Modeling of a Parabolic Trough Using Two Heat Transfer Fluids and an Economic Estimation in the Moroccan Dairy Industry

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Abstract. The aim of this article is modeling the parabolic trough (CSP) based on equations of the thermal balances of the different components taking into account all the different modes of heat transfer, as well as a comparison of the temperatures at the outputs in using two heat transfer fluids namely water and synthetic oil. The equations were solved using the finite difference method, and this developed model is validated by the results of the literature. The results obtained show the temperature at the outlet of the fluid, the absorber and the glass as well as the effects of flow, speed and irradiation on the temperature of the fluid, then an economic estimate of the energy consumption at the end.

1. Introduction
During previous work based on energy consumption in Morocco, it has been concluded that the agri-food industry precisely the dairy industry is among the energy-intensive in Morocco. During the production of dairy products, the el-jadida dairy plant requires a huge energy consumption of 247.8 kwh/t of electricity and 209.7 kwh/t of steam [1]. The figure 1 shows the global steam network.

In order to produce this steam, we resort to the use of oil boilers, and following that Morocco has a large solar deposit with more than 3000 h / year of sunshine or irradiation of about 5 kWh/m²/day as shown in figure 2 below [2], and in the context of Moroccan strategies for the development of renewable energy and the reduction of the energy bill from fossil sources it is within this frame-work that we propose use solar energy including parabolic solar collector technology for direct steam generation.

![Figure 1. Global network of steam.](image-url)
2. Parabolic Trough
Parabolic trough technology has proven to be the most mature and lowest cost solar thermal technology available today. The parabolic trough consisting of a mirror and a receiver this consists in concentrating the solar rays by orienting the mirror in order to heat a fluid at a high temperature and supply it with an industrial process. The following figure shows the components of a parabolic trough [3].

3. Modelisation of a Parabolic Trough
Among the methods common to modeling, we re-run the method of determining the temperature of each element of the trough by a monodimensional discretization. Taking into account all the heat transfer modes, the equations of the energy balance of the trough is as follows [4, 5].

Heat quantity of heat transfer fluid in Watt:
$$Q_f(x, t) = \rho_f * C_p * D_f * T_f(x, t)$$

Quantity of heat absorbed in Watt:
$$Q_{ab}(t) = \rho * \alpha * \tau * S * G(t)$$

Heat exchanges between components.
Between the heat transfer fluid and the absorber:
$$Q_a(x, t) = h_f * S_{ai} * (T_a(x, t) - T_f(x, t))$$
\[ h_f = \frac{N_u \cdot \lambda_f}{D_{ai}} \]

Between the absorber and the glass: \( Q_{a,v} = Q_{a,v/\text{conv}} + Q_{a,v/\text{ray}} \)

\[
Q_{a,v/\text{conv}} (x, t) = \frac{2\pi K_{\text{air eff}}}{\ln \left( \frac{D_{ei}}{D_{ae}} \right)} \left( T_a(x, t) - T_v(x, t) \right)
\]

\[
K_{\text{air eff}} = K_{\text{air}} \cdot 0.386 \left( \frac{\text{Pr}}{\text{Pr}_{\text{annu}}} + 0.861 \right)^{0.25} \left( F_{\text{cyre}} R_{\text{Da e}} \right)^{0.25}
\]

\[
R_{\text{Da e}} = \text{Gr} \cdot \text{Pr} = \frac{g \cdot \beta_{\text{Da e}} (T_a - T_v)}{\varphi^2} \cdot \text{Pr}
\]

\[
Q_{a,v/\text{ray}} (x, t) = \frac{\sigma \pi D_{\text{Da e}} (T_a^4(x, t) - T_v^4(x, t))}{1 + \left( \frac{1 - \varepsilon_v}{\varepsilon_v} \right) \left( \frac{D_{\text{Da e}}}{D_{vi}} \right)}
\]

Between the glass and the environment: \( Q_{v,\text{amb}} = Q_{v,\text{amb/conv}} + Q_{v,\text{amb/ray}} \)

With: \( Q_{v,\text{amb/conv}} (x, t) = h_{v,\text{amb}} S_v (T_v(x, t) - T_{\text{amb}}) \)

\[
Q_{v,\text{amb/ray}} (x, t) = \varepsilon_v \sigma S_v (T_v^4(x, t) - T_{\text{amb}}^4)
\]

Thermal efficiency: \( \eta = \frac{\int_0^t Q_{dt}}{\int_0^t G_{\text{dt}}} \)

3.1. Validation of the model
A modeling of the parabolic trough was developed by Matlab to solve the equations whose resolution is based on the finite difference discretization method. The results of the model developed were compared with the experimental results presented by the Sandia laboratory [6].

![Figure 4. Comparison between the numerical model and the experimental model of the Sandia laboratory.](image)

4. Results and Discussions
The parabolic trough chosen for our study is an S10 parabolic trough from Rackam. This parabolic trough has already been used in the agricultural cooperative of Taroudant (COPAG). The characteristics of this parabolic trough are shown in the table 1 and the figure 5 show us the installation of parabolic through in industry [7].
Table 1. The characteristics of the parabolic trough.

| Characteristics                        | Data          | Symbols       |
|----------------------------------------|---------------|---------------|
| Internal / external absorber diameter (m) | 0.065/0.07   | D_{ai}/D_{ae} |
| Internal / external glass diameter (m) | 0.119/0.125   | D_{vi}/D_{ve} |
| Collector Length (m)                   | 12.19         | L             |
| Collector Area (m²)                    | 13.7          | S             |
| Collector number                        | 4             |               |
| Interception factor                    | 0.92          |               |
| Coefficient of reflection              | 0.92          | ρ             |
| Transmissivity of glass                | 0.97          | τ             |
| Absorption coefficient                 | 0.955         | α             |
| Wind speed EL-Jadida city (km/h)       | 5-28          | V             |

![Figure 5](image1.png)

**Figure 5.** Installation of parabolic through in industry.

4.1. Variation of heat exchange coefficient of heat transfer fluids

![Figure 6](image2.png)

**Figure 6.** Variation of heat exchange coefficient of heat.
According to the graph, there is, on the one hand, a significant exchange coefficient on the part of the two fluids and, on the other hand, a small increase in this coefficient which translates the heat exchange quality.

4.2. Variation of Grashof number of heat transfer fluids

![Figure 7. Variation of Grashof Number-Water.](image)

![Figure 8. Variation Grashof number-synthetic oil.](image)

There is a decrease in the number of grashof for the two fluids reflecting the presence of reinforced convection.

4.3. Variation of the temperature according to irradiation

![Figure 9. Variation of the temperature of the output according to irradiation.](image)

The figure 9 shows the temperature of the fluids at the exit depending on the irradiation; There is an increase in the two temperatures in addition we also note the output temperature of synthetic oil is greater than that of water.
The figure 10 shows an increase in absorber temperatures and the glass when increasing the intensity of irradiation and we notice that the temperature at the absorber level is the highest temperature while the temperature of the glass is less high compared to the absorber temperature.

4.4. Variation of the temperature according to volume flow rate and wind speed

![Figure 11. Variation of the outlet temperature according to volume flow rate.](image1)

![Figure 12. Variation of the temperature according to wind speed.](image2)

An inverse proportionality is observed between the fluid temperature and the volume flow rate, this implies an increase in the flow velocity and, for this purpose, impacts the heat exchange process between the fluid and the absorber.

According to the figure 12 presented above, we notice an increase of the speed of the wind causing a decrease of the temperature of the glass while the other temperatures are less affected, this concludes to say that the speed of the wind influences the temperature of the glass.

4.5. Variation of the efficiency according to tube length

![Figure 13. Variation of the efficiency according to tube length.](image3)
When the length of the tube increases the efficiency also increases. This increase has limitations related to thermal resistance of materials.

4.6. Economic valuation and environmental impact

The cost of the steam is calculated by:

\[
C_v = \frac{L_v \times C_r}{P_c \times \eta}
\]

Table 2. Annual gain steam.

| Description                      | Value   |
|----------------------------------|---------|
| Cost of Parabolic Through (MAD)  | 7720    |
| Daily gain steam (Kwh/day)       | 2880    |
| Cost of the steam \(C_v\) (MAD/Kwh) | 0.106   |
| Annual gain steam (MAD/year)     | 111427  |

Table 3. Energetic cost.

| Description                        | Value   |
|------------------------------------|---------|
| Daily fuel consumption (Kwh/day)   | 60      |
| Cost of fuel (MAD/Kwh)             | 4.12    |
| Annual energetic cost (MAD/year)   | 88003   |

Table 4. Net annual gain.

| Description                        | Value   |
|------------------------------------|---------|
| Annual gain steam (MAD/year)       | 111427  |
| Annual energetic cost (MAD/year)   | 88003   |
| Net annual gain (MAD/year)         | 23424   |

➢ Return on investment

It calculated using the below formula

\[
ROI = \frac{Investment\ cost}{Net\ annual\ gain}
\]

The company would be able to cover the costs it has invested over the course of 4 months.

➢ Environmental impact

The fuel consumption emits 0.271kg / Kwh of CO2 implies an emission of 5790T/year.

5. Conclusion

This work presents a resolution to the issue of hot water production in a dairy industry by proposing to integrate the parabolic cylindro sensors by presenting a numerical simulation of the output temperature. This study favors the choice of synthetic oil as heat transfer fluid in relation to water, but because our aim is to directly generate steam in industrial production and also because of the availability of water and an economy at the level of the purchase price of synthetic oil. It is better to use water as a heat transfer fluid.

Nomenclature

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| \(Q_f\) | Heat quantity of heat transfer fluid (W)         |
| \(Q_{a,v/\text{ray}}\) | Quantity between the absorber and the glass by radiance (W) |
| \(Q_{a,\text{amb}}\) | Quantity of heat absorbed (W)                   |
| \(Q_{v,\text{amb}}\) | Quantity between the glass and the environment (W) |
Qu : Quantity of useful heat (W)

\[ Q_{\text{a,amb/conv}} \] Quantity between the glass and the environment by convection (W)

\[ Q_{\text{a,amb/ray}} \] Quantity between the glass and the environment by radiance (W)

\[ Q_{\text{a,g/conv}} \] Quantity between the absorber and the glass by convection (W)

\[ \rho \] Density of the fluid (kg/m³)

\[ C_p \] Massic heat (j/Kg.K)

\[ D_f \] Flow rate of fluid (m³/s)

\[ \Delta T \] : Temperature difference (K)

\[ G \] : Irradiation (W/m²)

\[ Nu \] : Nusselt number

\[ h_c \] : Exchange coefficient (w/m².K)

\[ T_a \] : Absorber temperature (K)

\[ T_f \] : Fluid temperature (K)

\[ Gr \] : Grashof Number

\[ S_{\text{ai}} \] : Absorber area (m²)

\[ \lambda_f \] : Conductivity coefficient (w/m.K)

\[ R_{\text{Rayleigh}} \] Rayleigh number

\[ Pr \] : Prandlt number

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References
[1] BENHAFID Abdelhakim and EL-GAGHLOULI Abdelhafid, 2016, Reduction of fuel and electricity consumption at the Danone power plant in El-Jadida, page: 30-80
[2] “Morocco renewable energies”. [Online]. Available: https://www.fellah-trade.com/fr/developpement-durable/energies-renouvelables-maroc/solaire. [Accessed: 21-Mars-2019]
[3] Caliot and Flamant, 2016, Cylindrical-parabolic concentrator technology, page: 4
[4] Boukelia, Mecibah, and Laouafi, 2016, Performance simulation of parabolic trough solar collector using two fluids (thermic oil and molten salt), Journal of Fundamental and Applied Sciences, 8(2),600-626.
[5] Ghodbane, Boussad BOUMEDDANE and Soulef LARGOT, 2015, Optical and thermal study of a cylindrical-parabolic concentrator on the Algiers site, Algeria, 9th International Congress on Renewable Energy and the Environment,10
[6] “Solar Industrial Process Heat- COPAG” [Online]. Available: https://rackam.com/en/studies/copag/. [Accessed: 03-Mai-2018]
[7] Garcia-Valladares O, Velazquez N 2009 Numerical simulation of parabolic trough solar collector: Improvement using counter flow concentric circular heat exchangers Int. J. Heat and Mass Transfer 52(3-4) 597-609.