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Development and performance analysis of a phosphate flash dryer integrated with PTC array

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ABSTRACT

This paper presents a phosphate flash dryer integrated with a parabolic trough collector (PTC) at bench scale. Due to the discontinuity of the solar radiation, the dynamic response of the system is analyzed for the performance prediction and the control strategy design. For this purpose, a solar flash dryer model is developed and simulated using the Engineering Equation Solver software. Then, the impact of the environmental parameters on the drying temperature is examined. Regarding the dynamic behavior of the solar flash dryer versus the months of year, it was shown that the oil temperature is more affected by the solar radiation and the solar incidence angle, conducting then to a maximum drying air temperature and a maximum product mass flow rate of 140°C and 60 kg/h respectively. Also, in order to keep drying conditions stable during tests, the oil temperature regulation is covered by the electrical heater. Finally, the global performance of the process is evaluated and compared to other solar industrial processes. According to the obtained results, the gained output ratio of the solar flash dryer is limited to 0.11 compared to 0.34 by the solar distillation. This value will be optimized in the future work based on the process model and exergy analysis.

Keywords: Solar energy for industrial application, gained output ratio, parabolic trough collector, flash dryer

NONMENCLATURE

A	Collector area (m^2)
I_b	Direct nominal irradiance (W/m^2)
MC	Product moisture content (%)
Q_{dry}	Required heat for drying (W)
$T_{dry,in}$	Inlet temperature of drying air (°C)
$T_{f,in}$ / $T_{f,o}$	Inlet and outlet temperature of HTF
T_{phosp}	Temperature of phosphate particles
η	Energy efficiency of the system
Abbreviation	
DNI	Direct nominal irradiations
HTF	Heat transfer fluid

1. INTRODUCTION

In 2030, the world's energy demand will increase by 60%, due to the growing economic development [6]. This will result in high stress on dwindling nonrenewable resources and the increase of the effect of green gas emissions. Hence, a shift of energy consuming industrial processes towards the use of renewable energy sources is the best option for environmental preservation. In this sense, the Moroccan government has launched several programs to promote the use of solar energy in industrial applications as 85% of its energy is imported. PTC represents thus the most promising concentrating solar technology, working at temperature up to 550°C [1], and used as a heat source in electricity production or to supply heat for industrial processes. Several studies [2,7,8] summarized the major applications of PTC in industrial processes, such as desalination, chemical industries, refrigeration and drying. However, actually, PTC is limited to low and medium temperature applications, despite its better exergy efficiency at high temperature [1].

The drying technologies are classified among the most energy consuming processes, and was identified as a possible candidate for the use of the solar energy [6]. The technical feasibility of a phosphate flash dryer integrated with a PTC array should, however, be explored under a drying temperature range of 100-700°C.

In the present study, a phosphate flash dryer combined with a PTC loop was designed and installed at bench scale. The good comprehension of the dynamic response of the system allows the performance prediction and control strategy design to carry out drying tests in the best conditions. In this regard, a solar flash dryer model was developed and simulated using the Engineering Equation Solver software. Then, the effect of the environmental parameters and optical performances of PTC on the drying air temperature are investigated. Finally, control strategy design is deduced and the global performance of the process is discussed.

2. MATERIAL AND METHOD

A bench scale phosphate flash dryer integrated with parabolic trough collectors was designed [3] and installed in green energy park, Morocco. As illustrated in figure 1, the developed solar flash dryer contains three main components: PTC test loop used to heat the oil before entering the heat exchanger, compact heat exchanger, and a flash dryer unit for phosphate particles.

The performance evaluation of the system is performed under climate conditions of Benguerir (*Morocco)*, located at a Latitude of 32.029955 and a Longitude of -7.88535.

The solar radiation, wind speed, ambient temperature, flow rate of both fluids, solid moisture content, and temperature of different parts of the system are measured and recorded by a data logger.

To ensure a better operability of the designed process, a good comprehension of its dynamic response under working is essential. This allows predicting its performance, and selecting the relevant control and regulation system with respect to the experimental design of drying tests. For this purpose, a mathematical model of the process was developed. The model allows the investigation of the environmental parameters and the operational conditions effect on the system performance. The model also enables the process optimization of the drying conditions as a function of the PTC operating parameters.

3. MODELING OF THE SOLAR FLASH DRYER

In this section, the modeling approach and equations for the solar flash dryer are detailed. Mathematical models are developed for the PTC array [1], the heat exchanger [4], and the flash dryer [3].

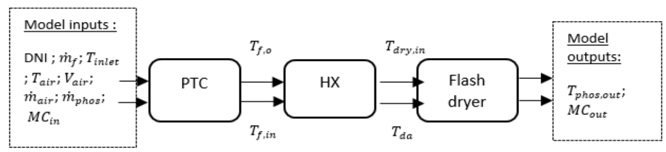

Figure 1:inputs and outputs of the solar flash dryer model

3.1 Solar system

PTC model consists of an energy balance between incoming solar radiation, the Heat transfer fluid, the absorber, and its surroundings. [1]

3.2 Flash dryer

The model is based on simultaneous momentum, heat and mass transfers between the solid and gas phases [3].

3.3 Heat exchanger

The HX thermal model is based on the first law of thermodynamics between the hot and the cold fluids, and the (ε -Ntu) method [4].

To evaluate the system performance, the gained output-ratio is used as the *evaluation criterion* defined as follow:

$$\mathrm{GOR} = \frac{Q_{dry}}{I_b A_{col}} = \eta_{sol} \times \eta_{HX} \times \eta_{Dry}$$

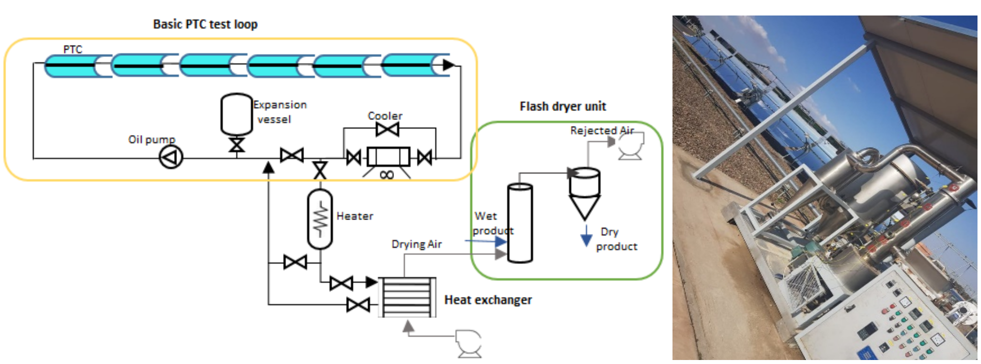

Figure 2: schematic of phosphate flash dryer combined with a PTC loop and photo of the bench scale

4. RESULTS AND DISCUSSION

4.1 Effects of the environmental parameters on the thermal performance of the solar flash dryer

The variation of DNI and the incidence angle modifier during March, June, September, and December are shown in fig (3) and (4) respectively. The four months were selected for simulation as they represent the four seasons of the year.

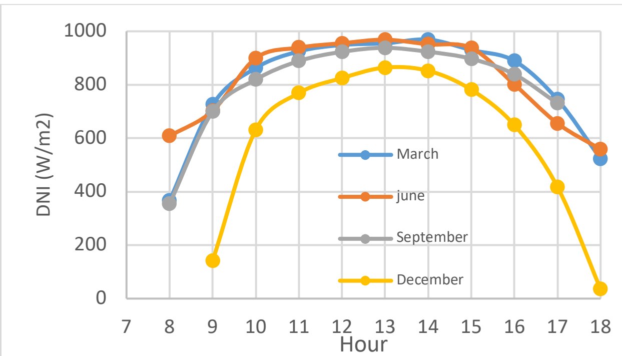

Figure 3: variation of the direct solar radiation along the day

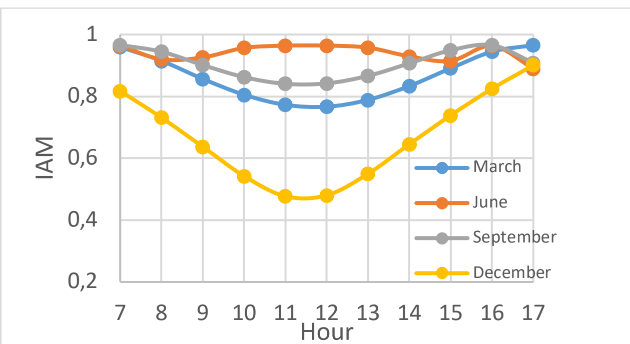

Figure 4: Variation of the incidence angle modifier along the day

It can be observed that the DNI is lower in the morning and the evening and reaches a maximum value close to noon. As for the incidence angle, its impact is more significant at noon, particularly, in December, because the PTC loop is oriented north-south [5].

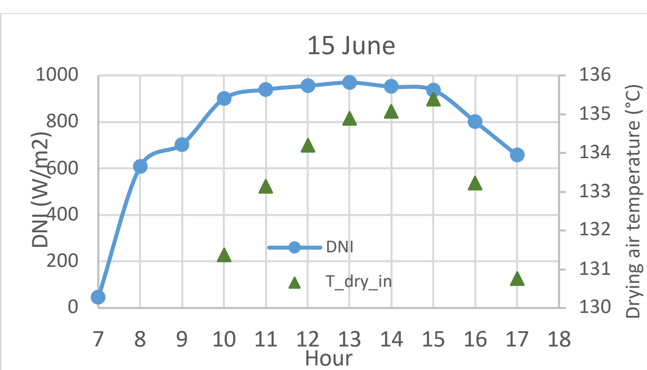

Figure 5: Drying air temperature at the exit of the HX versus time, for June 15

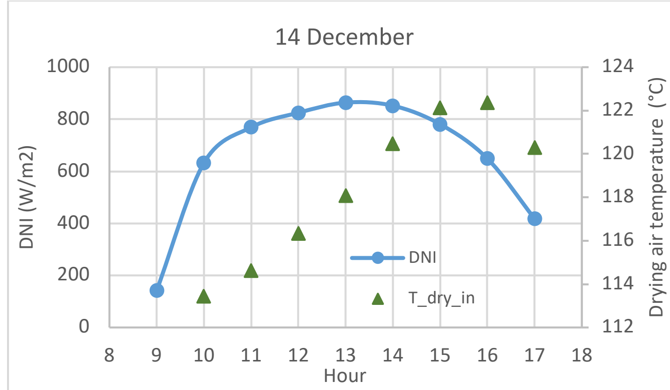

Figure 6: Drying air temperature at the exit of the HX versus time, for December 14th, 2018

Considering the hourly data of DNI and IAM on June 15th and December 15th, figures (5) and (6) show the variation of drying air temperature along the day.

As it can be seen, the drying air temperature follows the trend of the solar radiation, especially, on June 15th, 2018. However, on December 15th, 2018 the heat gain by PTC decreases due to the high incidence angle of the solar radiations leading to a drying temperature less than the maximum value achieved in June.

4.2 Control system for the dynamic operation on the test bench

After evaluating the performance of the PTC&HX for the weather data, a control strategy is deduced to conduct the drying tests regarding the specific requirements in terms of the drying outputs. Indeed, Figure (7) presents the phosphate mass flow rate that should be treated during the day to obtain 2% as a final moisture content of the phosphate, considering the PTC loop as the unique source of thermal energy.

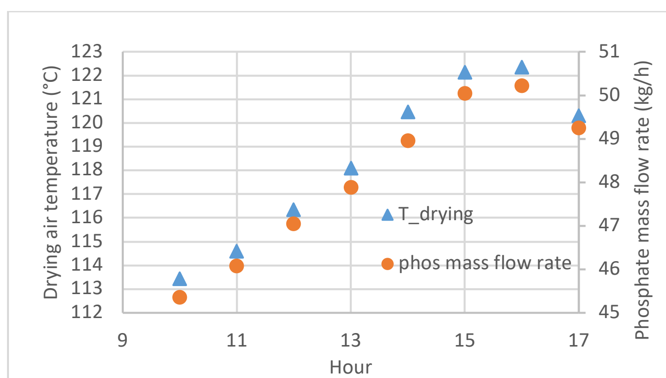

Figure 7: phosphate mass flow rate that should be treated during the day to obtain 2% as a final moisture content

Figure (8) shows the variation of the inlet and outlet temperatures of HTF from 14PM to 15PM, on November 30th. It can be deduced from the simulation results that the drying air temperature follows the trend of the oil temperature which is affected by the solar incidence angle, inducing then a drying air temperature decline from 124 °C to 105 °C.

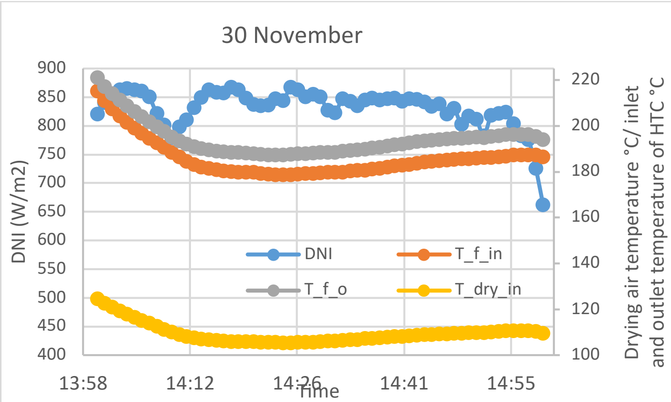

Figure 8: variation of the inlet and outlet temperatures of HTF and the corresponding drying air temperature at the exit of HX

In order to keep this latter constant during a drying test, the oil temperature entering the HX must be adjusted.

Indeed, as shown in figure (9), in winter the solar heat gain is more affected by the high solar incidence angle (Figure 4), resulting then in a thermal heat production by PTC of 74% lower than the nominal capacity 26 kW. Therefore, in these conditions, drying tests will be performed using the beck-up system.

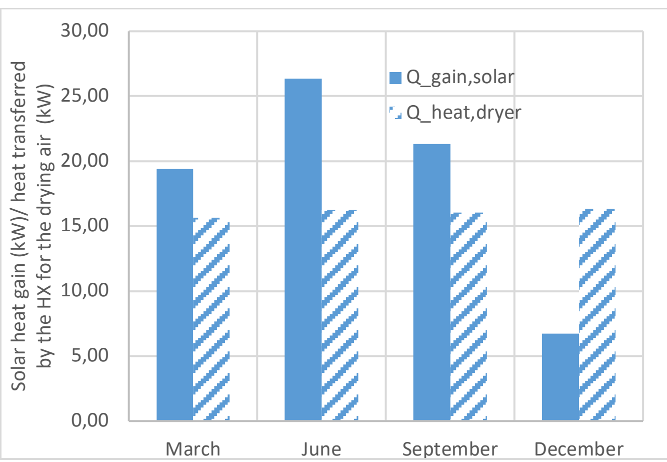

Figure 9: Average heat gain and heat transferred by the HX versus the months

This latter is an electrical heater installed upstream of the HX, with a nominal capacity of 15 kW (figure 2).

Figure 10 illustrates the oil temperature regulation covered by the heater to maintain the drying air temperature at 124 °C.

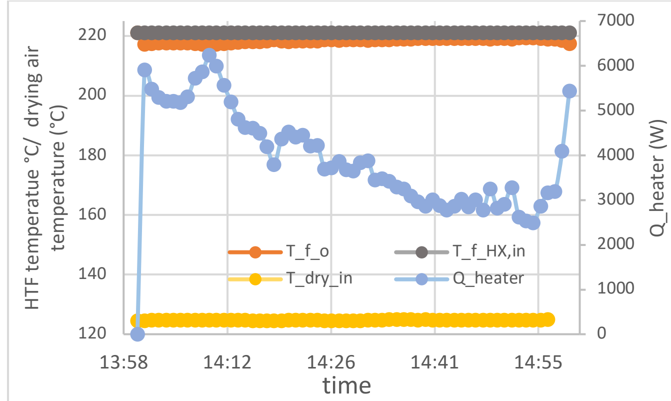

Figure 10: Oil temperature regulation to maintain the drying air temperature at 124°C (day: November, 30th)

In addition, to increase the drying air temperature up to 140°C, especially in bad weather conditions, the HX efficiency must be improved by increasing the HTF inlet temperature (Figure 11). However, this temperature at the PTC exit must not exceed 250°C mainly for the thermal stability of the oil.

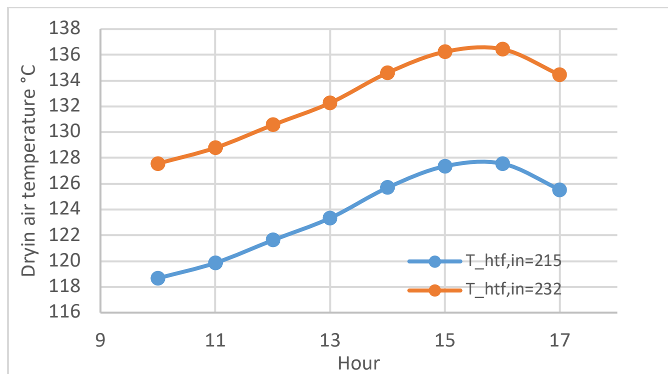

Figure 11: Variation of the drying air temperature with the HTF inlet temperature simulated for December 14th, 2018

Hence, the phosphate solar drying will be tested under temperature from 100°C to 140°C, with a maximum product mass flow rate of 60 kg/h to achieve a final moisture content lower than 2%.

On the other hand, as illustrated in figure 9, it could be seen that the maximum heat transferred by the HX is limited to 17 kW, although the solar heat gain achieves 27 kW. This is explained by the low Heat exchanger efficiency which does not exceed 0.54.

Furthermore, Regarding the air temperature along the dryer (inlet and outlet air temperature are 120°C and 78°C respectively), the drying efficiency is so low, around 0.32.

All these factors affect the global performance of the solar flash dryer at the bench scale, whereas the average PTC efficiency is 0.6 during all the year. Indeed, figure (12) illustrates the gained output ratio of the solar flash dryer and the maximum drying air temperature during the four chosen months.

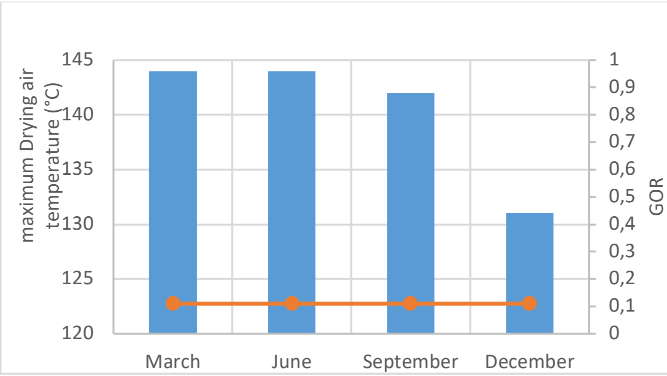

Figure 12: gained output ratio of the solar flash dryer and the maximum drying air temperature

It can be observed that the maximum value of GOR is 0.11. This value is low compared to other industrial processes such as, the solar distillation (GOR=0,34) and the solar desalination (GOR= 1,5). This difference in the global performance between the processes is resulted in the average productivity per day of the evaporated water by drying of 0.83 kg/m2/day, against 1.5 kg/m2/day and 4 kg/m2/day of the fresh water by distillation and desalination respectively [2].

Conclusion

In this paper, the performance prediction and the control strategy of a phosphate flash dryer integrated with a PTC array were conducted. For this purpose, a solar flash dryer model was simulated under different weather conditions and regarding the drying tests requirements. The main results of this study are presented as follows:

-The solar radiation and the solar incidence angle have the most significant impact on the oil temperature, and hence, on the drying air temperature;
-In bad weather conditions, the drying tests will be performed using the back-up system in order to maintain the drying temperature constant during tests;
-Regarding the simulation results, the experimental design of drying tests will be conducted under temperature from 100°C to 140°C, with a maximum product mass flow rate of 60 kg/h;
- The gained output ratio (GOR) of the solar flash dryer is around 0.11 compared to other solar industrial processes. This limitation is due to the low efficiency of the HX and the flash dryer of 0.54 and 0.32 respectively. Accordingly, the process will be optimized in the future work based on the validated model of the process and an exergy analysis as well.

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