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Research Article
Temperature Distribution on a Plant Receiver Adapted from a Commercial Solar Plant in Ait Baha-Morocco

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Abstract
Background and Objective: The trapezoidal cavity absorber for linear fresnel reflectors has been frequently studied by researchers. In this study, the temperature distribution was determined using this same absorber to consider the solar conditions of Meknes city (Morocco) during two different chosen days from cold and hot seasons in the city at 12 pm, when the maximum direct normal irradiance (DNI) was reached. The plant considered was adapted from a commercial solar plant in Ait Baha, Morocco. **Materials and Methods:** Simulation tools were used to carry out this study, indeed, design and simulation of the linear fresnel system for the trapezoidal cavity absorber were done by Tonatiuh. Mathematica 9 program was generated for post processing binary files obtained from Tonatiuh and finally, temperature distribution was simulated in COMSOL Multiphysics 5.2a. **Results:** The proposed plant reached considerable and satisfying values, especially for the day when the DNI was high, thus a concentrated solar power (CSP) plant in Meknes city will be beneficial. It was found that temperature was low in January in comparison with that in July, but it could increase if considering the receiver during the entire duration of sunshine; Indeed, it could attain a high value of up to 650°C on 15 July at 12 pm and reach a low value of 180°C on 30 January, 2016 at the same fixed time. **Conclusion:** On the basis of this study, the proposed installation achieves considerable and satisfying values for a fixed time, so a CSP plant in Meknes city will be beneficial. For months when the DNI is minimal, an energy storage study or the use of waste heat from industry is needed to increase the heat at the output of the receiver.

Key words: Cavity receiver, linear fresnel reflector, ray tracing model, heat flux density, cavity receiver temperature

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Recently, the foreseeable exhaustion of fossil fuels and environmental concerns caused by their consumption encourage consumers to use renewable energy sources. Solar energy is currently used as a power source by the photovoltaic (PV) effect or thermal systems (solar thermal energy at low and high temperature (CSP)). Currently, sustainable development has become one of the major priorities in Morocco. Morocco is known to have abundant solar resources (a potential of 2 600 kWh m^{-2}/year) and great wind energy potential and to have a key strategic position[1]. In recent years, renewable energies have become the subject of diversified projects in Morocco. It is implicated in various social and economic programs and aims to reach 42% of the installed electrical power in 2020, compared with that of 26% currently[2]. That is why scientific studies and development projects are involved to support and strengthen the national strategy. The current study contribution is the study of temperature distribution on a trapezoidal cavity absorber for the linear fresnel reflector considering solar conditions of Meknes city (33°53'36" N, 5°32'50" W) (Morocco). The idea of this study is to benefit from solar conditions of Meknes-Morocco and orientate researchers to think about CSP plants in this city. In this study, an open source Monte Carlo ray tracing program was designed for the analysis and simulation of the optics and energy behavior of CSP systems called Tonatiuh. Once the solar concentrating system and the incoming direct solar radiation were modeled, the results were directly saved into several binary files for post processing using Mathematica[3] to obtain a heat flux density distribution (HFDD) in the receiver. The COMSOL Multiphysics 5.2a[4] was used as computational fluid dynamics (CFD) software to find the final temperature distribution on the absorber. This study was to examine, for a fixed time, the temperature for two different days from two different seasons in Meknes city.

MATERIALS AND METHODS

The current study determines the temperature distribution on a trapezoidal cavity absorber for the linear fresnel reflector. The configuration was a four parallel tubes' absorber, which encircled in its upper part by a secondary trapezoidal reflector, forming a cavity by a glass placed at its bottom. This cavity receiver for a linear fresnel solar collector had been frequently studied by previous researchers. Facao and Oliveira[5] analyzed its optical and thermal performance using simplified ray-tracing and computational fluid dynamics. Moghimi *et al.*[6] also studied it to find an optimal design for a set of operating conditions and Manikumar *et al.*[7] analytically simulated a set of linear multi tube absorber, with and without plate underneath, in a trapezoidal cavity absorber to find a better design to maximize the heat transfer rate supplied to the absorber tube fluid. The contribution of this study was the study of the temperature attained in the receiver by locating the installation proposed in Morocco (more specifically in Meknes city (33°53'36" N, 5°32'50" W)) that can be used as a heater for a heat engine. The simulation tools that are used for this study are Tonatiuh, Mathematica 9 and COMSOL Multiphysics 5.2a. Tonatiuh was an open source Monte Carlo ray tracing program designed for the analysis and simulation of the optics and energy behavior of CSP systems, Mathematica 9 was used as an external program to generate the heat flux maps and COMSOL Multiphysics 5.2a was used as a CFD software to obtain the final temperature distribution on the receiver.

Definition of trapezoidal cavity absorber: The present linear fresnel reflector system is shown in Fig. 1. It uses 12 rows of reflective mirrors, of width 600 mm each, on either side of the absorber and mirror spacing is 900 mm. The trapezoidal cavity, under vacuum, surrounds a parallel four-pipe, forming a cavity by a glass placed at the bottom. The dimensions of the cavity absorber, which were chosen according to the objective and parameter ranges table provided by Moghimi *et al.*[6] is shown in Fig. 2.

Design and simulation of the linear Fresnel system for the trapezoidal cavity absorber: A ray trace model, as shown in Fig. 3, was created using Tonatiuh software tool. Tonatiuh is a software that gives a model of the concentrating system, the entering solar radiation, the interactions between the radiation and the elements of the system and a flexibility in establishing the results that the program produces[8].

By choosing Tonatiuh, the designed system was able to visualize before running the program and the ray tracing was simulated later. The flux maps were generated by using an external program, contrary to Soltrace, where the visualization, the ray tracing and the flux maps were obtained after running the program, which produced difficulty to progress. In addition, preliminary validation of Tonatiuh and SolTrace revealed identical results between the two programs but Tonatiuh provided free access to the source code for anyone interested in using or contributing to its development[9]. In this ray tracing procedure, the sun position was defined considering Meknes city's hottest period from late June-August and its coldest one from December-March[10].

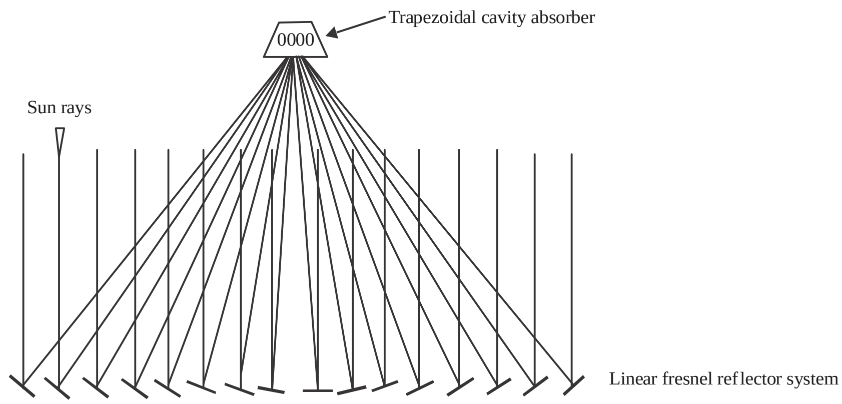

Fig. 1: Solar concentration on a trapezoidal cavity absorber for the linear fresnel reflector system

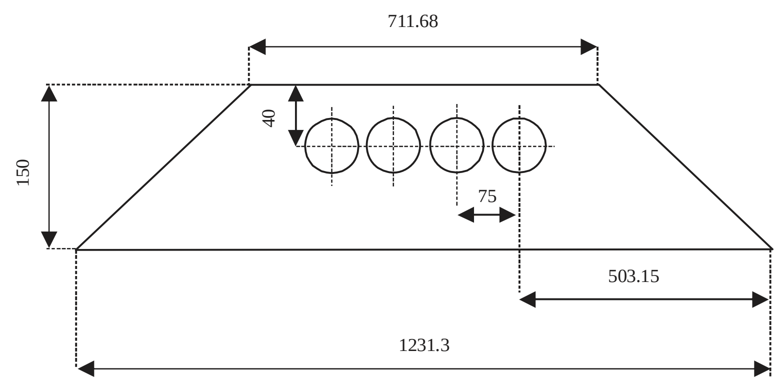

Fig. 2: Geometry of the fresnel receiver cavity

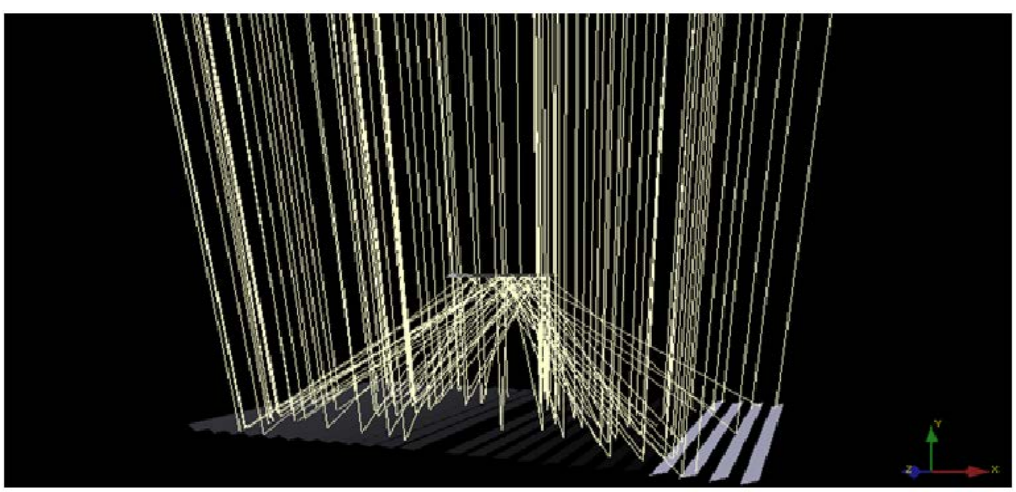

Fig. 3: Ray tracing for the linear fresnel solar field in Tonatiuh. Isometric view of the entire optical domain (number of rays = 200)

Using the sun position calculator integrated in Tonatiuh, the sun position was calculated on 15 July, 2015 and 30 January, 2016 at 12 pm (G.M.T) when the maximum DNI was reached[11-13]. Delgado *et al.*[14] indicated that accuracy of simulation software was affected by static sun shape instead of a dynamic one, this choice can lead to an underestimation of the intercepted energy at approximately 5% for both external cylindrical and cavity receivers. In

Tonatiuh, the sun shape was considered to be constant. In this study, the pillbox sun shape was chosen. Tonatiuh software requires DNI at a fixed time; thus, hourly DNI was considered using data provided by the solar radiation data (SoDa Services)[15]. Simulations were established with 5000000 sun rays. Once the solar concentrating system and the incoming direct solar radiation were modeled, the results were directly saved into several binary files for post processing.

Estimate of solar flux distribution at the receiver using Mathematica 9: Tonatiuh's binary data files were processed with Mathematica. It is a software package that has been ideal for use in a wide range of fields, such as engineering, mathematics and physics. It makes possible the communication of scientific ideas, whether with the visualization of a concept or the creation of a simulated a new idea. It is a powerful computing environment[4].

The Mathematica program was generated in collaboration with Mr Amaia Mutuberria Larrayoz, Innovation Service and Technological Development, Solar Thermal Energy Department, at National Renewable Energy Centre (CENER). The program contains 3 parts:

- **Receiver definition:** Where dimensions of the receiver and number of cells in which it was divided, were defined
- **Read simulation data:** In this part, the program was directed to the location of all the binary files obtained from Tonatiuh and read them
- **Obtain the HFDD in the receiver:** In this part, a set of functions is used for the determination of the HFDD in four pipes. The formula used to calculate the heat flux density (HFD) is as follows:

$$\text{HFD} = \frac{\text{Total number of photons at the tube} \times \text{power/photon}}{\text{The elementary area of the tube}}$$

3D simulation of the receiver using COMSOL Multiphysics 5.2a: The COMSOL Multiphysics 5.2a was used to find the distribution of the temperature in the four absorber tubes. It's a powerful numerical simulation software based on finite element method that can be applied to a large range of physics and engineering problems[5]. In this case, 3D numerical simulation was built using the heat transfer in solids interface which is used to model heat transfer by conduction, convection and radiation. The laminar flow and temporal study were chosen.

To correctly model the thermal transfers in absorbers, a precise understanding of its mechanism is essential. In Fig. 4, the installation of the located receiver was adapted from a commercial solar plant in Ait Baha, Morocco (30°13' 1" N, 9°8' 6" W)[16,17]. Thereby, the fluid flowing inside the pipes would absorb the solar energy irradiated by fresnel mirrors and the temperature of the fluid increased. Forced convection occurred because of fans which circulated the process air, at a speed of 0.01 m sec^{-1}. The trapezoidal cavity containing the four absorbers was under vacuum to create an insulation effect. The heat flux densities found previously were used in the boundary of each pipe by utilizing the equation that governed them. The initial values of temperature are chosen based on the hour and the day[10]. In this case study, air was chosen as heat transfer fluid which is costless, environmentally friendly, without a working temperature limit and easy to handle. By choosing cobalt alloy as a material of the absorber, we were able to benefit from its resistance to high temperatures[18,19]. Haynes 6B was selected because of its

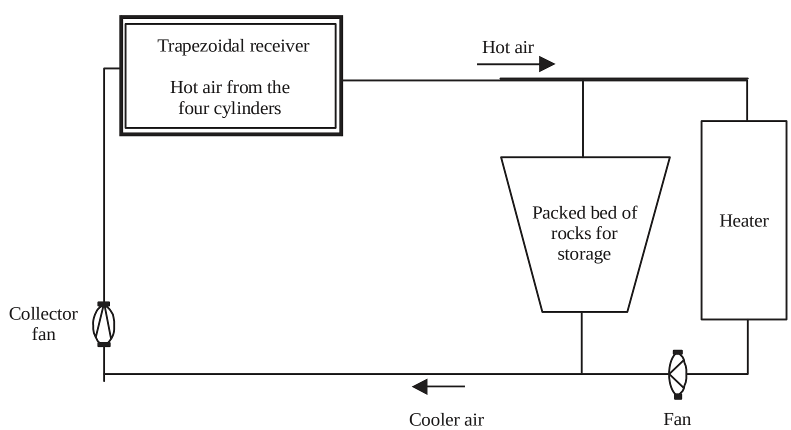

Fig. 4: Entire plant of the trapezoidal cavity absorber for the linear fresnel reflector concentration system, based on the solar plant in Ait Baha

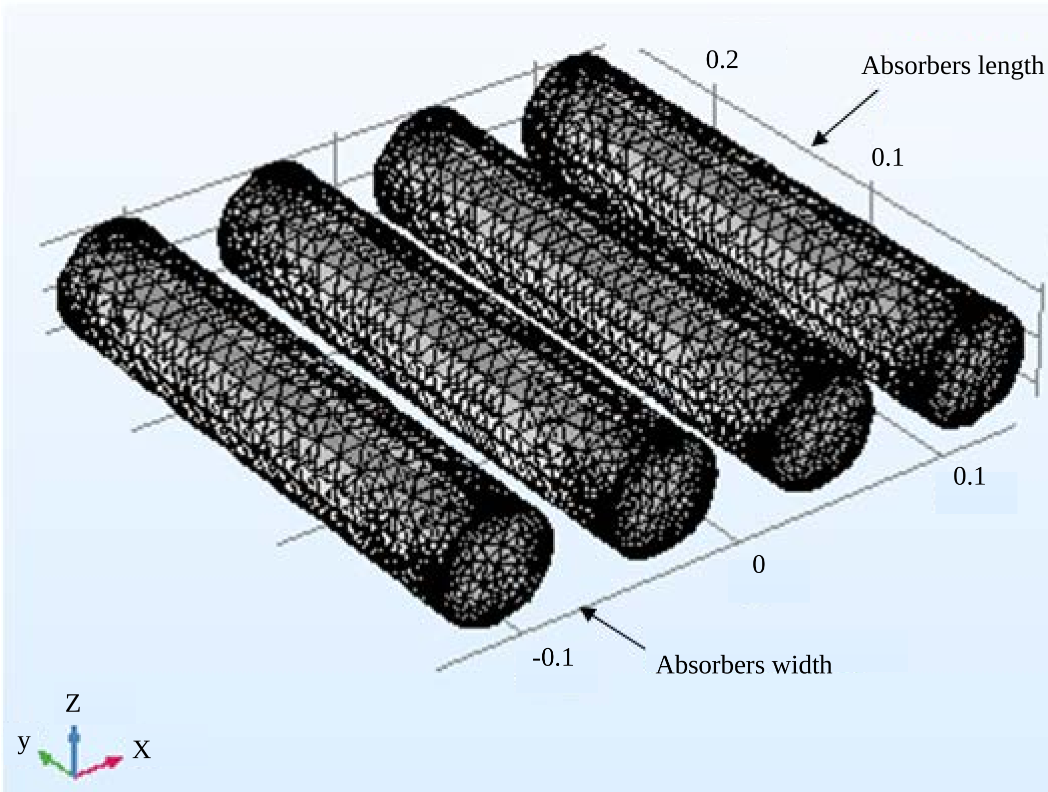

Fig. 5: Four absorber entire mesh

successful use in applications relating to difficult attrition conditions and attrition coupled to corrosion and/or high temperature[20,21]. To give a higher freedom for mesh generation during the process, a mesh with coarsest size in parameters controlled by physics was selected (Fig. 5). Future study will couple the plant in Fig. 4 with a heat engine and study it for the whole sunshine duration.

RESULTS AND DISCUSSION

In this section, the obtained results are shown. The results concern a trapezoidal cavity receiver used for CSP system installed in Meknes (Morocco). As mentioned before, previous studies had led off the study of this CSP system. Facao and Oliveira[5] used simplified ray-tracing and computational fluid dynamics to analyze the optical and thermal performance of a new trapezoidal cavity for a small linear fresnel receiver[7]; Manikumar *et al.*[7] simulated natural convection below the absorber and radiation between the surfaces using MATLAB program[9] and Moghimi *et al.*[6] used the ray-tracing code, sol-trace, to calculate the solar heat flux pattern on the pipes. The results were mapped as a volumetric heat source on the pipes in ANSYS Fluent[6]. In this study, the HFDD was first determined using Tonatiuh software, the Tonatiuh's results binary data files were then post-processed using Mathematica and the temperature distribution was finally obtained using COMSOL Multiphysics 5.2a.

The HFDD values at the four pipes on 15 July, 2015 and 30 January, 2016 at 12 pm using radar plots are shown I n Fig. 6 and 7, respectively. The perimeter was divided into 100 divisions.

It can be seen from the two figures that the HFDD is not uniform and does not show symmetry between the two cylinders on the left and those on the right. This result is due to the sun position calculated directly on Tonatiuh: The graphical interface of Tonatiuh showed that the sun in the chosen days and time was not perpendicularly above the plant. In addition, as it can be seen from Fig. 6, HFD can attain high values up to 20000 W m^{-2}. HFD can reach lower values from 5000-6000 W m^{-2}, as shown in Fig. 7. The results didn't reflect HFDD generated during the day when the plant was exposed to high DNI. In that case, the flux density distribution obtained during the entire day will be higher than that for a fixed time.

Temperature distributions obtained in two cases of this study are represented in Fig. 8 and 9. According to Fig. 8 and 9, temperature of the air on 15 July, 2015 at

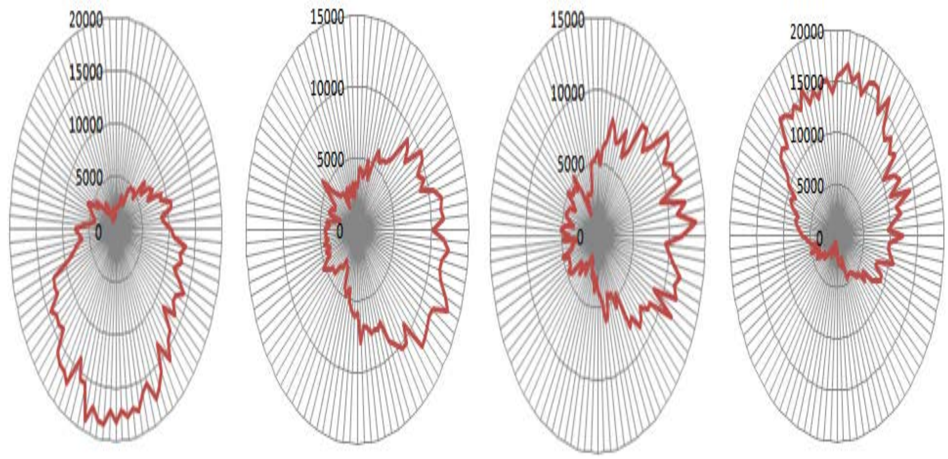

Fig. 6: Heat flux density distribution as calculated by Mathematica using results obtained from Tonatiuh at the four pipes on 15 July, 2015, in W m^{-2}

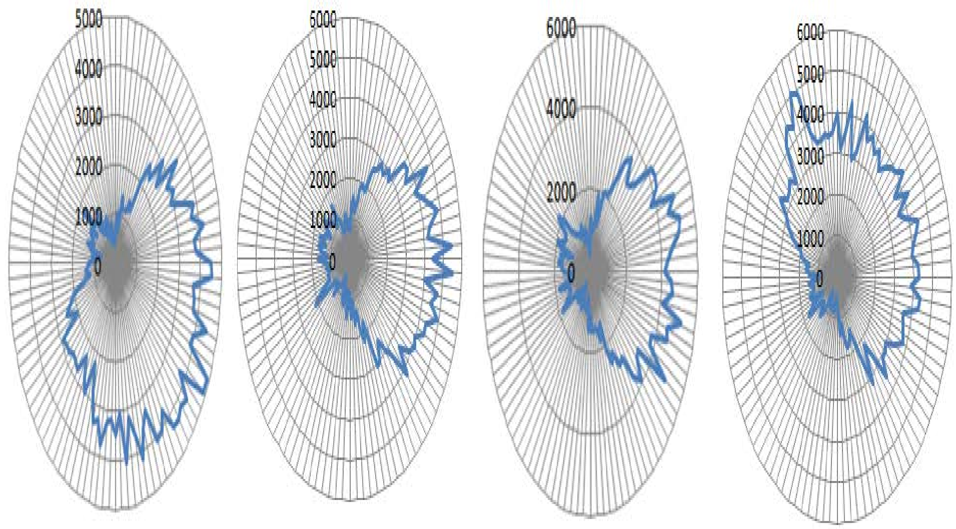

Fig. 7: Heat flux density distribution as calculated by Mathematica using results obtained from Tonatiuh at the four pipes on 30 January, 2016, in W m^{-2}

Table 1: Daily DNI (W m^{-2}/day), in Meknes city, for both months, January and July, provided by National Renewable Energy Laboratory using its moderate resolution[23]

Month	Daily DNI (W m^{-2}/day)
January	3889
July	5855

12 pm was remarkably high in comparison with that on 30 January, 2016 in the same fixed time. Indeed, the temperature could attain a high value of up to 650°C on 15 July at 12 pm and it could reach a low value of 180°C on 30 January, 2016 at the same fixed time. Similar temperature ranges were reported in pervious studies[6,22]. Moghimi *et al.*[6] found a temperature going from 166.85-226.85°C around absorbers in there optimization study. Qiu *et al.*[22] also found a temperature reaching up to 446.85°C. However, solar conditions in these previous studies were not similar to those of the current case study and the materials used were not the same.

It is evident that temperature generated during the day will be higher because of the DNI recorded along the sunshine duration as shown in Table 1. On the basis of this study, the proposed plant reaches considerable and satisfying values for a fixed time, so a CSP plant in Meknes city will be beneficial. For months when the DNI was minimal, an energy storage study or the use of waste heat from industry were needed to increase the heat at the output of the receiver.

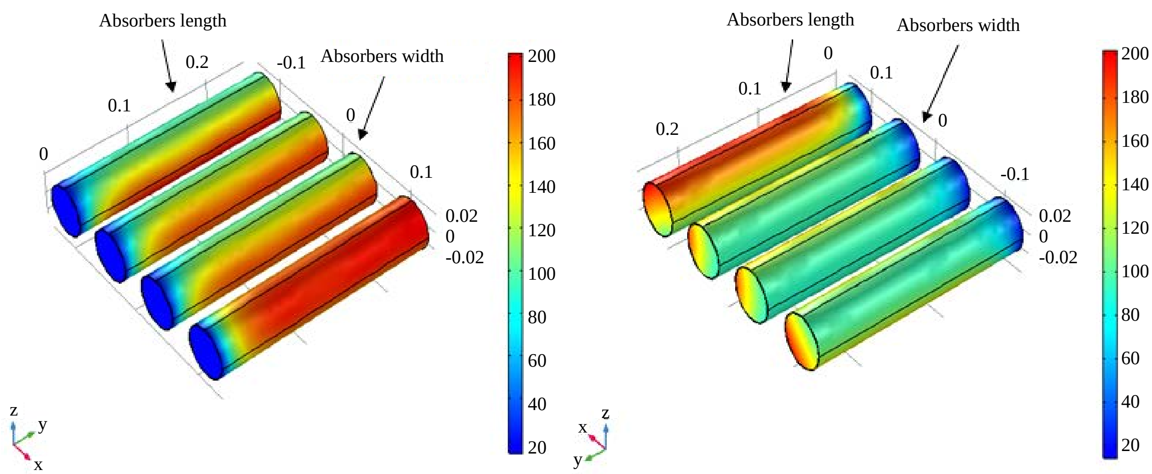

Fig. 8: Temperature distribution at the four pipes as visualized by COMSOL Multiphysics 5.2a, on 15 July, 2015, in celsius for 180 sec, (a) Inlet side and (b) Outlet side

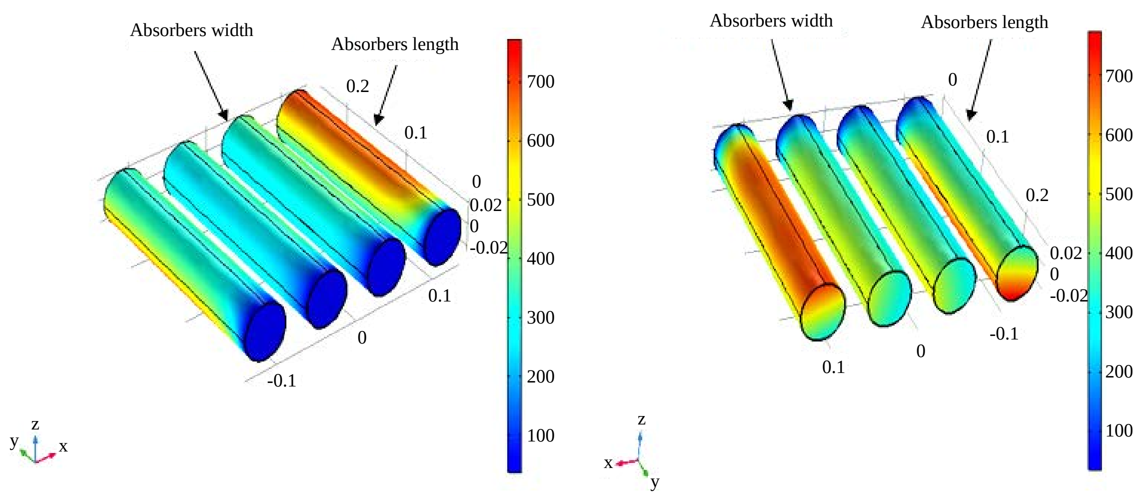

Fig. 9: Temperature distribution at the four pipes as visualized by COMSOL Multiphysics 5.2a, on 30 January, 2016, in celsius for 180 sec, (a) Inlet side and (b) Outlet side

As mentioned earlier, the temperature obtained from the plant will be used as a heater of a heat engine. That is to say, depending on the desired performance of the engine, we will react, inter alia, to the temperature difference between the cooler and the heater by increasing heater temperature.

CONCLUSION AND FUTURE RECOMMENDATIONS

The current study examined values obtained by temperature on two different days are chosen from hot and cold seasons. Indeed, the compared temperature attained on 15 July, 2015 and 30 January, 2016 at 12 pm, when DNI reaches its maximum value. The following conclusions can be drawn from this study:

- For Meknes city, the temperature in four absorbers surrounded by a trapezoidal cavity under vacuum can reach 180°C on 30 January, 2016 at 12 pm and on 15 July, 2015, the temperature attained was approximately 650°C. Temperature generated during the day will be higher because of the DNI was recorded in the sunshine duration
- The proposed plant reaches considerable and satisfying values, especially for months where the DNI is high, for a fixed time, so a CSP plant in Meknes city will be beneficial
- For months when the DNI is minimal, an energy storage study or the use of waste heat from industry were needed to increase the heat at the output of the receiver

Based on the results of this basic case study, our future study will focus on the study of coupling the proposed plant with a heat engine. Existing studies regarding this coupling are insufficient or do not adequately address this issue. The aim of the future study is to analyze the different parameters governing this coupling in order to achieve its optimization.

SIGNIFICANCE STATEMENTS

This study discovers that temperature in a trapezoidal receiver, considering solar conditions of Meknes-Morocco. That can be beneficial in consideration of a concentrated solar power (CSP) plant in this city. This study will help researchers to have an overview on the temperature reached in given CSP plant in Meknes. Thus, on the basis of this study, researchers can be directed towards the study and the implementation of CSP plant in Meknes-Morocco.

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