materials proceedings

Proceeding Paper

A Vegetable Oil as Heat Transfer Fluid for Parabolic Trough Collector: Dynamic Performance Analysis under Ouagadougou Climate Conditions †

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Abstract: In this study, the thermal performance of the parabolic trough collector (PTC) has been addressed under Ouagadougou climate conditions. Thus, after developing a model, the effect of mass flow on PTC performance showed that the Jatropha curcas oil (JCO) temperature difference increases when the mass flow rate ($\dot{m}$) decreases while the thermal efficiency (η_{th}) increases. For $\dot{m}$ of 1 kg s^{-1}, a collector length of 46.8 m or collection area of 230 m^2 is required to obtain an outlet temperature of 210 °C with an average η_{th} of 82.69%. This paper can support the decision for a demonstration plant implementation regarding JCO use in the CSP plant.

Keywords: collector; vegetable oil; thermal performance

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1. Introduction

To reduce the environmental impact due to the increased use of fossil fuels, many countries have now focused on renewable sources of energy for electricity generation, hydrogen and solar fuel production, cooking, cooling, and heating [1]. Solar energy is a major resource and is exploited by thermal and photovoltaic technologies for electricity generation. Concentrating solar power (CSP) technology is not yet developed in Sahelian countries or is still less known, while solar thermal technologies are the worthy investment option to provide the world with 25% of the electricity needed by 2050 [2]. In addition to the lack of data on CSP technologies in Sahelian countries, the technology is still costly [3]. A CSP plant consists of solar collectors (solar field), a storage system, and a power block. There are four types of CSP technologies: parabolic trough collector(PTC), linear Fresnel collector, heliostat, and parabolic collector or dish technology useful for electricity generation which can reach a temperature of more than 300 °C depending on the collector size and length [4]. Among CSP technologies, PTC is the most mature (95% of CSP installed) [5]. In the long term, PTC has been proven to be durable and reliable with modular components and compatible with combined cycles. However, the thermal oils used to transfer the heat to the power block and storage system are expensive, making the technology less attractive in developing countries. In addition, those oils have some wizards like high inflatability, high vapour pressure (up to 10 bars), and harmfulness. The contribution of the present study is to assess the thermal performance of a PTC when using vegetable oil (Jatrapha curcas oil) as HTF. To achieve this objective the city hall authorities, the West African Science Service Centre in Climate Change and Adapted Land Use and the Intergovernmental Panel on Climate Change (IPCC) have supported data collection on the dynamic performance of a PTC using JCO as HTF based on observation DNI data. So, the landfill of Ouagadougou has been chosen to install a weather station for DNI data collection. A control model of the PTC has been developed in the Fortran language to assess its performance.

2. Methodology

2.1. Parabolic Trough Collector Model

In this study, various simplifying assumptions were considered, and physical and model mathematical models [6,7] are presented in Table 1.

Table 1. The parabolic trough collector model after assumptions.

Physical Model (See Figure 1)	Mathematical Model	
	For the heat transfer fluid (HTF) energy balance: $\dot{Q}_{store,f} + \dot{Q}_{adv,f} = \dot{Q}_{diff,f} + \dot{Q}_{f\rightarrow abs}$	(1)
	For the absorber pipe $\dot{Q}_{abs,a} = \dot{Q}_{conv,\ a\rightarrow f} + \dot{Q}_{diff,a} + \dot{Q}_{conve,annulus} + \dot{Q}_{rad,a\rightarrow g}$	(2)
	Similarly, the energy balance on the glass envelope is computed $\dot{Q}_{abs,g} = \dot{Q}_{store,g} + \dot{Q}_{diff,g} + \dot{Q}_{rad,g\rightarrow a} + \dot{Q}_{conv,annalus} + \dot{Q}_{rad,g\rightarrow sky} + \dot{Q}_{g\rightarrow\infty}$	(3)

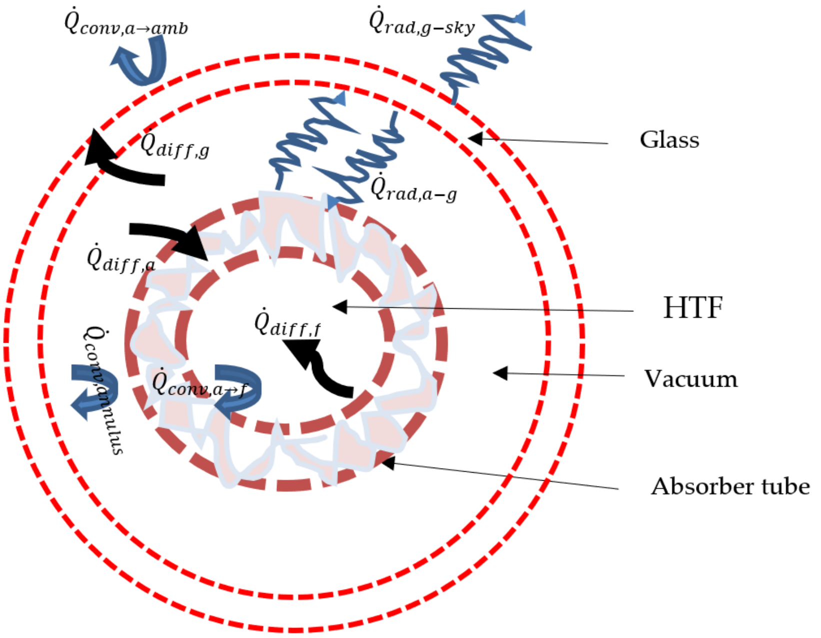


Figure 1. Receiver model with the different heat transfer phenomena, view of a cross-section.

2.2. Boundary and Initial Condition and Numerical Solution for the Proposed Model

Since the numerical models consider a one-dimensional model (Figure 1), the boundary conditions consider only one at the inlet and one at the outlet of the collector. Table 2 illustrates the boundary and initial conditions.

Table 2. Boundary and initial conditions.

Boundary Conditions		**Initial Conditions**	
$T_f(x=0) = T_L$	(4)	$T_f(t=0) = T_{abs} = 160\ ^{\circ}\mathrm{C}$	(5)
$\frac{\partial T_f}{\partial x}(x=0) = \frac{\partial T_{abs}}{\partial x}(x=0) = 0$	(6)	$T_{glass}(t=0) = T_{ambient}$	(7)
Hot heat transfer fluid leaves the collector, an adiabatic condition for the fluid. $\frac{\partial T_f}{\partial x}(x=L_{abs}) = \frac{\partial T_{abs}}{\partial x}(x=L_{abs}) = \frac{\partial T_{glass}}{\partial x}\left(x=L_{glass}\right) = 0$	(8)	If DNI is less than the minimum sunshine value to heat up the fluid, the outlet temperature is less than T_{inlet}	

The difference finite method was used to numerically discretise the different equations. The solution was found using an iterative approach based on the Gauss–Seidel computational method. From the model output, the instantaneous and normalized efficiencies were assessed based on Equations (9) and (10) [6,7].

$$\eta_{th,inst} = \frac{\dot{m} \times c_{p,f} \times (T_{out} - T_{inlet})}{DNI \times A_{coll}} \tag{9}$$

$$\eta_{th} = \frac{\int Q_u dt}{A_{coll} \int DNIdt} \tag{10}$$

2.3. Study Area and Data Collection Materials

The study area is located in Burkina Faso (Figure 2a). The waste treatment and valorisation centre of Ouagadougou has been chosen as study area (Figure 2b,c). So, a weather station (stationary pyrheliometer, Figure 2d) has been installed. The site has been chosen due to the important surface emission of methane from waste [8] (geospatial methane (CH_4) average emission rate of 657 mgm^{-2} h^{-1} in 2017 and 1210 mg m^{-2} h^{-1} in 2018 with a concentration ranging between 35% to 60% from one well to another [9]).

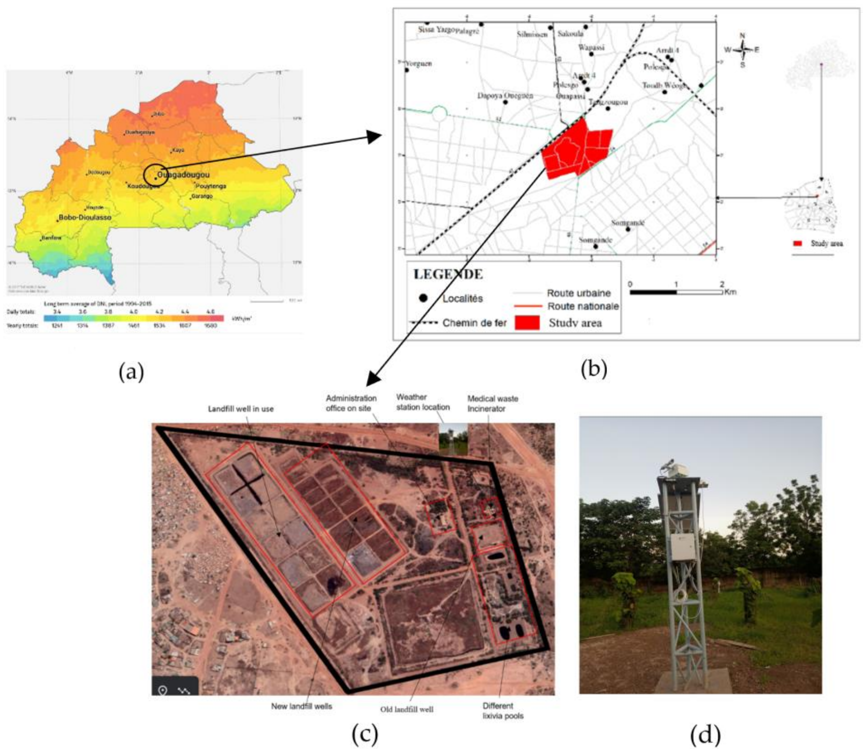


Figure 2. DNI map of Burkina Faso (**a**), landfill location in Ouagadougou city (**b**), top view of study area (**c**), weather station used for data collection (**d**).

3. Results and Discussions

3.1. Model Validation

The simulation results obtained were compared to experimental data obtained at the SNL Laboratory (Sandia National Laboratories) reported in [10]. A maximum deviation of 8.087% has been observed (see Table 3). In addition, despite some deviation, the PTC model generally predicts the outlet temperature with an acceptable accuracy. Therefore, the present model can be useful to simulate the PTC performance.

Table 3. Comparison of the experimental [10] and simulated outlet temperature to the new model.

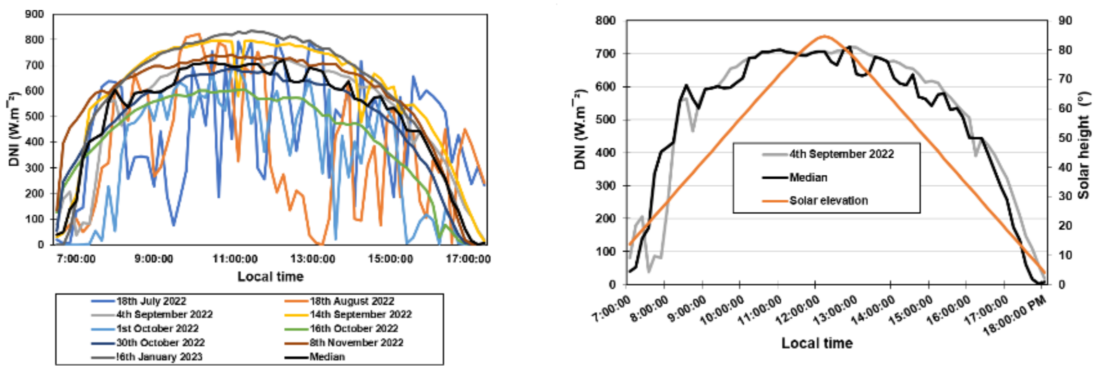
Case	DNI (W m^{-2})	$\dot{m}_f$ (kg s^{-1})	T_{inlet} (°C)	T_{out} (°C)	ΔT (Model)	ΔT (Exp)	Model Error (°C)
1	937.9	0.6206	297.8	317.46	19.66	19.1	2.932
2	933.37	0.678	102.2	122.237	20.037	21.8	8.087
3	920.9	0.5457	379.5	397.1	17.6	18.5	4.86
4	880.6	0.6205	299	317.27	18.27	18.2	0.38
5	909.5	0.6580	250.7	270.5	19.8	18.7	5.88
6	968.2	0.6536	151	173.35	22.35	22.3	0.224
7	982.3	0.6350	197.5	219.7	22.2	22	0.91

3.2. PTC Performance under Ouagdougou Climate Condition

The PTC performance in this chapter is assessed using an innovative vegetable oil as a new transfer oil. The thermal properties of this oil are illustrated in [11].

3.2.1. Direct Normal Irradiance for Some Days from July 2022 to January 2023

Figure 3a,b illustrate the DNI from 6 July 2022 to February 2023 for some days. For all the days, the DNI increases from a lower value at 7:20 to a maximum value at around 13:00 and decreases to a lower value around 18:00. After the analysis of the collected data based on median computation, the 4th of September 2022 (Figure 3b) was more representative with DNI profile fitting with the median values.



(**a**) (**b**)

Figure 3. DNI data was collected at Polesgo for some days using the weather station (**a**), DNI, and solar elevation data of the 4th of September 2022 (**b**).

3.2.2. The Effect of Mass Flow Rate on Collector Performance

To assess the effect of mass flow ($\dot{m}_{HTF}$) on the PTC performance, a module with 7.8 m length and 5 m width (around 39 m^2 of collection area) was considered. The $\dot{m}_{HTF}$ is an important parameter for CSP designing. It is related to the saturated steam flow rate generation in the boiler and can be computed from a steady-state energy balance [12] using Equation (11):

$$\dot{m}_{HTF} C_{p,HTF} (T_{HTF,in} - T_{HTF,out}) = \dot{m}_{steam} \times H_{fg} \quad (11)$$

$C_{p,HTF}$ is the HTF specific heat capacity, $T_{HTF,in}$ the HTF inlet temperature in the boiler from the solar field or TES system. $T_{HTF,out}$ the HTF outlet temperature from the boiler, $\dot{m}_{steam}$ the steam flow and H_{fg} the enthalpy of vaporization of the working fluid.

Figure 4a–c illustrates, respectively, the effect of JCO mass flow on its outlet (T_{out}) and difference temperature (ΔT) and the instantaneous efficiency (η_{inst}) of the PTC. The results show that whatever the mass flow rate the (T_{out}) (Figure 4a) and ΔT (Figure 4b) increase with sun radiation, reach a maximum value at the zenith, and decrease when the DNI decreases. This shows that T_{out} and ΔT depend highly on DNI. The higher the DNI, the higher the heat gain by the JCO and the higher are T_{out} and ΔT. Depending on the mass flow rate, the heat effect will be difference driving at different T_{out} and ΔT. So, the lower the mass flow rate is, the higher T_{out} and ΔT are. However, there is a low effect of $\dot{m}_{HTF}$ on the PTC thermal efficiency (Figure 4c); a slight increase is observed when the mass flow rate increases. A better outlet and different temperature (maximum values of T_{out} = 179.667 °C and ΔT = 19.667 °C at 13:10 min) are achieved at low mass flow leading to the increasing heat loss because the lowest average η_{inst} is 83.77% $\mp$ 16.66% for a mass flow rate of 0.5 kg s^{-1} against 84.56% for a mass flow rate of 2 kg s^{-1}.

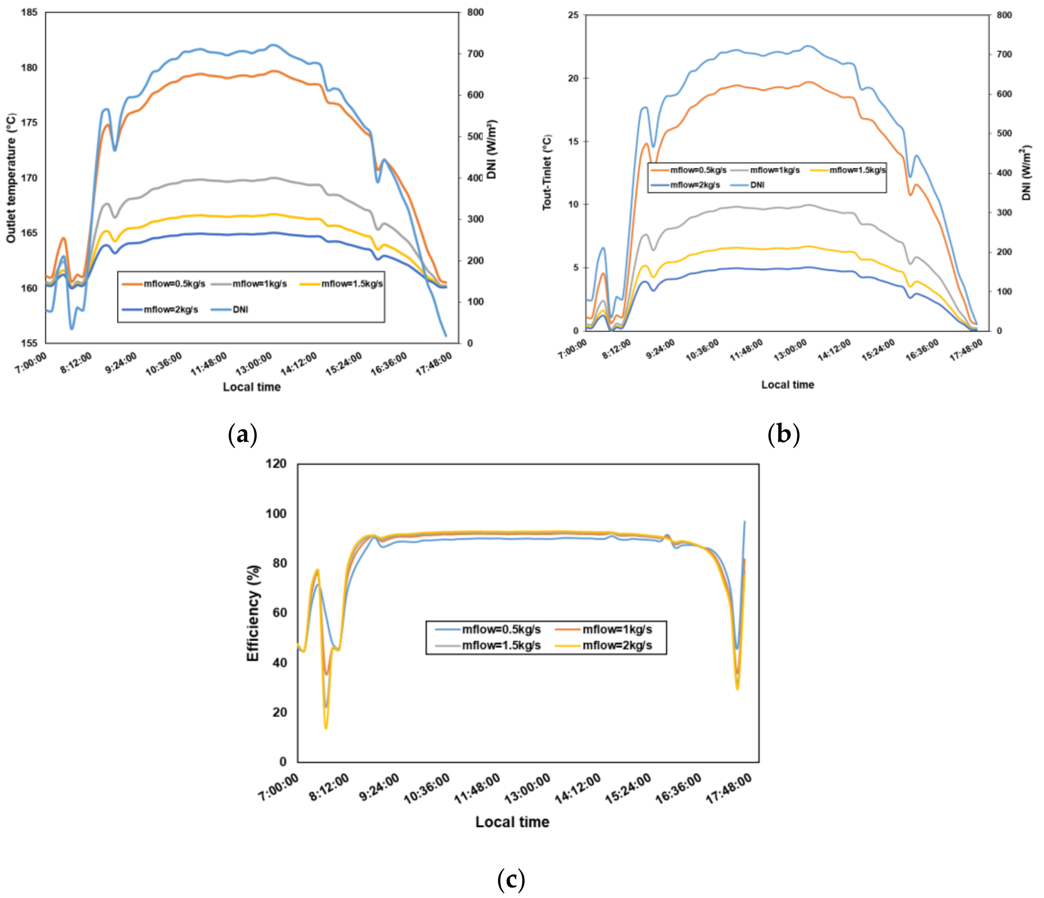


Figure 4. Effect of JCO mass flow on its outlet (**a**) and difference (**b**) temperature profile and Instantaneous thermal efficiency (**c**).

3.2.3. The Effect of Collector Length Rate on Collector Performance

From the assessment of the outlet temperature with one collector module, no mass flow was allowed to reach the desirable T_{out} (210 °C). In addition, for a demonstration PTC plant, the mass flow should reach about 1 kg s^{-1} [13]. So, in this study, a mass flow rate of at least 1 kg s^{-1} and inlet temperature of 160 °C are considered in this section. With a mass flow of 1 kg s^{-1}, the outlet HTF temperature is less than 210 °C To handle this issue, the solution is to put the collector's module in series by increasing the PTC collection area.

Figure 5a–d illustrate the effect of absorber length or collector size on the JCO T_{out}, ΔT, η_{inst} and heat gain by the HTF. T_{out} and ΔT increases when the collector length increases (Figure 5a,b). The results show that a collection area of 230 m^2 is needed to achieve 210 °C as T_{out}. A maximum T_{out} of 218.8 °C can be reached at 13:20 min (Figure 5a) with maximal, ΔT of 58.8 °C (Figure 5b). Thus, the increase in collector length or area led to an increase in the heat gain (Figure 5d) by the fluid. Considering the PTC thermal efficiency as illustrated in Figure 5c, it increases when the DNI increases whatever the collector length and reaches a maximum value at 9:00 remains constant till around 15:30 and decreases to 40%. Due to DNI fluctuation, unreasonable transient evaluation such as more than 100% instantaneous efficiency is observed between 17:30 and 18:00. This is due to the DNI fluctuation [14]. It can be observed that the η_{inst} decreases when the collector size increases. For the average η_{th}, it decreases from 86.28% to 82.69% when the collector length increases from 7.8 m to 46.8 m (Figure 6).

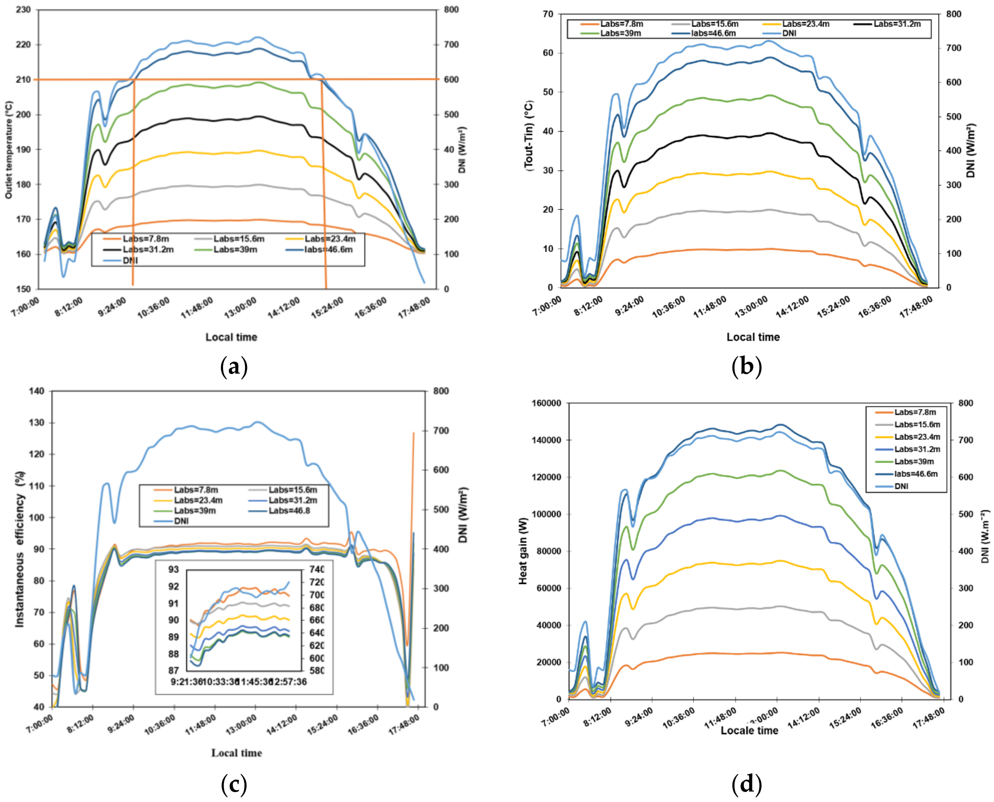


Figure 5. Effect of the collector length on JCO outlet temperature (**a**), JCO temperature difference (**b**), PTC Instantaneous efficiency (**c**) and JCO heat gain (**d**).

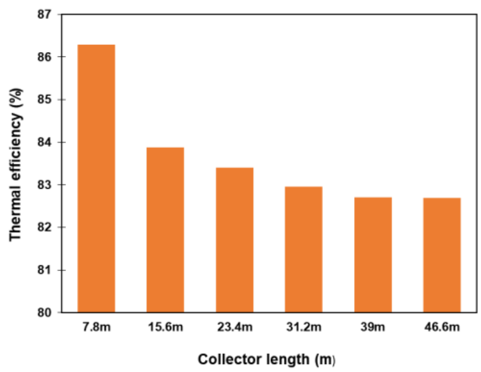


Figure 6. Effect of the collector length on PTC average efficiency.

4. Conclusions

In this work, a model has been developed for dynamic performance analysis of a PTC under Ouagadougou climate conditions. The model was validated with a maximum relative error of 8.08%. The DNI data collected with the weather station show that the 4th of September was the more representative day for the PTC performance analysis. The effect of mass flow rate shows that a low mass flow rate increases the outlet temperature driving the decrease in thermal efficiency. Also, for the collector length effect on the PTC performance (efficiency) with a mass flow rate of 1 kgs^{-1}, more heat losses are observed at longer collector length leading to a reduction in instantaneous efficiency. This is due to the increase in outlet temperature. In conclusion, the increase in JCO temperature leads to more heat losses in the PTC. For a mass flow of 1 kg s^{-1}, a collector length of 46.8m is required to obtain an outlet temperature of about 210 °C within the day.

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