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Parabolic trough system operating with nanofluids: comparison with the conventional working fluids and influence on the system performance

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Abstract

To analyse the behaviour of a parabolic trough operating with nanofluids, and compare its performance to the more traditional ones using oil, a model for the thermal analysis of the system has been developed and implemented in Matlab. The simulations have been performed for a suspension of Al_2O_3 in synthetic oil and its characteristics compared to the corresponding basic liquid used by itself. The string has been assumed to have a length of 100 m and a concentrating surface area of 550 m^2. The simulations have been carried out for different DNI (Direct normal irradiance) and variable mass flow, ensuring a temperature at the collector outlet below 400 °C. For a proper comparison, the following variables and efficiency indicators have been checked: power output, pumping power, thermal efficiency and overall efficiency of the parabolic trough system.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Parabolic trough system; Nanofluids; Matlab.

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1. Introduction

Water, synthetic oil and ethylene glycol represent the most conventional heat transfer fluids. They play an important role in many industrial processes, such as power generation, chemical processes, automotive and microelectronics applications. However, the continuous technological development has led to new challenges in the heat transfer field. The conventional method for increasing the heat exchange is to increase the available area. In the last decades, instead, the research has been focused on the development and analysis of a new generation of fluids, known as nanofluids, which could offer new possibilities to increase the heat transfer performance. The term nanofluids has been introduced, for the first time, by Choi in 1995 [1], to indicate promising fluids, consisting of a suspension of nanoparticles in a basic fluid. The nanoparticles could be either metallic (Cu, Al, Fe, Ag, Au) or non-metallic (CuO, Al_2O_3, Fe_3O_4, TiO_2, SiC), while the basic fluid is usually one of the conventional heat transfer fluids, currently used [2]. The extremely small particle dimension ensures a high specific surface area, i.e. a larger surface area is available for heat transfer between particle and fluid. Moreover, the risk of sedimentation and clogging, typical of the early generation of solid suspensions based on the use of micro and millimetric particles, can be avoided. Depending on the particle type and their concentration, a variation of the fluid properties, like thermal conductivity, density and viscosity, can be obtained. This determines a higher flexibility of nanofluids, which makes them suitable for various applications [3].

In this work, the use of nanofluids in a parabolic trough system has been analyzed. A mathematical model of the parabolic trough has been developed in Matlab, in order to investigate the effects of using nanofluids and compare it with the conventional heat transfer fluids. In particular, the behavior of a suspension of Al_2O_3 in synthetic oil has been analysed and compared to synthetic oil used by itself.

Nomenclature

A	area, m^2
C_p	heat capacity, $J/(kg\ K)$
D	diameter, m
h	convective heat transfer coefficient, $W/(m^2\ K)$
k	conductive heat transfer coefficient, $W/(m\ K)$
Q	solar thermal power, W/m^2
R	thermal resistance, $(m^2\ K)/\ W$
T	temperature, K
x	axial coordinate, m
ε	emissivity
θ	angle, rad
ϕ	particle volumetric concentration
μ	viscosity, (Pa s)
Subscript	
a	air
abs	absorber tube
bf	basic fluid
ext	external
int	internal
nf	nanofluid
par	parabolic mirror

2. Mathematical Model of a parabolic trough system

A two-dimensional model of a parabolic trough has been developed in Matlab. It has been assumed that the temperature of both the absorber and the fluid change only along the axial direction (x), while the temperature profile in the radial direction has been evaluated under steady state conditions. The radiation has been considered homogeneous along the external surface of the receiver and the presence of metallic bellows, reducing the exchanging area, has been neglected.

Based on these assumptions, a representation of the parabolic trough system (figure 1a) and a schematic representation of a section of the trough system and its analogue electrical circuit are reported in figure 1b.

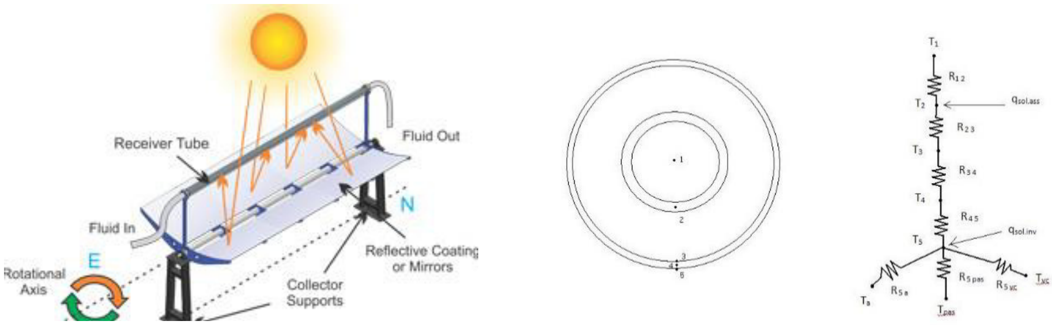

Fig. 1. a) Parabolic trough system. b) Analogue electrical circuit of a parabolic trough.

The heat transfer occurs according to the following mechanism: forced convection inside the absorber; radiation between the shell and the absorber, since the convective transfer can be neglected due to the vacuum, (possible infiltration and breakage of the shell are not considered); conduction in the radial direction inside the shell (conduction in the axial direction is neglected) and natural convection on the external surface of the shell.
For each node, the energy balance has been written:

$$\dot{m}_f\left(C_p T_{f0} - C_p T_1\right) + \frac{T_2 - T_1}{R_{12}} = 0 \quad (1)$$

$$\frac{T_1 - T_2}{R_{12}} + \frac{T_3 - T_2}{R_{32}} + Q_{sol,abs} = 0 \quad (2)$$

$$\frac{T_2 - T_3}{R_{23}} + \frac{T_4 - T_3}{R_{43}} = 0 \quad (3)$$

$$\frac{T_3 - T_4}{R_{34}} + \frac{T_5 - T_4}{R_{54}} = 0 \quad (4)$$

$$\frac{T_a - T_5}{R_{a5}} + \frac{T_{par} - T_5}{R_{par5}} + \frac{T_{sky} - T_5}{R_{sky5}} + \frac{T_4 - T_5}{R_{45}} + Q_{sol,shell} = 0 \quad (5)$$

The resistances have been calculated as reported in table 1. The required heat transfer coefficients have been determined by the Nusselt number obtained with the correlations reported in table 2 for both the base fluid and the nanofluids, as will be described in section 3; for the air instead the correlations of McAdams have been used [4].
The set of equation has been solved with the Gauss-Siedel method, through an iterative process, for each of the elements (dx), in which the parabolic trough has been discretized.

Table 1. Calculation of the resistances.

Heat Transfer Regime	Resistance
Convection resistance between the fluid and the absorber	$R_{12} = \frac{1}{h_{abs,f} \cdot \pi \cdot D_{abs,int} \cdot \Delta x}$

Radiation resistance between the absorber and the shell	$R_{23} = \dfrac{\dfrac{1}{\varepsilon_2} + \dfrac{1-\varepsilon_3}{\varepsilon_3} \cdot \dfrac{A_2}{A_3}}{5.67 \cdot 10^{-8} \cdot A_2 \cdot (T_2 + T_3) \cdot (T_2^2 + T_3^2)}$
Conduction resistance in the shell	$R_{34} = \dfrac{\log \dfrac{D_4}{D_3}}{2 \cdot \pi \cdot k_{shell} \cdot \Delta x}$ $R_{45} = \dfrac{\log \dfrac{D_5}{D_4}}{2 \cdot \pi \cdot k_{shell} \cdot \Delta x}$
Radiation resistance between the sky and the shell	$R_{sky5} = \dfrac{1}{5.67 \cdot 10^{-8} \cdot \varepsilon_{shell} \cdot (\pi + 2\theta) \cdot \dfrac{D_{inv,ext}}{2} \cdot \Delta x \cdot (T_5 + T_{sky}) \cdot (T_5^2 + T_{sky}^2)}$
Radiation resistance between the parabolic mirror and the shell	$R_{23} = \dfrac{\dfrac{1}{\varepsilon_5} + \dfrac{1-\varepsilon_{par}}{\varepsilon_{par}} \cdot \dfrac{A_5}{A_{par}}}{5.67 \cdot 10^{-8} \cdot A_5 \cdot (T_5 + T_{par}) \cdot (T_5^2 + T_{par}^2)}$ with $A_5 = (\pi + 2\theta) \cdot \dfrac{D_{shell,ext}}{2} \cdot \Delta x$ $A_{par} = (\pi + 2\theta) \cdot \dfrac{D_{par}}{2} \cdot \Delta x$
Convection resistance between the air and the shell	$R_{a5} = \dfrac{1}{h_{shell,a} \cdot \pi \cdot D_{shell,ext} \cdot \Delta x}$

3. Properties of the nanofluids

Many researchers have investigated the nanofluids properties, suggesting different correlations [2].

The correlations used in this work, based on that reported in [5] for a suspension of Al_2O_3 in synthetic oil, are summarized in table 2. They are valid for low particle volumetric concentration (ϕ), below 0.07.

Table 2. Correlations for the fluid\nanofluid properties.

Property	Correlation	Synthetic oil / Al_2O_3
Viscosity	$\mu_{nf} = (1 + 2{,}5\Phi)\mu_{bf}$ [m$Pa\ s$]	$\mu_{bf} = 98.8562 - 0.730924 \log T_f + 2.21917 \times 10^{-3} T_f^2 - 3.42377 \times 10^{-6} T_f^3 + 2.66836 \times 10^{-9} T_f^4 - 8.37194 \times 10^{-13} T_f^5$
Density	$\rho_{nf} = (1 - \Phi)\rho_{bf} + \Phi\rho_p$ $[\frac{kg}{m^3}]$	$\rho_p = 3850$ $\rho_{bf} = -0{,}9985 T_f + 1236$
Thermal Conductivity	$k_{nf} = k_{bf} \dfrac{k_p + 2k_{bf} - 2(1-\beta)^3 \Phi (k_p - k_{bf})}{k_p + 2k_{bf} + \Phi(1-\beta)^3 (k_p - k_{bf})}$ $[\frac{W}{mK}]$	$k_{bf} = -5.7534 \cdot 10^{-10} T_f^2 - 1.875266 \cdot 10^{-4} T_f + 1.900210 \cdot 10^{-1}$ $k_p = 5.5 + 34.5 e^{-0.0033 T_f}$
Heat Capacity	$c_{p,nf} = (1 - \Phi) c_{p,bf} + \Phi c_{p,p}$ $[\frac{kJ}{kgK}]$	$c_{p,bf} = 1.708 T_f + 1107.798$ $c_{p,p} = \left(22{,}08 + 0{,}008971 T_f - \dfrac{522500}{T_f^2}\right) \dfrac{4{,}186}{0{,}102}$
Attrition Factor	$f_{nf} = 0{,}3164 \mathrm{Re}^{-0{,}25} \left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{0{,}797} \left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{0{,}108}$	$f_{bf} = 0{,}184 \mathrm{Re}^{-0{,}2}$
Nusselt Number	$\boldsymbol{Nu_{nf} = 0{,}065(Re_{nf}^{0{,}65} - 60{,}22)(1 + 0{,}0169\phi^{0{,}15}) Pr_{nf}^{0{,}542}}$	$\boldsymbol{Nu_{bf} = 0{,}023 Re_{bf}^{0{,}8} Pr_{bf}^{0{,}33}}$

Based on these correlations the thermal conductivity (figure 2a), density (figure 2b), heat capacity (figure 3a) and viscosity (figure 3b) have been reported as a function of temperature and for different particle volumetric concentration.

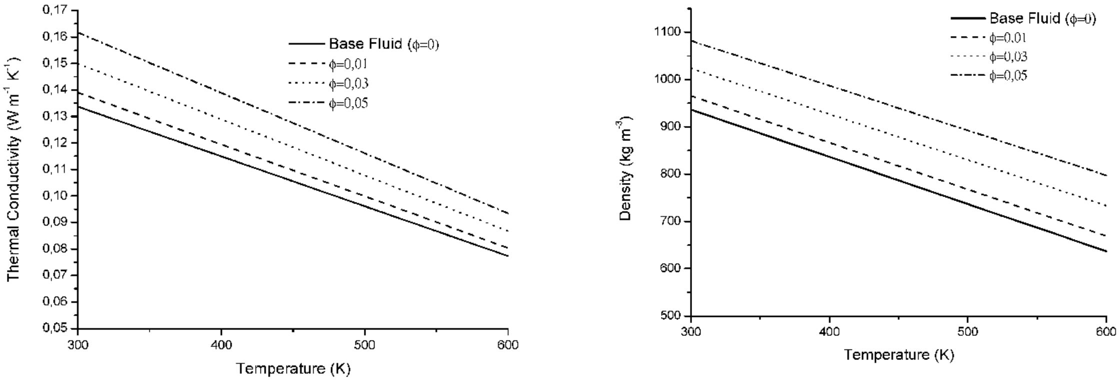

Fig. 2. a) Thermal conductivity. b) Density.

It would be important to focus the attention on the heat capacity and the thermal conductivity. In this particular case, at higher particle volumetric concentration, the former decreases while the latter increases. An opposite trend is also observed for the temperature, if the temperature increases the thermal conductivity decreases while the heat capacity increases.

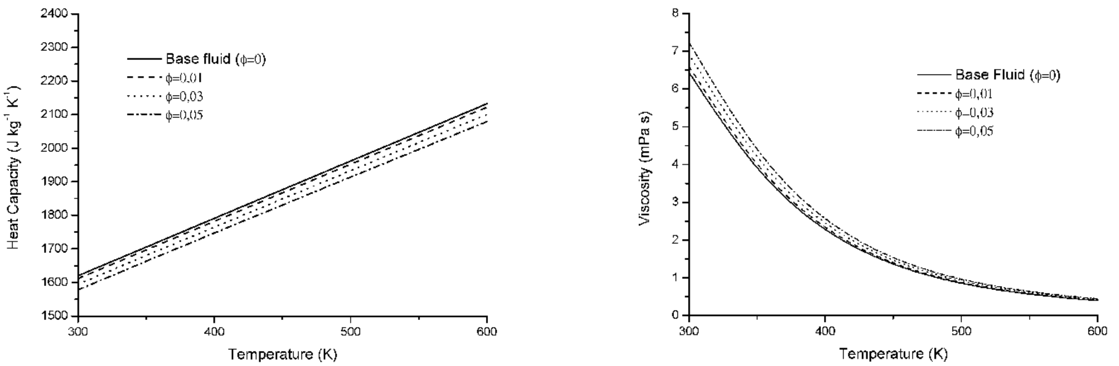

Fig. 3. a) Heat capacity. b) Viscosity.

These trends should be considered to analyse and understand the variation of the heat transfer coefficient. In fact, as described by Trisaksri [6], the higher thermal conductivity determines the enhancement of the heat transfer coefficient. Based on the correlations of the Nusselt number, reported in table 2, the ratio between the heat transfer coefficient of nanofluids and basic fluid has been obtained, through simple mathematical manipulations.

$$\frac{h_{nf}}{h_{bf}} = \frac{Nu_{nf} \cdot k_{nf}}{Nu_{bf} \cdot k_{bf}} = C \frac{c_{Pnf}^{\ 0.542}}{c_{Pbf}^{\ 0.33}} \frac{k_{nf}^{\ 0.458}}{k_{bf}^{\ 0.67}} \tag{6}$$

$$C = 2.8261 \cdot \left[\left(\frac{\pi D}{4\dot{m}} \right)^{0.15} \cdot (1 + 2.5\phi)^{-0.108} \cdot \mu_{bf}^{\;0.362} - 60.22 \cdot \left(\frac{\pi D}{4\dot{m}} \right)^{0.8} \cdot (1 + 2.5\phi)^{0.542} \cdot \mu_{bf}^{\;1.012} \right]$$

Equation 6 shows that the heat transfer coefficient is proportional to the nanofluid thermal conductivity and to the heat capacity. However, as already observed these two properties show an opposite trend in terms of both volumetric particle concentration and temperature variation, which is responsible of the different heat transfer performance of the nanofluid compared to the conventional synthetic oil.

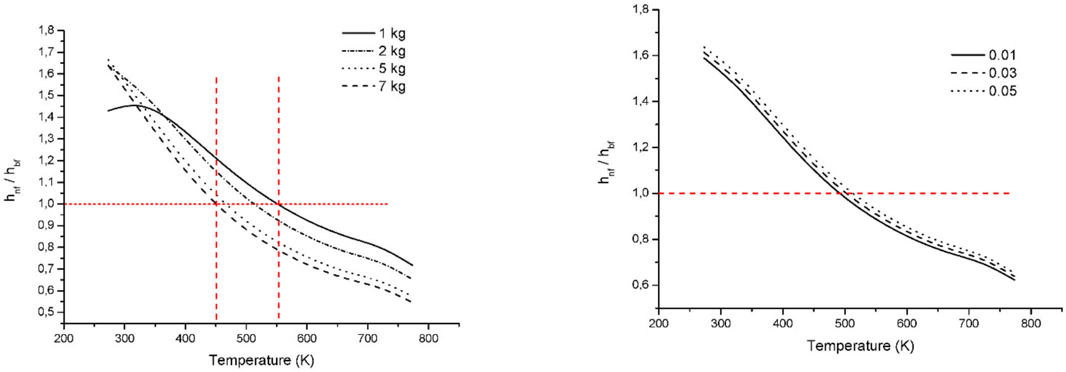

Fig. 4. a) Heat transfer coefficient ratio for different mass flow. b) Heat transfer coefficient ratio for different particle volumetric concentration

In particular, for the Al_2O_3-synthetic oil, three regions could be identified. The first one at low temperatures, in which the nanofluid shows a better heat transfer because of the effect of the higher thermal conductivity. A transitional region in which the value of the heat transfer coefficients depends on the amount of working fluid and a third region in which the heat transfer coefficient is lower than that of the basic fluid. It is evident that the advantage of using Al_2O_3-synthetic oil could be maximized operating at low temperatures. Figure 4b shows the heat transfer coefficient ratio for 2 kg of nanofluid and different particle volumetric concentration, underlining the increase of the heat transfer for higher amount of dispersed particles.

4. Model Results: trough system with nanofluids vs. basic fluids

The model described has been used to evaluate the use of Al_2O_3-synthetic oil and compare it with the traditional synthetic oil. The string has been assumed to have a length of 100 m and a concentrating surface area of 550 m^2. The absorber diameter was considered to be 0,065 m. The simulations have been carried out for different DNI (Direct normal irradiance).

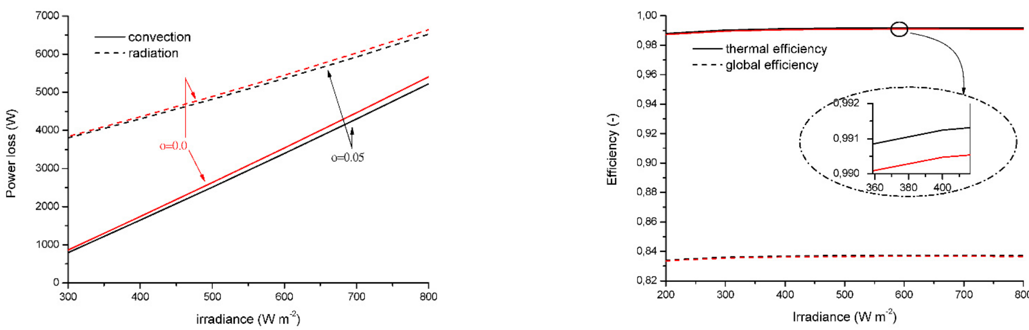

Fig. 5. a) Power loss vs. Irradiance. b) Efficiency vs. Irradiance

Figure 5 a) shows the power loss due to convection (solid line) and radiation (dash line) for both basic fluid and nanofluid. Only a slight reduction could be observed if a nanofluid with a particle concentration of 5% is used. This trend is confirmed by the thermal efficiency and the overall efficiency slightly increased by using Al_2O_3-synthetic oil. The main advantage of using nanofluids is the reduction of the pumping power.

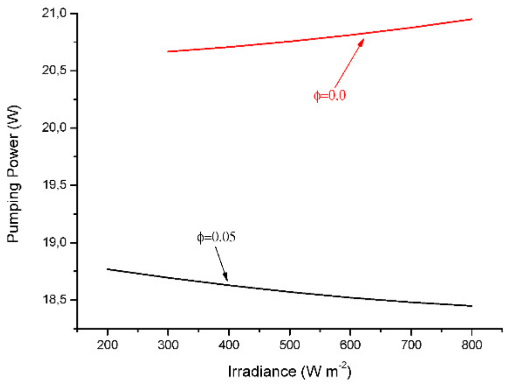

Fig. 6. a) Pumping Power vs. Irradiance.

Figure 6 highlights this reduction, which increase increasing the irradiance. The temperature profile and the heat transfer coefficient have been investigated. Figure 7 a) and b) show the obtained profile along the absorber. It is evident the higher heat transfer coefficient of the nanofluid, which is responsible of the lower ΔT between the fluid (T_f) and the tube (T_2).

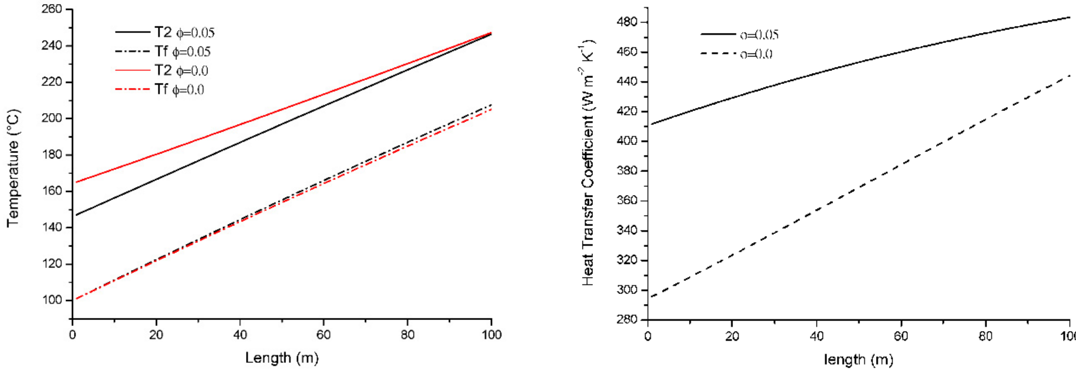

Fig. 7. a) Fluid and tube temperature vs. string length. b) Heat transfer coefficient vs. string length

5. Conclusions

The performances of a parabolic trough operating with Al_2O_3-synthetic oil have been analysed and compare to the more traditional ones using oil. The following variables and efficiency indicators have been checked: power loss, pumping power, thermal efficiency and overall efficiency of the parabolic trough system. Only slight differences have been observed for the power loss and the efficiency while main advantage is represented by the lower pumping power.

References

[1] Choi S.U.S., Eastman J.A.. Enhancing thermal conductivity of fluids with nanoparticles, in: Conference: 1995 International Mechanical Eengineering Congress and Exhibition, San Francisco, CA (United States), 12-17 Nov 1995, ASME, San Francisco, pp. 99–105, (1995).

[2] Ghadimi A., Saidur R., Metselaar H.S.C.. A review of nanofluid stability properties and characterization in stationary conditions. Int. J. Heat. Mass Transf., 54, pp. 4051–4068, (2011).

[3] Yu W., France D. M., Choi S. U. S., Routbort, J. L.. Energy Systems. Review and assessment of nanofluid technology for transportation and other applications. United States. doi:10.2172/919327, (2007).

[4] McAdams W.H.. Heat Transfer. 3rd Ed. McGraw-Hill, New York, (1954).

[5] Sokhansefat T., Kasaeian A.B., Kowsary F.. Heat transfer enhancement in parabolic trough collector tube using Al2O3/synthetic oil nanofluid. Renew Sustain Energy Rev, 33, pp. 636–644, (2014).

[6] Trisaksri V., Wongwises S.. Critical review of heat transfer characteristics of the nanofluids. Renew. Sustain. Energy Rev., 11, pp. 512–523, (2007).