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Defocus Controller for a Rotatory Fresnel Collector

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Abstract. Solar heat for industrial processes (SHIP) is becoming one of the most attractive solutions for industry decarbonisation. Solar plants require a complex control system to manage the fluctuation of their source, solar radiation. One of the problems of this system is the possibility of overheating when solar production is greater than consumption. The main objective of this study was to design a defocus controller for the SunDial, the rotatory Fresnel collector. A dynamic simulation was carried out for a SHIP system with the defocus controller. Finally, a solution to satisfy the accuracy needed for the SunDial was presented.

Keywords: SHIP, Dynamic Simulation, Defocus Controller

1. Introduction

The industry sector consumes 37% of the total energy in the world and 80% is delivered by fossil fuels which are responsible for greenhouse gas emissions [1]. Solar thermal energy is a sustainable and manageable solution for the industry due to it converts solar irradiation to heat and has the possibility to include thermal energy storage that provides reliability to the system when there is no solar irradiation. Commercial solar collectors can supply heat at medium-high temperatures, such as the parabolic trough collector (PTC) and the linear Fresnel (LF). Concentrators use the direct component of solar radiation, so a tracking system to follow the Sun's trajectory is required.

The heat consumed by each industry varies in capacity, temperature, and periodicity. Therefore, each factory needs a customized solar system. ASTEP (Application of Solar Thermal Energy to Process) is an H2020 project which seeks the reduction of the cost of solar heat. This is done by means of a modular system composed of a rotatory Fresnel collector, the so-called SunDial, and a phase-change material thermal storage. The SunDial is a Fresnel collector mount above a rotatory platform that follows the sun azimuthally (Fig. 1).

Figure 1. SunDial prototype sketch for Greece.

One of the problems of solar thermal plants is that they require a complex system to control the variable source of solar radiation. The system can overheat if thermal energy storage (TES) is full and solar radiation is high. Therefore, the maximum allowed temperature of the heat transfer fluid (HTF) of the system could be exceeded. This would produce degradation of the fluid that would have to be replaced, leading to economic losses. To avoid this, the tracker system has a control that partially defocuses the SunDial mirrors to reduce the heat generation and maintain the maximum temperature of the system to a safe value.

Solar tracking systems can be categorized by different characteristics such as: control strategy, degrees of free motion, drives, or tracking strategy (Fig. 2). The solar industry has a long history of solar tracking systems. Solar concentrators such as PTC and LF used a single axis. The drives most used are the actives, such as slew drives. The closed-loop strategy is more precise than the open loop but requires a sensor to monitor the radiation. For the tracking strategy, there are two options: the photodiodes or the solar algorithms that calculate the position of the sun.

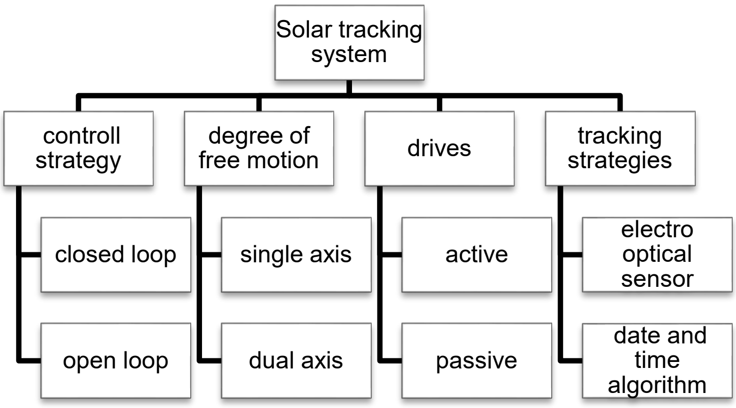

Figure 2. Types of solar tracking technologies.

The main objective of this paper is to design a defocus controller for the SunDial so that we can select an appropriate tracker system. First, we will describe the ASTEP system. Then, we will present a description of a dynamic simulation performed to test the defocus controller. Finally, in the results and discussion section, we evaluated the performance of the controller, and we estimate the acceptance error of the tracking system.

2. Description of the ASTEP system

The defocus controller will prevent the degradation of the components of the ASTEP system, specialty the HTF. To have a better understanding of the controller we are going to give a brief description of ASTEP system which is represented in Fig. 3. The ASTEP principal components the SunDial, the TES, and the heat exchangers (HX1 & HX2) are connected in series in a closed loop. An expansion tank is used to equalize the pressure and absorb pressure variations due to thermal expansion. Four pumps are used to control the SunDial flow to a fixed value (SP), the TES flow to a fixed value (MP), the inlet temperature of HX1 (RP), and the inlet temperature of HX2 (CRP). In addition, two control valves are needed to regulate: the inlet flow to HX1 (BPV) and the inlet flow to HX2 (CCV). Finally, two on/off valves are installed to isolate the SunDial and HX1. The first HX1 was used to feed a boiler and the HX2 to the chiller. We need a higher solar energy production to analyse the defocus controller than demand, so it is assumed that the TES is full. Due to end-user constraints, this could happen on the weekend because only one HX will operate.

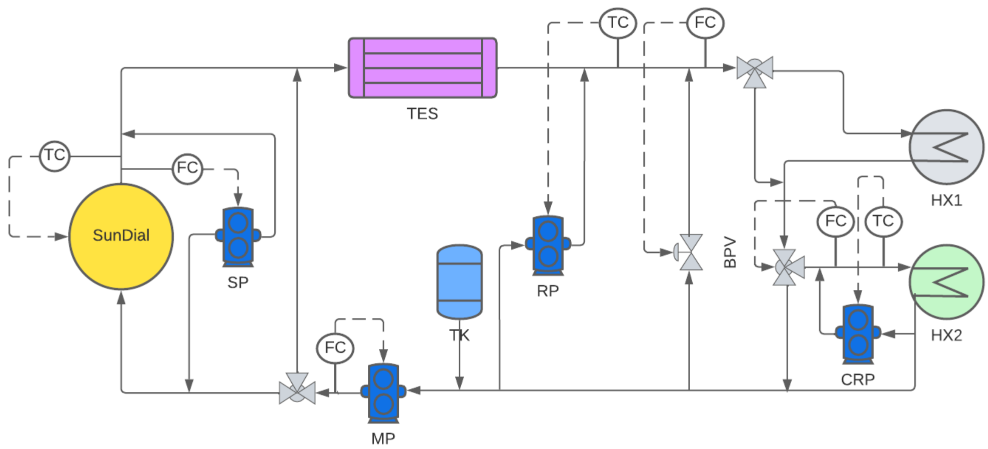

Figure 3. Process diagram for ASTEP system.

The dynamic simulation was performed in Dymola software, which used the Modelica language [2]. We selected this software due to its flexibility to create new components and its standard library, which includes all the elements of a typical hydraulic system. Fig. 4 shows the diagram for the ASTEP Dymola model. For the SunDial and the TES, we have developed tailored sub-models. The SunDial was previously explained in a previous publication [3]. The TES model was approximated by equations obtained from the results of computational fluid dynamic simulations. The rest of the system components, such as pipelines, pumps, valves, instruments, and controllers, were taken from the Modelica Standard library. The heat transfer fluid, Therminol 59, property data from the vendor was used to estimate polynomial equations in dependence on the temperature. PI controllers were designed with the Ziegler–Nichols method [4] separately by feeding the system with a step variation of the manipulated variable.

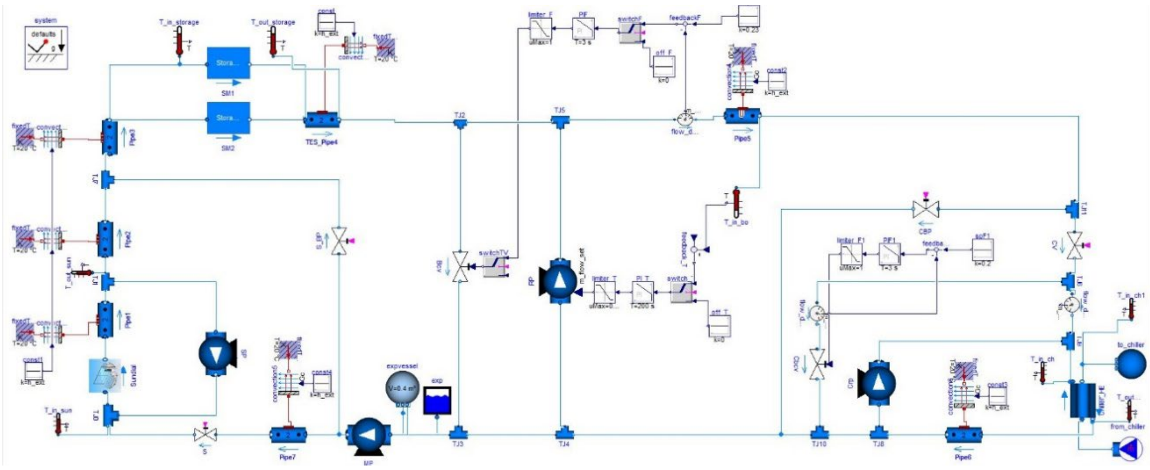

Figure 4. Dymola flow diagram for the ASTEP model.

3. Description of the Defocus control

Fig. 5 shows a box diagram of the defocus controller diagram. The objective of this controller is to limit the outlet temperature of the SunDial below the maximum admitted preventing degradation of the HTF. For Therminol 59 [5] this temperature is 300 ° C, but we had set the limit at 240 ºC. The SunDial outlet temperature is subtracted from the setpoint to calculate the error between both, and this error was fed to the PI controller, which corrects the error and sends a signal to the defocus matrix. Before entering the defocus matrix, a tracking error is added to the signal. This defocus matrix contains information about the reduction of the impinging power generated by a movement in the azimuthal direction of the platform. Fig. 6 shows the information of the matrix, which was previously calculated using ray-tracing [6]. This matrix is an input in the defocus controller. The impinging power, as Fig. 6 shows, depends on the defocus angle and the zenith solar angle. So, for a higher zenith angle, a larger defocus angle will be needed. Finally, the percentage of power reduced by the defocus is an input of the SunDial model. In the prototype, the controller will send a signal to a variable-frequency drive that will activate a motor coupled with a reducer. This will move the wheels of the platform to defocus the mirrors.

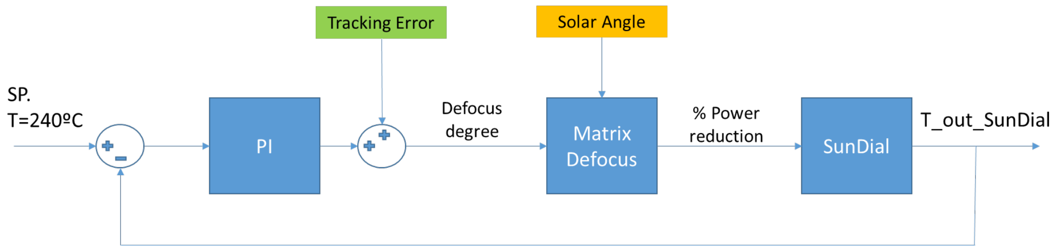

Figure 5. Box diagram for the defocus controller.

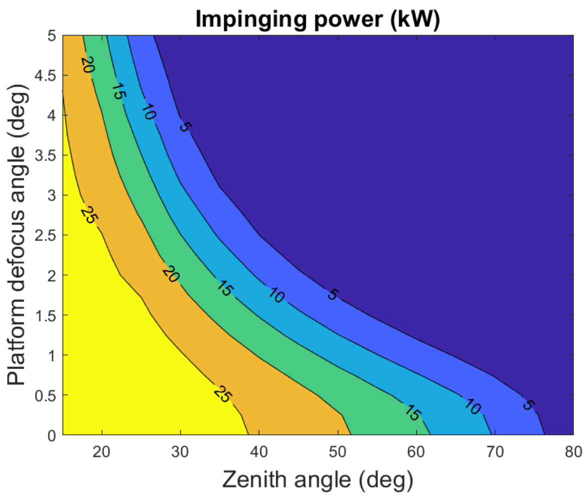

Figure 6. Defocus degree, zenith angle, and impinging power.

Fig. 7 shows the Dymola model for the defocus controller. The controller has an on/off switch and would only be activated when the outlet temperature is higher than 242 ºC and will be deactivated when it decreases below 238 ºC. The outlet of the PI controller is limited between the ranges of 0-10º. The platform movement error, which was modeled with a normal noise, is summed to the outlet of the PI. This error was simulated as a normal standard deviation with the values: 0.1°, 0.2º, and 0.5º. Defocus matrix data and the typical meteorological year (TMY) are introduced as tables. The TMY is from Corinth, Greece, where the dairy factory is located.

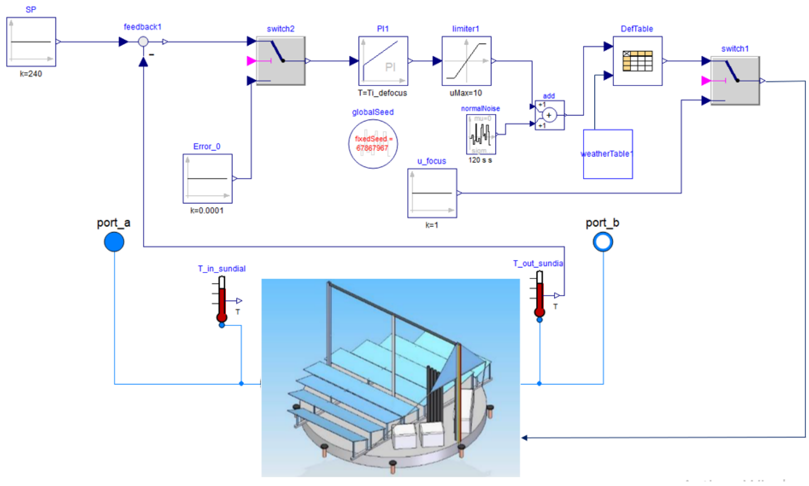

Figure 7. Dymola model for the defocus controller.

4. Results and Discussions

In this section, we will present the results obtained for the three simulations with different tracking errors. Fig. 8 shows temperature results for the simulation with a 0.5º error. The TES salts and the HTF fluid start at a temperature of 190 ºC. Then, the SunDial outlet temperature (green) increases until the temperature reaches 242 ºC when the defocus controller is activated. We can see that the controller maintains the temperature at 240 ºC by moving the platform from the focus position, which is the solar azimuth for that day and time. Fig. 9 shows the movement of the platform done by the PI signal, which represents the defocus angle from the azimuthal position of the Sun. In Fig. 8 we can see that the average temperature of the TES salts (red) and the HTF at the TES outlet reaches 240 ºC half an hour later when the storage is full. Also, we notice that the oscillations present in the SunDial temperature are damped in the TES, due to a series connection between them. The inlet temperature to the demand (magenta) is controlled at 190 ºC.

In Fig. 9 we can see that the maximum defocus angle achieved is 1.5º and this implies a power reduction of 90%. This power reduction is shown in Fig 10. We can see that the defocus controller started working at 15:20 when the impinging power (magenta) decreased abruptly. The oscillations generated by the defocus controller in the SunDial power have no effect on the power supply, which remained constant because the TES functions as a buffer.

As we have previously commented, if the zenith angle is high, the defocused angle needed is small (Fig. 6). If we compared the defocus efficacy with a PTC collector, we noticed that the SunDial is more sensible than a PTC. Fig. 11 shows the typical curve for a PTC collector where for a 10% efficiency a 4º defocus is required, while, with the SunDial, a 1.5º is required.

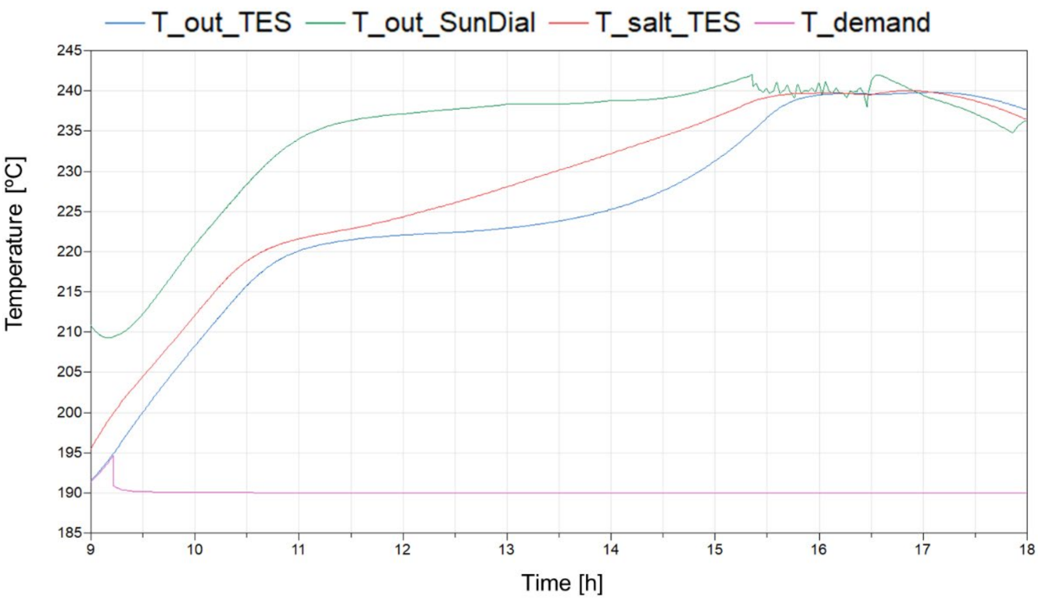

Figure 8. Temperature results for the simulation with an error of 0.5.

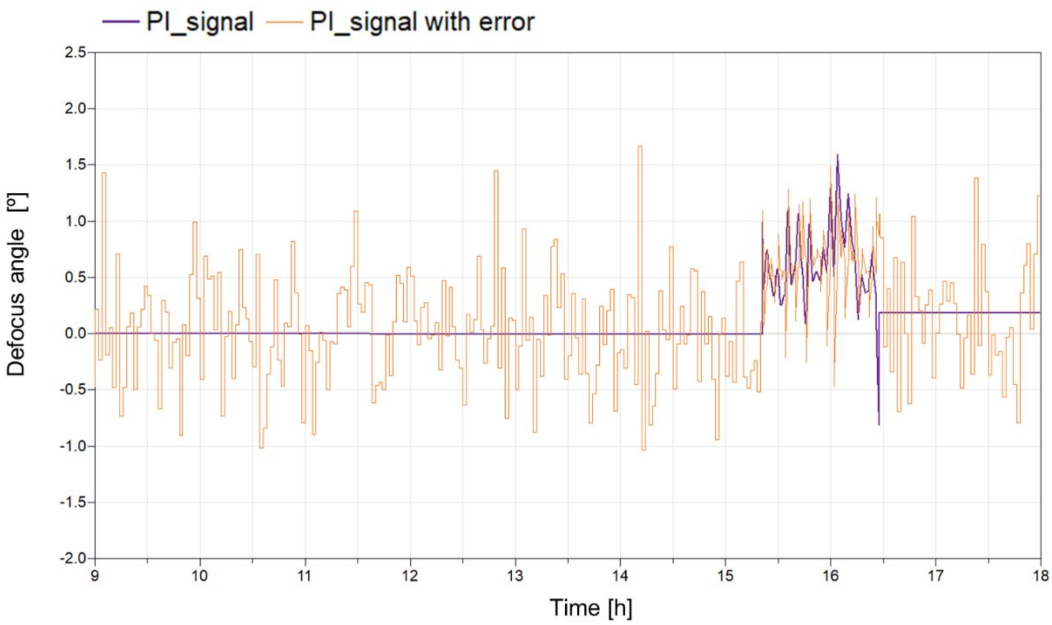

Figure 9. Controller signal in degrees of defocus for the simulation with an 0.5 error.

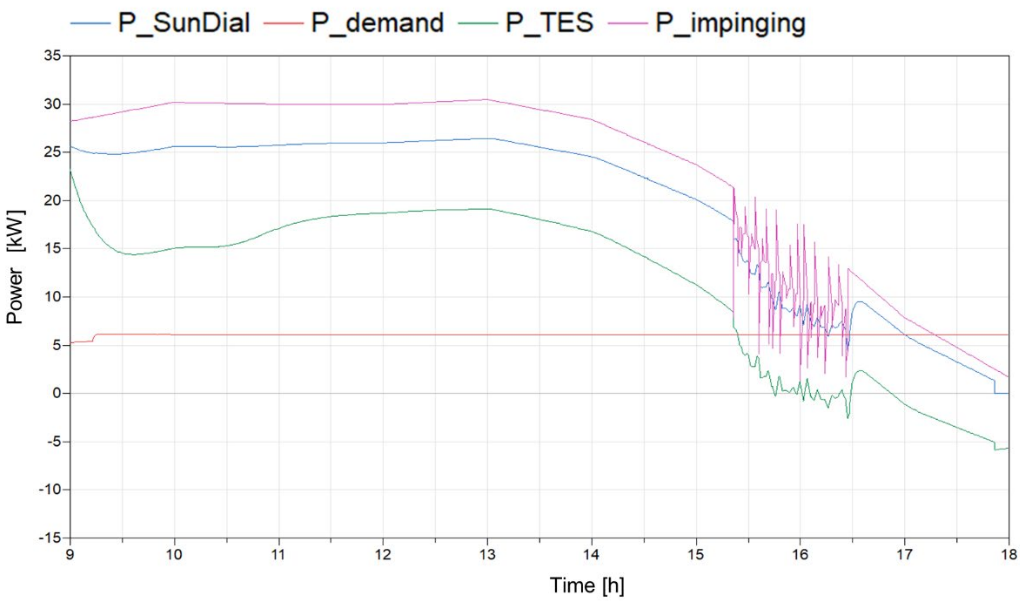

Figure 10. Power results for the simulation with an error of 0.5.

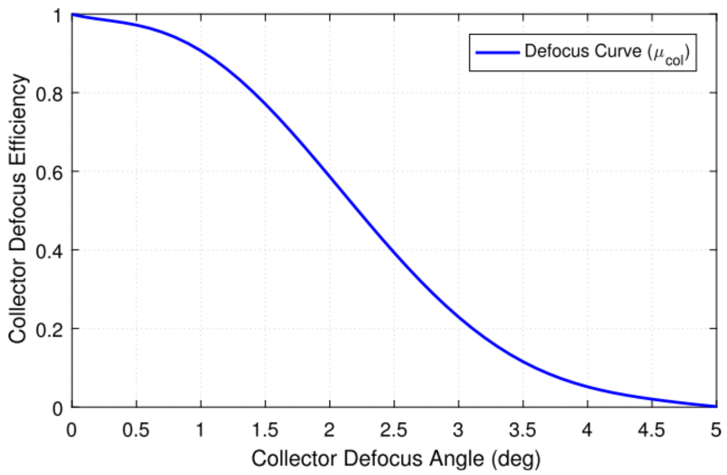

Figure 11. Collector defocus angle vs defocus efficiency for a PTC [7].

Fig. 12 shows the outlet temperature of the SunDial for different tracking errors. The controller with a tracking error of 0.1 and 0.2 managed to maintain the temperature near the set point of 240 ºC. On the contrary, the controller with the tracking error of 0.5 presents oscillations, and at 16:20 the controller stops working because the temperature is below the lower limit of 238 °C. Fig. 13 shows the defocus angle; where we can see that for the simulation with a 0.5 error, the platform moves back and forth constantly, and the defocus angle is twice the value of the previous simulations.

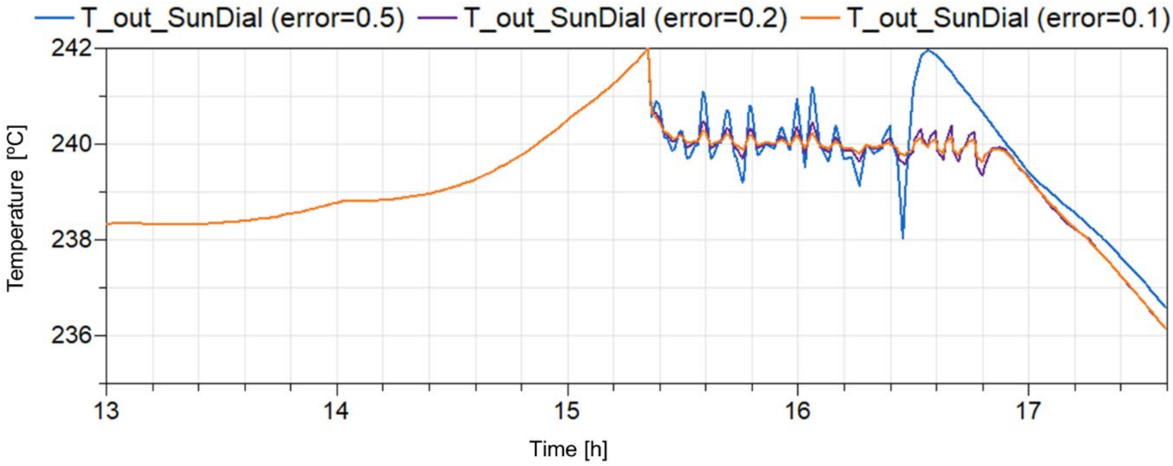

Figure 12. SunDial outlet temperature for different tracking errors.

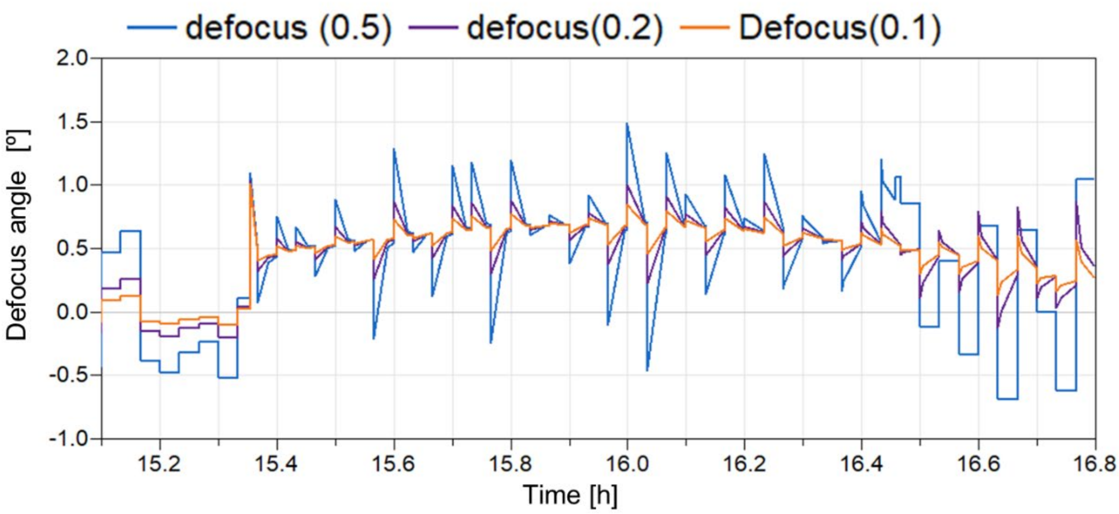

Figure 13. Defocus angle for different tracking errors.

We can conclude that the SunDial tracking system needs a more sensitive controller than the one used in the vast commercial concentrators because the SunDial requires a smaller movement in degrees to defocus the same amount of imping power that a PTC. This implies that the tracking system will need a resolution of at least 0.2º of the azimuthal position of the Sun. However, as the rotation movement is done from a wheel of 0.2 m located at a diameter of 8,1 m from the center, the resolution of the motor is equivalent to 8º. Another finding is that the oscillations in the SunDial outlet temperature were damped by the TES, which is connected in series. So, the heat supply to the process is kept constant throughout all the simulations including when the defocus controller is working.

5. Conclusions

We designed a defocus controller to limit the outlet temperature of the SunDial, the rotatory Fresnel collector, below the maximum admitted by the HTF to prevent fluid degradation. We tested the control in a dynamic simulation for the ASTEP (Applications of Solar Thermal Energy to Process) system. And we have found that a tracking system with a minimum accuracy of 0.2º in the platform position was required. Fortunately, there are tracking systems that can achieve an accuracy of 0.2º, such as the one proposed by Sidenk et al. [8]. This system is composed of a microcontroller that calculates the sun's trajectory through an algorithm, a GPS and a digital compass sensor that are used to determine the tracker's position, and an encoder and PID controller to increase the position accuracy.

Another finding reveals that the connection of the TES in series with the collector can dampen the oscillations of SunDial outlet temperature. Without a TES, a more complex control for the inlet temperature of the demand will be necessary.

One limitation of this study was not considering the assembly in the dynamic model: frequency driver, reducer, and motor. But those errors are clustered in the tracking error, which was modelled as normal standard deviation noise. The next step in this research will be to test the controller designed in a test ring of the SunDial prototype that is under construction in Madrid. The final application of the ASTEP project will be to install the system in a real dairy factory in Greece and a steel tube manufacturer in Romania.

Author contributions

Magdalena Barnetche: Conceptualization, Methodology, Software, Writing-Original Draft, Visualization. **Luis F. González-Portillo**: Conceptualization, Writing-Review and Editing. **Rubén Abbas**: Conceptualization, Writing-Review and Editing, Supervision. **Mercedes Ibarra**: Writing-Review and Editing. **Rubén Barbero:** Writing-Review and Editing**. Antonio Rovira**: Writing-Review and Editing.

Competing interests

The authors declare no competing interests.

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