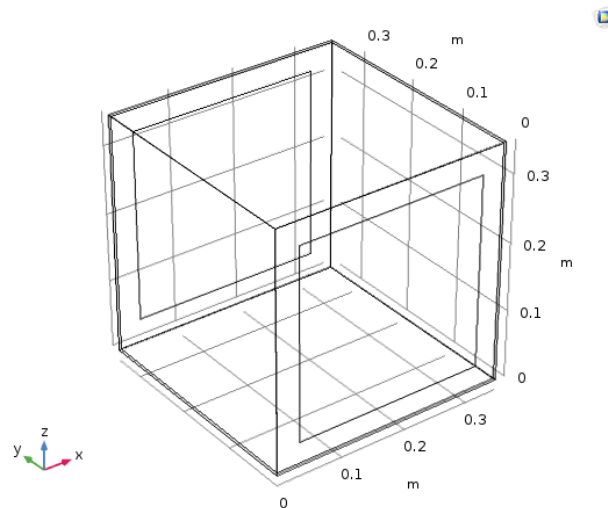


Fig. 7: Virtual 3D model of the receiver

Modelling the Receiver under Load

We assume that the empty receiver's temperature is 293.15 °C and the absolute pressure is 1 bar. Once the receiver is loaded (Figure 8), the temperature decreases and reaches the ambient temperature of 29.72 °C. A heat flux of $q_H = 1000 \text{ W/m}^2$ continues to be applied to the absorbing surfaces of wall 1 (north) and wall 2 (south) of the receiver (Fig. 9) until the PE reaches its melting point.

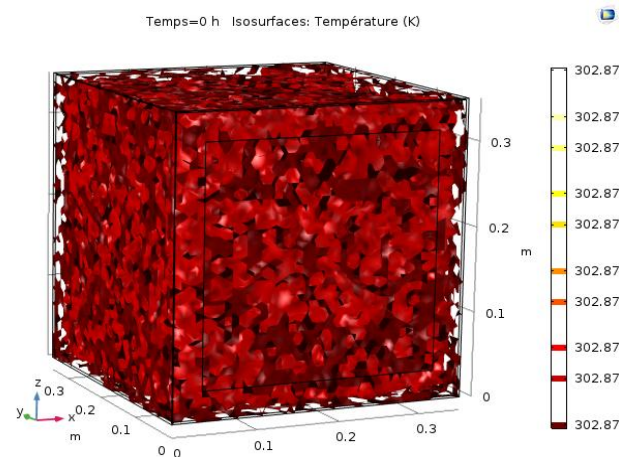


Fig. 8: Model of the PE receiver under load

Simulation Results

A three-dimensional simulation of the process was carried out using COMSOL Multiphysics software version 5.3a to evaluate the heat distribution across the absorber, as shown in Figure 9. To this end, the furnace-type receiver was modelled using a tetrahedral structured mesh, as illustrated in Fig. 10. The regime is steady-state. The transfer coefficient $\lambda = k(T[1/K])$ has been assigned to high-density polyethylene (HDPE) and low-density polyethylene (LDPE). The surrounding area of the receiver is insulated with 20 cm thick rock wool. The absorbing surfaces are coated with matt black paint.

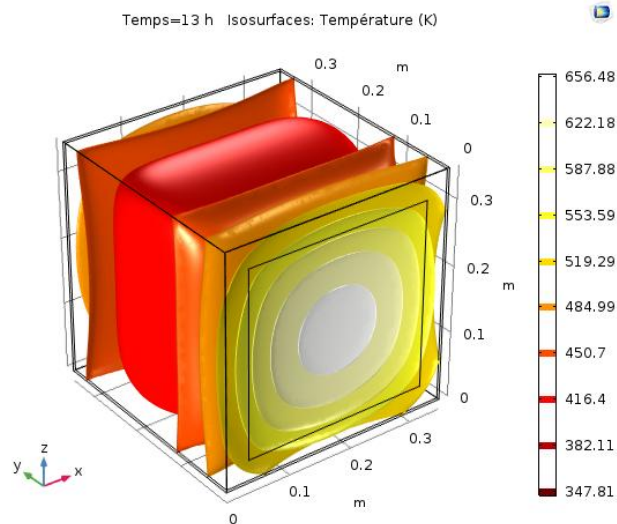


Fig. 9: Isosurfaces and temperatures of polyethylene in an iron cavity 2 mm thick: 0.35 m × 0.35 m × 0.35 m.

The isosurfaces and temperature readings show that the plastic begins to melt from the north and south sides (absorbent surfaces) towards the centre of the receiver. The temperature is 333.44°C on the wall and 72.32°C inside the receiver.

Description of the Grid

The grid for our receiver was generated using the standard Model Builder interface of COMSOL Multiphysics 5.3a (Fig. 10). A system grid is a structure consisting of geometric elements that enables the representation of surface subdivisions using a set of polygons. The grid is fine-meshed and consists of 2,067 grid points, 63,368 tetrahedra with degrees of freedom, 31,238 triangles and 87 point elements.

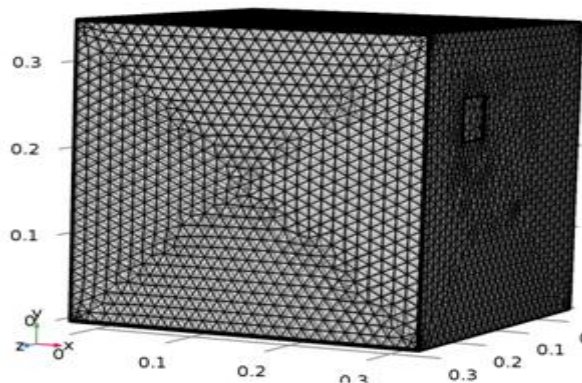


Fig. 10: Grid of the receiver with 0.35 m sides.

The curves in Fig. 11 show the distribution of heat from the primary reflector (Eg primary reflector) to the receiver (Eg receiver) between 6.00 and 18.00, with an average direct solar radiation of 800 W/m².

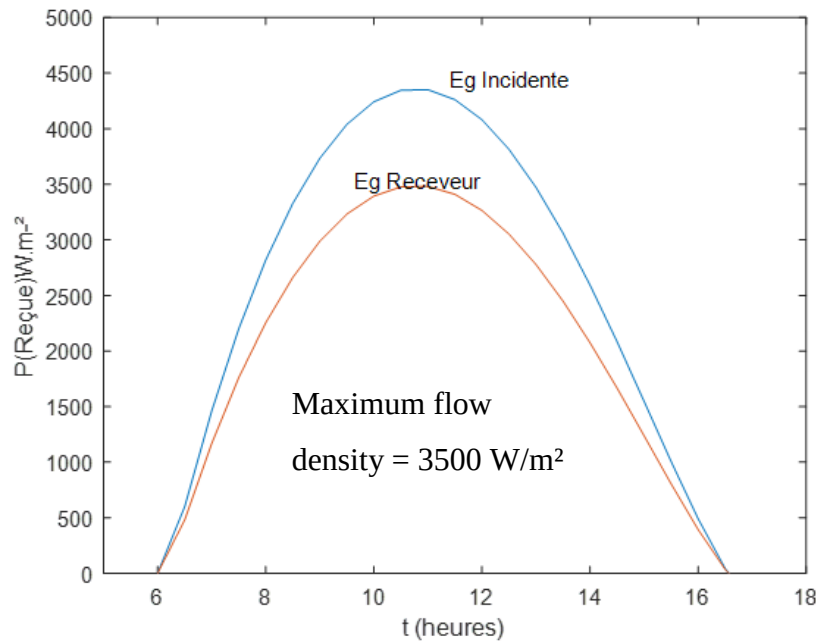


Fig. 11: Flow density received by the primary reflector and by the receiver.

The Eg curve for the collector shown in Fig. 11, which takes the form of a bell curve, illustrates the variation of the flow over the course of a day. The flow is zero before 6 am, reaches a maximum of 458.75 W, corresponding to an irradiance of 3,500 W/m² at 11 am, and drops to zero after 5 pm. This flow raises the temperature to over 300°C, as shown in Fig. 9.

The heat flux available on each wall from 9.00 am is approximately 306.25 W. This is sufficient to raise the temperature inside the receiver chamber above the melting point of PE (200 °C) for at least 5 hours (up to 14 hours).

The average available energy at the receiver between 7 am and 3 pm (8 hours) is estimated at 10.204 kWh, which corresponds to a power output of approximately 1.27 kW when the solar irradiance is 800 W/m².

The isotherms in Fig. 12 show a temperature peak of 346.85°C on the absorbent walls at 13:00 on 21 March. The data in Fig. 9 confirm this peak (348.85°C) and indicate that the temperature of the flux ranged between 196.85°C and 210.85°C. The Eg curve for the receiver in Figure 11 shows that the average temperature of 203.85 °C of the melt is obtained by a heat flux of 352.19 W, corresponding to a flux density of 2,875 W/m² incident on the wall.

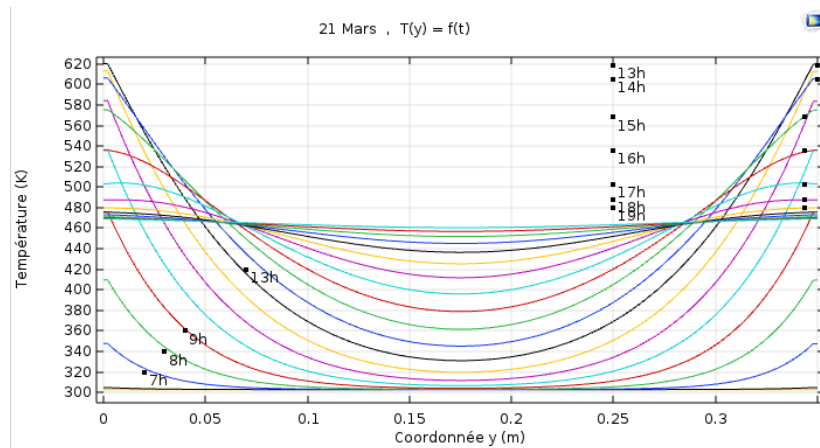
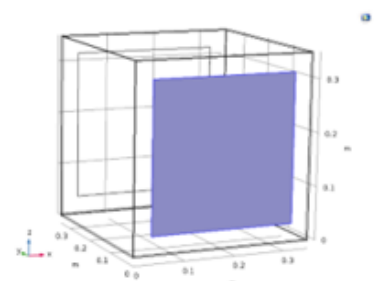
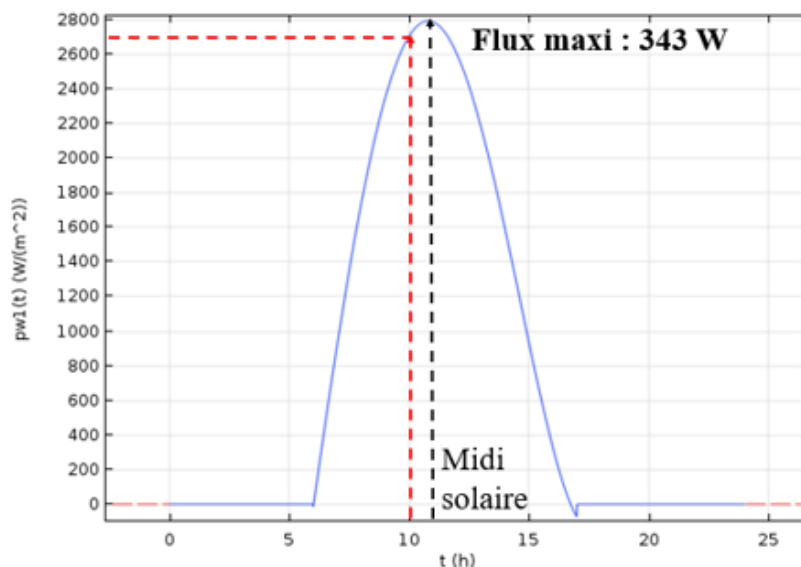


Fig. 12: Isotherms on March 21, 2021.

The isothermal curves for the solar gain show that the average energy absorbed by the receiver raises the average wall temperature to 186.85°C and the average internal temperature to 201.85°C over the duration of sunlight exposure (12 hours).

The energy absorbed by the receiver wall raises the temperature inside the receiver to above the melting point of PE.

The heat flow on the absorbing surfaces differs because they do not receive the same amount of sunlight at the same time. Figures 13a and 13b show the temporal evolution of the simulated flux densities on walls 1 and 2 respectively.



Maximum flux density received by wall 1 : $2,800 \text{ W/m}^2$

Fig. 13a: Temporal evolution of the simulated flux densities of wall 1

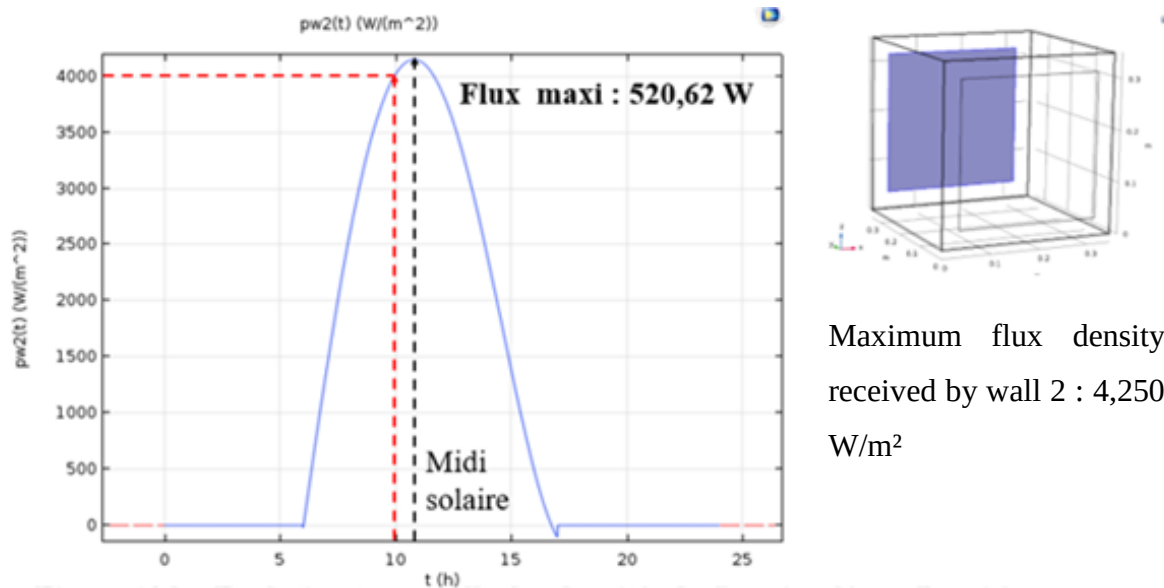


Fig. 13b: Temporal evolution of the simulated flux densities of wall 2

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

The expected flux at the receiver (E_p) for the experiment is calculated to be 2,249.95 W, compared with a maximum flux of 560.62 W given by the numerical heat equation, Eq. (1). The relative error of 0.75, which exceeds the scientific benchmark (0.05), is due to the fact that certain parameters were not taken into account in the simulation, such as the effects of radiation.

In terms of temperatures, we have 216.85°C, which is the average internal temperature of the simulation. The average internal temperature of the experiment was 206.4°C on 30 April 2021. When compared with the melting point of PE, which is 200°C, the following relative deviations can be observed:

- The average internal temperature in the simulation differs by 16.85°C from the melting point of PE (200°C) ;
- The average internal temperature during the experiment differed by 6.4°C from the melting point of PE (200°C) ;
- The average internal temperature in the simulation differs by 10.45°C from that in the experiment.

Based on his analyses, we can see that the experimental results show a higher efficiency of 96.89 per cent in the heat production required to melt 2 kg 200 g, compared with the simulation's efficiency of 92.22 per cent. The experimental results are more efficient than those of the simulation.

CONCLUSION

The results of the experiments and simulations are in agreement, with a discrepancy of 0.0522, thereby validating the oven-type receiver model and the Scheffler concentrator comprising an 8 m² reflector Scheffler directed to the north (RSDN) with an area of 8 m²

made of glass mirror and a reflector Scheffler directed to the south (RSDS) with an area of 8 m² made of aluminium mirror. Based on the results of the experiment, we generated the heat required to melt 2 kg 200 g of waste under an average solar irradiance of 473 W/m² and an average internal temperature of 206.4 °C. This temperature enabled us to produce two paving slabs without reinforcement. We can conclude that experimental work provides greater precision than simulation.

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