Dynamic Analysis of the SunDial, the Rotatory Fresnel Collector

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Abstract. The SunDial is a new rotatory Fresnel designed for solar heat industrial process (SHIP) applications. This study aims to carry out a dynamic analysis of the SunDial against different transients such as start-up, defocus, and cloud passage. We used Dymola software to simulate the SunDial connected to a heat exchanger, which represents industrial heat demand, in a closed-loop with several controllers. The system could maintain the demand inlet temperature at a constant value, operating the SunDial at a constant flow despite the variability of the solar resource. The defocus control could manage to limit the temperature to the maximum admitted, preventing overheating.

INTRODUCTION

Concentrating solar power could substitute fossil fuels to produce heat. However, unlike fossil fuels, solar energy is an intermittent source. To analyze the effect of these variabilities on the solar system, researchers used dynamic simulations: for example, Rodin et al. [1] used Dymola to simulate a Fresnel collector system with a thermal oil. They analyzed the ability of the system to maintain the outlet temperature constant by varying the collector flow against different transients. They concluded that the thermal inertia of the thermal oil system could address short-term variations in the resource.

This study focused on the dynamic performance of the SunDial, a rotatory Fresnel collector that is part of the European Project ASTEP (Application of Solar Thermal Energy to Processes), a new concept of Solar Heat for Industrial Processes (SHIP). The SunDial is built on an 8-meter-diameter platform with an azimuthal sun tracking system. It has a two-tube receiver connected in series, uses oil as a heat transfer fluid, and has 8 mirrors with a 20-25 m2 aperture area [2].

The main objective of this study was to develop a dynamic model of the SunDial receiver and test its operation connected to a heat demand in a closed system. We designed a control system to guarantee a supply of constant temperature and flow operating the SunDial at a constant flow. We analyzed the response of this system to different dynamic situations such as start-up, defocus, and cloud passage.

SUNDIAL DYNAMIC MODEL

Previous studies of dynamic solar thermal systems used Dymola software [3], the results of these studies are open source libraries: ThermoPower [4], ThermoSysPro [5] or ThermoCycle [6]. Dymola is based on Modelica language, an object-oriented and equation-based language. This software uses the Modelica library that contains basic elements: pipes, pumps, valves, among others. These elements can be connected to a more complex generated system. We chose

Modelica language because of its flexibility to build new elements, but the main reason to use Dymola instead of OMEdit (the open source software of OpenModelica) was because Dymola had a powerful solver for non-lineal and large systems of equations [7].

The SunDial model was divided into two main parts: receiver and mirrors. The receiver model was built on Dymola using the Modelica library. The mirrors model was done externally using ray tracing and was not part of this study [8], so the incident power on the receiver and meteorological data were input to the dynamic simulation.

The receiver was built with two evacuated tubes connected in series of 8 m of length and 70 mm of diameter. The absorber tube was simulated by means of a discretized Modelica dynamic pipe divided into 33 nodes. All nodes were identical in length of 0.25 m except for the two ends of each tube of 0.125 m. Figure 1 is a simplified representation of 6 nodes of the Dymola model. The heat transference fluid was Therminol 55 [9], which was inserted into the model as a Modelica partial medium. We used polynomial equations for each property obtained from the provider's experimental data [9].

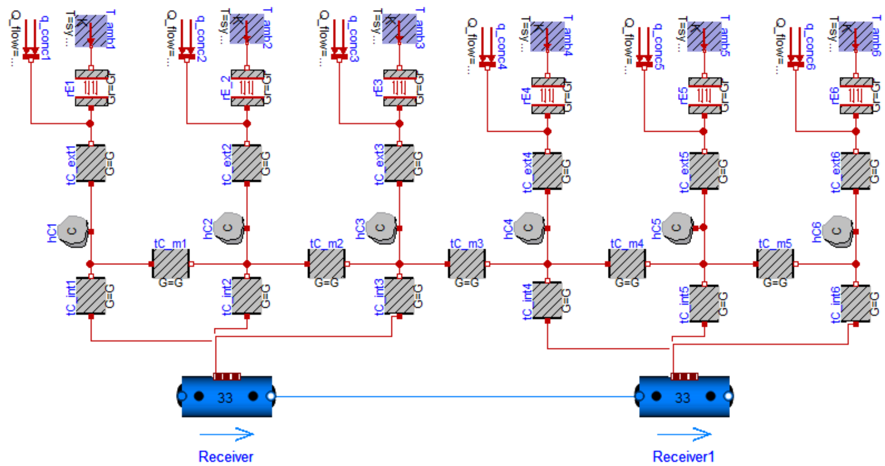

FIGURE 1. SunDial Dymola representation for 3 nodes for each receiver (the real model had 33 nodes).

The heat transfer coefficient (h_i) for the convection between the fluid and the absorber was calculated with the Nusselt correlation (Nu) for turbulent flow in a flat plate with Eq. 1[10]:

$$Nu = 0.0371 Re^{0.8} Pr^{0.33} \quad (1)$$

Where Re is the Reynolds number; Pr is the Prandtl number; the mass flow through the receiver is equal to 2.5 kg/s, and the internal diameter (D_i) of the receiver is equal to 0.066 m.

The conduction through the absorber tube was modeled with a Modelica thermal conductor. We consider three different parts of the tube, the internal wall, the external wall, and the connection between nodes. The thermal conductance (G) was calculated for each of these nodes with the thermal conductivity for steel (k_s= 45.5 W/mK) by means of Eq. 2:

$$G_i = \frac{2\pi k_s}{log\left(\frac{D_i}{D_m}\right)} \Delta x \quad (2)$$

This equation is for the internal wall, for the external wall and the connection wall the equation is the same but with the correspondent diameters. Where D_e is the external diameter of the absorber equal to 0.07m; D_m is the average between the external and internal diameter equal to 0.068 m; and Δx is the length of the node.

Between the two thermal conductors, there is a Modelica thermal capacitance to model the absorber tube heat capacitance (C), we used Eq. 3 with a heat capacity and density for steel (Cp_s= 536 J/kgK, ρ_s =7700 kg/m3).

$$C = Cp_s \pi \frac{(D_i^2 - D_e^2)}{4} \rho_s \Delta x \quad (3)$$

A heat flow inlet is connected to the external wall of the absorber. This represents the total heat absorbed in the tube wall (q_{abs}) Eq.4 [11]. This heat absorbed is calculated with the incident heat flow (q_{conc}) multiplied by three factors. The factor f is the effective surface of the receiver that considers the end losses of the receiver tube (C_{eff}=0.0135). The η factor depends on two coefficients α_r=0.955 and α_g=0.02 for the heat absorbed in the metal and glass tube. The variable d represents the defocus fraction of the collector mirrors which is calculated with Eq. 5 and 6.

$$q_{abs} = q_{conc} f\eta d, f = 1 - C_{eff}, \eta = \alpha_r(1 - \alpha_g) \tag{4}$$

The receiver included a defocus PI controller that was meant to control the maximum temperature of the system by reducing the incident heat, defocusing the mirrors of the collector. The controller sense the outlet temperature of the SunDial and compares it with the set point temperature of 240ºC. The difference between these temperatures is calculated and is enter as an input (u) to the PI controller. The output of the PI controller is the variable d that multiplies the incidence heat in Eq.4. The equations of the PI controller correspond to Eq. 5 and 6. The defocus controller would only be used if the SunDial power is bigger than the one that the demand could receiver.

$$d = k(x + u) \tag{5}$$

$$\frac{dx}{dt} = \frac{u}{T} \tag{6}$$

Where k is the proportional constant equal to 0.1 and T is the time constant equal to 400s. The variable d is limited between the values 0 and 1.

Finally, we model the radiative loss to the ambient with a Modelica body radiation. The Modelica body radiation was changed to consider an external heat transference coefficient (Gr) dependent on the absorber temperature (T_r), the wind velocity (vw), and the ambient temperature (T_a). For the air properties, the Modelica standard medium for air was used.

$$q_{re} = Gr\sigma(T_r^4 - T_a^4)\pi D_e \Delta x \tag{7}$$

$$Gr = 1.26x10^{-4}(T_r - 273.15) + 0.035, v_w < 0.5 \tag{8}$$

$$Gr = 0.000188{Re_g}^{0.01428}(T_r - 273.15) + \frac{1}{27.68{Re_g}^{0.0302}}, v_w > 0.5 \tag{9}$$

$$Re_g = \frac{D_g \rho_a v_w}{\mu_a} \tag{10}$$

Where σ is the Stephan-Boltzmann constant equal to 5.67x10^{-8} W/m^2; D_g is the external diameter of the glass tube equal to 0.115 m; ρ_a and μ_a are the density and dynamic viscosity of the air.

The equations were solved for each receiver node. Losses caused by shadowing of the receiver supports were considered constants and applied to node 16 of each receiver with a value of 124.6 W.

SYSTEM DYNAMIC SIMULATION

The SunDial was simulated in a closed system with a heat exchanger that produces steam (Boiler_HE), the Dymola diagram of the system is shown in Fig.2. The heat exchanger was taken from Modelica library, we used a constant heat transfer coefficient for the Therminol 55 and the steam. A PI controller (PI_T1) regulates the steam flow entering the heat exchanger to absorb all the power produced in the SunDial.

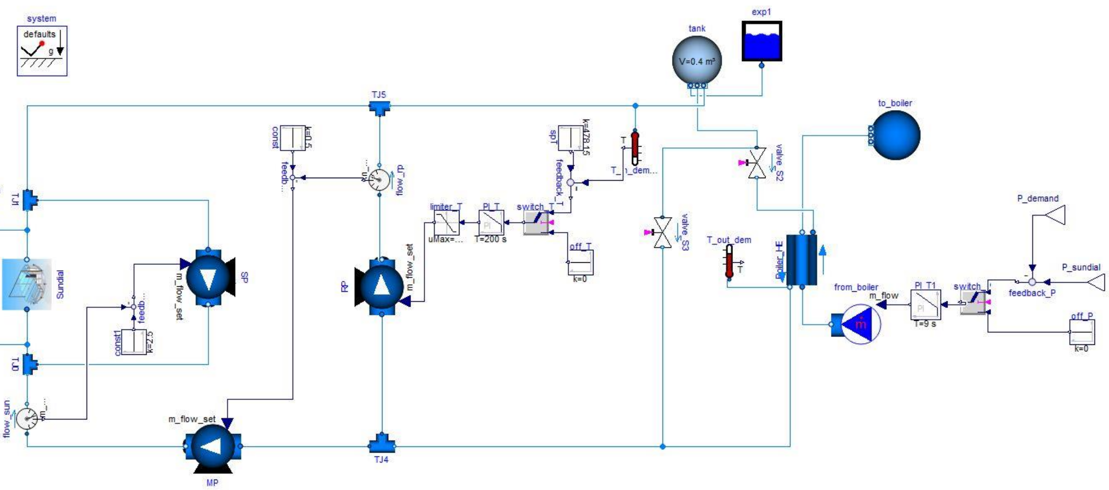

FIGURE 2. Dymola dynamic system to test the SunDial model.

The demand inlet temperature (T_in_demand) is maintained constant with a PI controller (PI_T) by mixing the hot outlet stream of the SunDial with the cold outlet stream of the heat exchanger. The PI controller varies the flow of the recirculation pump (RP). The demand mass flow is maintained constant by the main pump of the system (MP). The SunDial has a recirculation pump (SP) to guarantee constant flow through it and to ensure a minimum velocity to prevent fouling.

The closed system needs an expansion vessel (tank and exp1) to absorb the variation of pressure in the system. The expansion vessel was connected before the demand inlet so that its thermal inertia would help to reduce the variability of the solar irradiation. The expansion vessel model was taken from the Buildings open source library [12].

All sensors and controllers belong to the controller Modelica library; the constants of the controllers were adjusted with the Ziegler–Nichols method [13].

The external data (incidence power, ambient temperature, and wind velocity) was inserted with a Modelica table that read and interpolated the data; a connector was used to enter these data to the SunDial model. A typical meteorological year for a location in Corinth, Greece, was selected and the simulations were run between 5 am and 17 pm on the 8th of July. The simulation step was 86 s with a tolerance of 0.0001.

The first two simulations were done for a sunny day with short clouds of 3 minutes and a mass flow rate of 0.5 kg/s, and one simulation was carried out with the SunDial mirrors defocus control deactivated to analyse its functionality. Then we prepared another simulation with a long cloud duration of 30 minutes; in this case, the demand mass flow was of 1 kg/s to prevent the SunDial to defocus.

The system was initialized with a SunDial temperature of 190 ° C. The demand started with the inlet valve closed and the bypass opened, when the inlet temperature reached a defined set point of 205ºC, the demand valve opened. The defocus control would begin to operate when the temperature was 1 ºC above the maximum temperature set point of 240 ° C and would shut down 1 ºC below. The system was shut down when the input temperature of the demand reached 190 ° C.

RESULTS

Figures 3 and 4 show the temperatures and power of two simulations for a sunny day with clouds of short duration; in one of these simulations the SunDial had a mirrors defocus controller to limit the maximum temperature achieved in the SunDial outlet. The results of the simulation with the defocus mirrors controller are identified with the suffix defocus and are plotted with a dashed line. Figure 3 shows the evolution of the temperatures along the day. The start-up sequence began recirculating the SunDial flow until the outlet temperature reaches 225ºC. After this, the demand valve opened and the cold stream from the demand entered to the SunDial with an abrupt decrease in the temperature, this was the main motive for recirculating the SunDial until achieving a temperature 20 degrees above the demand inlet set point of 205ºC. After that, the demand inlet temperature control and the power heat exchanger control started to work. The simulation stopped when the SunDial outlet temperature decreased to 190 ° C. In this figure we see how the defocus PI controlled the SunDial outlet temperature at 240ºC (dash line); but in the simulation without this controller, the outlet temperature went up to 300ºC (continuous line). The action of the defocus is shown in Fig. 5, where the maximum defocus percentage needed was 80%. In both scenarios, the temperature differences between the outlet and the inlet were similar because the SunDial flow and the demand flow were constants and equal in both scenarios. Demand input temperature was controlled at a set point of 205°C except when the SunDial outlet temperature had a lower value at the end of the day. The first cloud appeared at 9 am and produced an increase in the demand outlet temperature because there is no heat transference in the heat exchanger. The second cloud appeared at 12 pm and had no effect on the system temperature probably because at this point of the day the incident power is practically constant and at its maximum value, so the thermal inertia of the system is higher than at the morning. Figure 4 shows the power of SunDial and the incidence power of the receiver, which was calculated externally with ray tracing. The power of the SunDial was lower than the incidence power because of the heat losses to the ambient. In the defocus simulation, the power of the SunDial was higher when the defocus PI was working because, even though the incidence power in this case was lower, the temperatures in the SunDial were 60 degrees lower and these implied lower thermal losses.

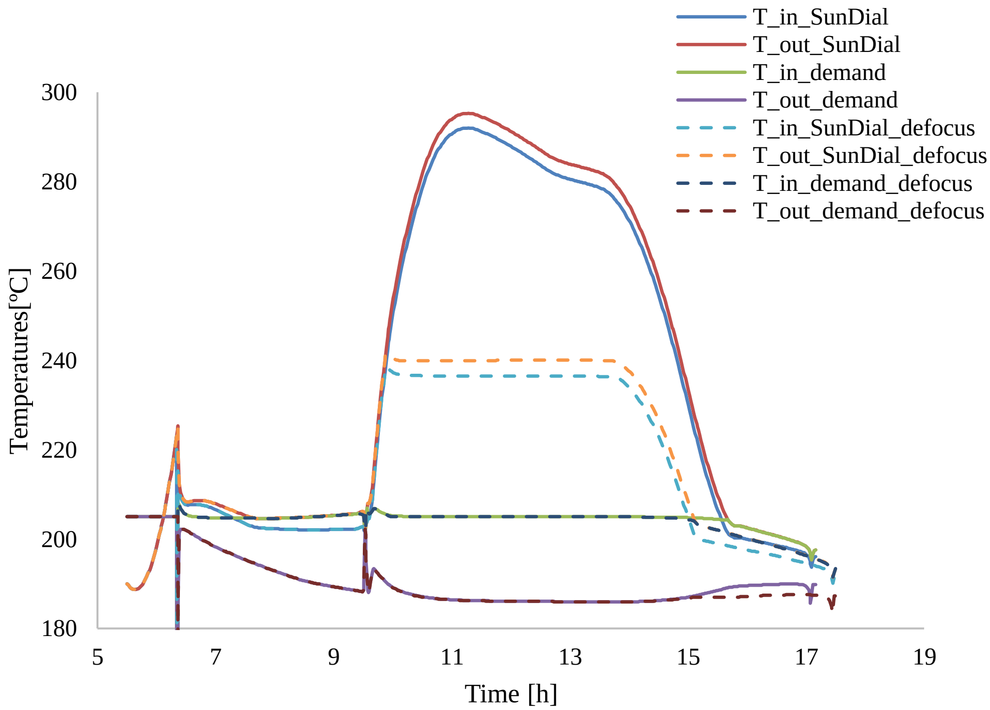

FIGURE 3. System temperatures for a simulation with two short-duration clouds and a demand flow of 0.5 kg/s, with and without defocus control.

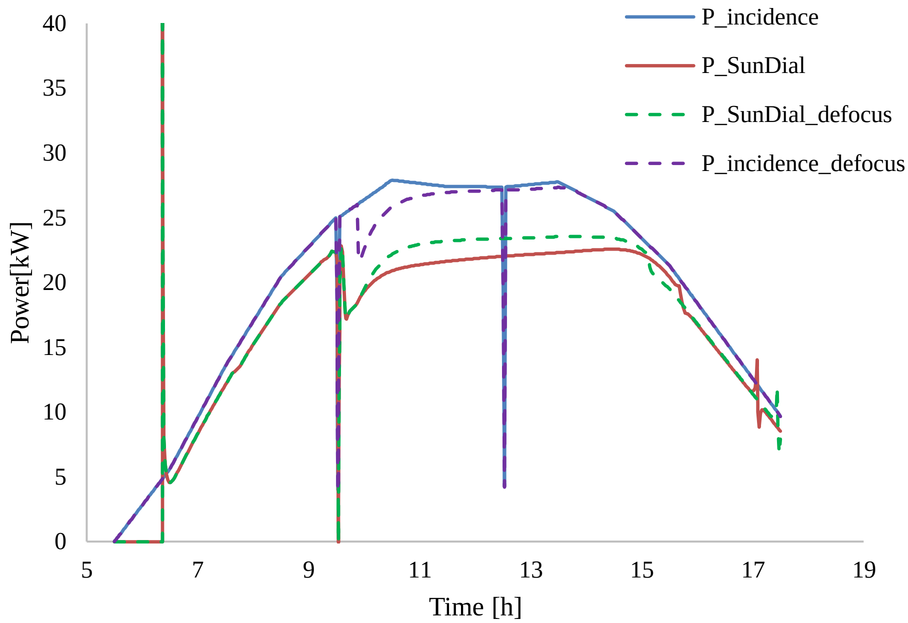

FIGURE 4. SunDial incident and useful power for a simulation with two short-duration clouds and a demand flow of 0.5 kg/s, with and without defocus control.

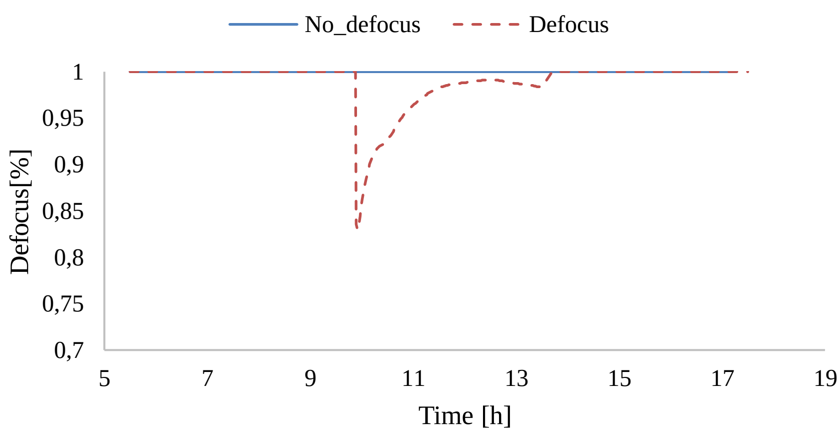

FIGURE 5. Defocus for a simulation with two short-duration clouds and a demand flow of 0.5 kg/s, with and without defocus control.

Figure 6 shows the incidence and the SunDial power for a day with clouds of 20 and 30 min of duration, the flow of the demand was 1 kg/s to avoid the defocus of the SunDial. Figure 7 shows the temperature evolution, where the demand inlet temperature maintained its value most of the time and only increased 2 degrees for some minutes when the clouds appeared. This was possible because the temperature controller actuated by varying the recirculation flow, as shown in Fig. 8 (left). The temperature of the SunDial decreased when the clouds passage with no effect on the demand inlet temperature. Figure 8 (right) shows the variation of the steam flow in the heat exchanger with the objective of absorbing all SunDial power.

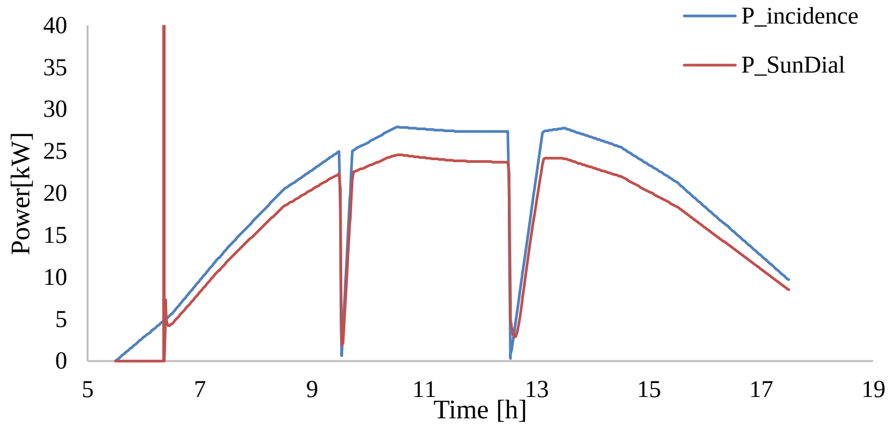

FIGURE 6. Incident and useful power of the SunDial for a simulation with long-duration clouds and a demand flow of 1 kg/s.

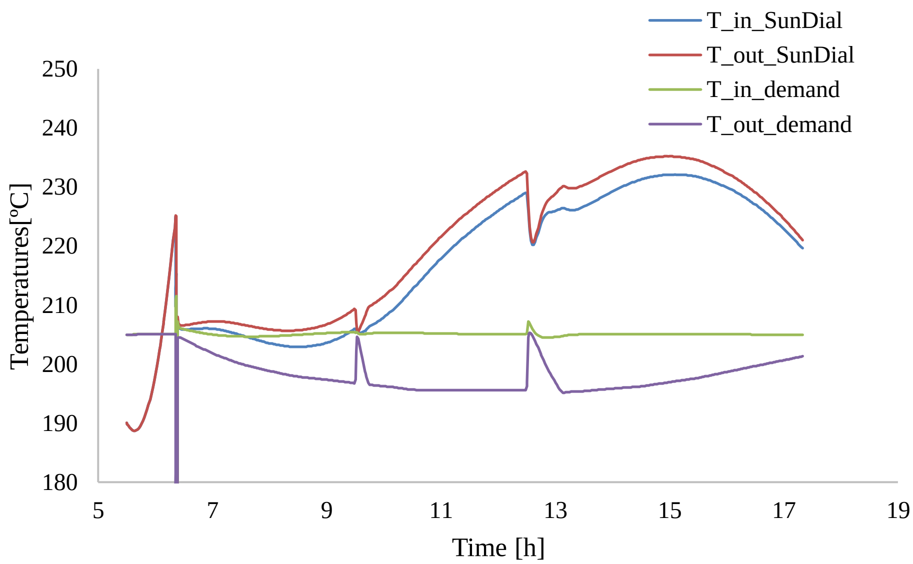

FIGURE 7. System temperatures for a simulation with long-duration clouds and a demand flow of 1 kg/s.

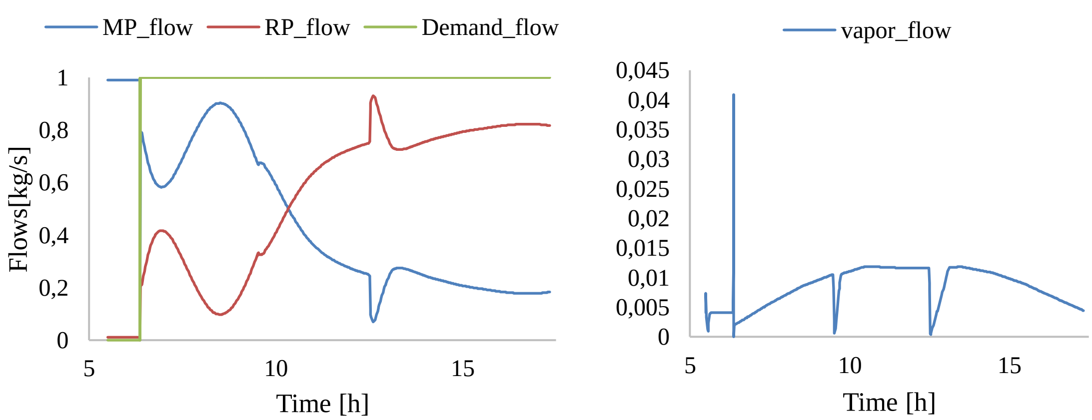

FIGURE 8. System flows for a simulation with long-duration clouds and a demand flow of 1 kg/s.

CONCLUSION

We found that the SunDial could supply constant temperature and constant flow to the demand despite the variability of the solar resource. This was possible because of the control system strategy and the thermal inertia of the system. The SunDial could operate all time at constant flow and this is important to guarantee a minimum velocity. In the case of higher radiation than the demand could absorb, the SunDial will defocus the mirrors to decrease the incident power and prevent damage the fluid because of high temperatures. As other studies in the field found [1], the thermal inertia of the system could eliminate short-term variations in irradiation. And the control system strategy could manage the long-term variations.

One limitation of this study was the lack of a storage system that could reduce the effect of variability of the resource on the demand and supply constant power to the demand for 24 hours without wasting energy. In these simulations, the power supply to the demand was variable because the steam flow varies in a wide range. The next step in this research would be to add storage and characterize the demands based on the real industries where the ASTEP project will be located.

This study showed that although the Sun was a variable source of energy, the SunDial could be a constant source of temperature with an adequate control system. This makes solar thermal energy a feasible solution for the replacement of fossil fuels in the industry sector.

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