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Thermosyphon effect in parabolic trough collector systems

Efecto termosifón en sistemas con colectores cilíndrico parabólicos

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RESUMEN

El efecto termosifón es un fenómeno de convección natural que le da a un fluido la posibilidad de circular dentro de un circuito cerrado sin ninguna fuente de bomba externa. En el presente artículo de investigación se realiza el análisis numérico y de simulación para verificar el comportamiento del efecto termosifón en diferentes fluidos de transferencia de calor, utilizando colectores cilindroparabólicos como sección de calentamiento del sistema. Además, se consideran las pérdidas por convección y radiación. Se obtiene que las simulaciones muestran variaciones en la densidad de los fluidos causadas por diferentes temperaturas y valores de calor específicos, alterando la velocidad del fluido dentro del sistema bajo las mismas condiciones iniciales.

ABSTRACT:

Thermosyphon effect is a natural convection phenomenon that gives a fluid the possibility to circulate inside a closed loop without any external pump sources. Numerical and simulation analysis are driven to check the behavior of thermosyphon effect in different heat transfer fluids, using parabolic trough collectors as the heating section of the system. Also, convection and radiation losses are considered. Simulations show variations in fluids density caused by different temperature and specific heat values, altering the velocity of the fluid inside the system with the same initial conditions.

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.1. Introduction

Nowadays, electric energy generation is not totally sustainable due to environmental issues and the ongoing scarcity of natural resources. One of the challenges of the twenty first century is to reduce the impact of the climate change through the design and implementation of renewable resources generation systems, mitigating the production of greenhouse effect gases and improving socio-economic aspects of the communities where these solutions are being installed, [1].

An important fact to highlight is that solar energy represents the second largest renewable source in the world, behind eolian, with a total production between 0,85% and 1% of world electricity demand that represented a total installed capacity of 139GW in 2013. That year was the first time the solar energy surpassed the eolian with an increment of 39 GW of installed capacity against 35 GW, [2].

The importance of these resources for energy generation is justifiable with the fact that 85% of the primary energy is generated using fossil fuels, representing a 57% of human emissions, that could be mitigated by installing or developing tools that exploits the virtually unlimited solar radiation, [3]. With the purpose of converting the energy radiated by the sun, the devices used can concentrate solar radiation to transform it into electricity by heating up a heat transfer fluid, usually carried inside a conductive material, to generate steam out of the system and propel a turbine, which will act as a generator to produce electricity, [4].

One of the motivations to create renewable sources systems for electricity generation is the fact that some communities are distant or decentralized to the electric grid, causing a problem when it comes to daily activities such as heating up food or supply power to electronic devices. Some researches, such as [5] and [6], show how in different regions like Colombia or Africa, there is a viability for the construction and usage of parabolic trough collectors on low cost and high efficiency.

Some other works are focused in the creation of a less polluting industry [7], or the sustainability of water resources in coastal regions through sea water desalination processes, [8]. With theoretical engineering points of view, some researches have analyzed and reviewed the existent technologies [9], as well as new proposals to improve already created devices with the usage of optimization and simulation [10], [11], aiming to enhance the performance. As a particular case for Colombia, there has been an important display of solar collectors for water heating in houses, hotels and hospitals over the past decades, [12], [13].

However, the associated costs of purchase and installation of these systems, plus the storage and backup needed, make it less viable to implement in contrast with natural gas, an economic solution for water heating. In another scenario, like petroleum liquid gas systems which its cost its significantly expensive, thermo-solar implementations are attractive specially in zones with high solar radiation like the coastal regions in Colombia, [14], [15].Some works are focused on tools for air conditioning, using the thermo-solar energy for heating and cooling tasks as presented in [16], where technical and economic barriers are exposed along with an analysis for future architecture development under the concept of solar cooling. Another related concept working with water heating or air conditioning is the heat transfer fluid transport inside these solar systems, where the thermosyphon effect comes up as a part of energy saving solution; this physical phenomenon is driven by buoyancy forces caused by fluids density variations in the system, making unnecessary the usage of external pumps in some applications, thus, saving electric energy, [17].

The following research shows the bulk velocity results of two different heat transfer fluid inside 3 linked parabolic trough collectors, driven by thermosyphon effect. The results were obtained by computational fluid dynamics simulations, considering radiation and convection heat losses.

2. Subject development

To understand how the parabolic trough collector works, geometric parameters and thermal performance are explained below.

2.1 Geometric model

To model the parabolic trough collector, geometric parameters such as focal distance, radius, length and minimum diameter of the receiver are needed. To calculate the parameters mentioned, are determined. Equation (1) shows how to calculate the focal distance f using W and φ.

$$f = \frac{W}{4\tan(\phi/2)} \quad (1)$$

Using the focal distance, the relation presented in (2) calculates the arc length L necessary to build the parable.

$$a = \sec(\phi/2)\, tan(\phi/2)$$

$$b = \ln(\sec(\phi/2) + tan(\phi/2))\; L = \quad (2)$$

$$(2f)(a + b)$$

Also, the radius r to every point at the parable is presented in (3) below, where focal distance and rim angle are considered.

$$r = (2f)/(1 + \cos(\phi)) \quad (3)$$

To finish with the geometric parameters necessary to build the collector, (4) presents how to estimate the minimum diameter d the receiver tube should have.

$$d = 2\, r \sin(0{,}2) \quad (4)$$

With the stablished parameters and the equations presented, table 1 shows the results of the evaluation for the respective construction with a computer assisted design software

Parameter	Value
Wide (W)	0,2 m
Length (L)	0,5 m
Rim Angle (ϕ)	90°
Focal Distance (f)	0,04 m
Arc Length (S)	0,24 m
Radius (r)	0,1015 m
Diameter (d)	7,94x10^{-4} m
Collector superficial area	0,1 m^2
Receiver superficial area	3,97x10^{-3} m^2

Table 1. Dimensions for the geometric design of the parabolic trough collector. Source: own.

Another important parameter considered for the parabolic trough collector is the concentration factor, which relates the area of the collector against the area of the receiver as (5) presents below.

$$C = A_c/A_r \quad (5)$$

2.2 Thermal performance

For this type of concentrating collectors, the direct radiation is the only one considered as the entrance of the system in form of heat as (6) presents below, where S_c is the collector superficial area, I_o is the direct radiation and θ is the incidence angle.

$$Q_{sol} = S_c I_o \cos(\theta) \quad (6)$$

As these devices present losses, the real heat entering the system should consider thermal and optical. Equation (7) presents the optic efficiency by considering material properties such as reflectivity, interception, transmissivity and absorptivity.

$$\eta_{opt} = \rho\gamma\tau\alpha \quad (7)$$

Thermal losses by radiation, convection and conduction are considered in the receiver tube and are grouped in a single constant value known as the heat transfer coefficient U_L Equation (8) also presents the temperature difference between the surface of the tube L and the air surrounding it, the length of the tube and the selected diameter for the receiver D.

$$Q_u = U_L \boldsymbol{\pi} DL(T_o - T_\infty) \quad (8)$$

As the heat losses occur due to changes in the characteristics of the air surrounding, conduction is less significant in comparison with convection and radiation. Also, when the air surrounding acquires velocity, the radiation losses are irrelevant too. Considering this, the convective coefficient is necessary to obtain the heat transfer coefficient as (9) shows.

$$h_o = N_u \frac{K_{air}}{D_0} \quad (9)$$

Where K_{air} is the air conductivity and N_u is the Nusselt number, which can be found on empirical correlations as presented in (10) below.

$$N_u = 1 + 1{,}44\left[1 - \frac{1.708}{R_a cos\theta}\right]\left\{1 - \frac{1.708(\sin 1{,}8\theta)^{1{,}6}}{R_a cos\theta}\right\} + \left[\left(\frac{R_a cos\theta}{5.830}\right)^{\frac{1}{3}} - 1\right] \quad (10)$$

This Nusselt correlation is recommended for any internal natural convection with $0 \leq \theta < 60°$ and $0 < R_a < 10^5$, where R_a is the Rayleigh number, the one that replaces Reynolds as there is no obvious characteristic velocity. This number is a function of Grashof number and

Prandtl as (11) shows below.

$$R_a = \frac{\beta \Delta T g L^3 P_r}{\mu} \tag{11}$$

Where $\beta = 1/T$ is the volumetric coefficient of expansion and relates the gradients of density caused by the gradients on temperature.

3. Materials

To develop the design of the parabolic trough collector, values presented in table 1 are needed along with the materials. For the receiver tube, cooper material with a conductivity of $K = 400 W/mK$ and a 5/16" diameter is selected, for the parable stainless steel with emissivity of $\varepsilon = 0{,}05$ and PCV for the storage tank. For the heat transfer fluids, water and refrigerant R134A were used.

4. Results analysis

As a first result, Figure 1 shows the computer assisted design of a single parabolic trough collector made with SolidWorks software considering the dimensions and materials selected before.

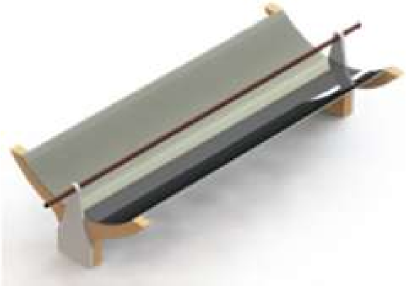

Figure 1. Parabolic trough collector designed in SolidWorks. Source: own

After the single collector is assembled, figure 2 presents three collectors linked in series as a tandem with the storage tank on top.

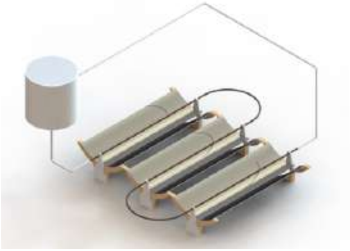

Figure 2. Tandem configuration assembled as a closed loop. Source: own.

To start the simulation process, initial conditions are set for the environment temperature at $293k$ in the storage tank and a direct radiation of $400\ W/M^2$.

The optic properties of the selected material have the following values: reflectivity of $\rho = 0{,}9$, interception of $\gamma = 0{,}95$ transmissivity of $\tau = 0{,}8$ and absorptivity of $\alpha = 0{,}9$. Using (6) and (7), the real heat entrance after optic losses for the collector area is $24\ W$, and, considering the concentration factor given in (5), $C = 25$ so the concentrated heat in the receiver should be $600\ w$.

Figure 3 presents the temperature distribution inside the collectors tandem, using water as heat transfer fluid, after the complement Flow Simulation finished the calculation.

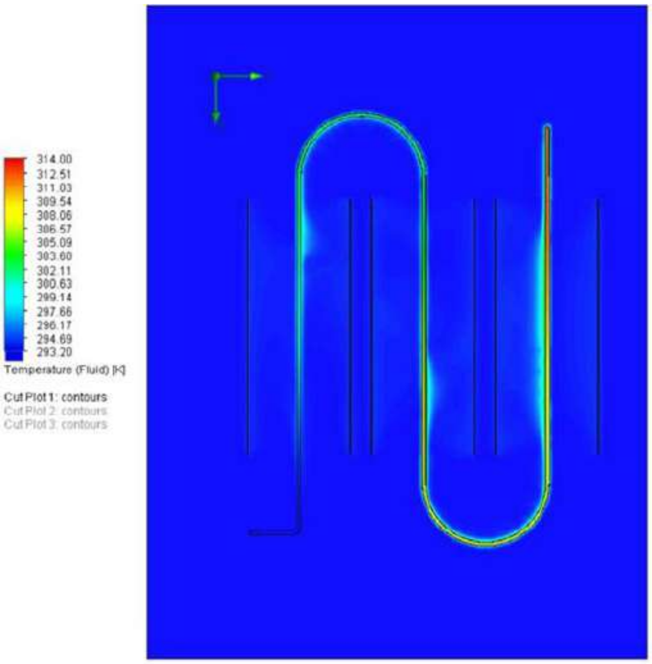

Figure 3. Water temperature variation along the system (Top plane view). Source: own

As expected, the heat transfer fluid starts at the initial condition defined for the storage tank, and after the radiative heating process, reaches to a peak temperature of $314\ k$ at the exit, leading this to a $\Delta T = 20k$. With this temperature variation, density changes too, as figure 4 presents below.

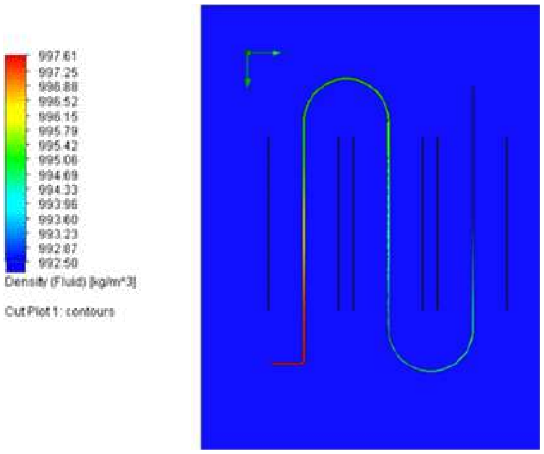

Figure 4. Water density variation (Top plane view). Source: own

The total density difference is about 5 *kg/m3* in the system, less than 1% variation, but is still enough for buoyancy forces to appear in the fluid, generating the thermosyphon effect. In Figure 5 this phenomenon is presented as velocity variations through the system.

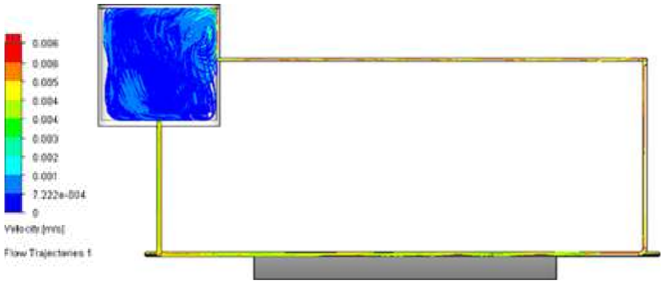

Figure 5. Velocity of the fluid (lateral plane). Source: own.

The top speed reached by the water is 0,006 *m/s*, which is pretty slow in comparison with the usage of an external pump but accomplishes the objective of transporting heat through the system without requiring extra energy. Figure 6 shows fluids velocity in the entire system with an isometric view.

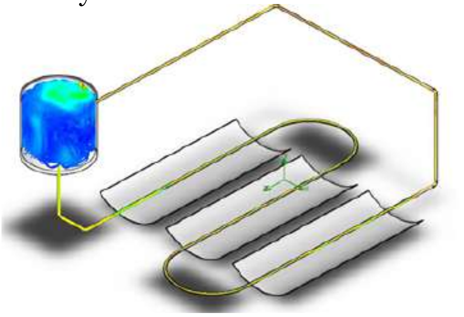

Figure 6. Velocity of the heat transfer fluid (Isometric view). Source: own.

Same procedure is made for the refrigerant R134A which presents different specific heat and density variations caused by temperature. Also, the same initial conditions are defined for the storage tank and the solar radiation heating section. As a first result for this heat transfer fluid, temperature distribution is presented in figure 7.

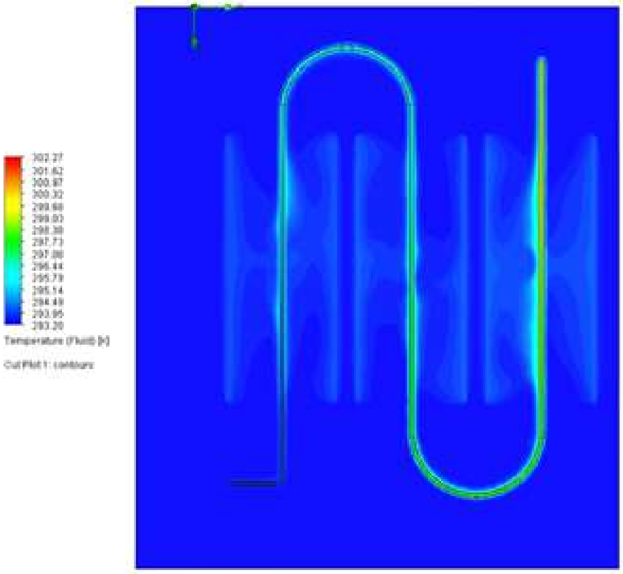

Figure 7. Temperature distribution for refrigerant R134A (Top Plane). Source: own.

The peak temperature for this fluid on the same initial conditions is 302*k*, way lower than the water case. However, density changes in the fluid are more significant as figure 8 presents below. Another interesting aspect of this figure is how the external air surrounding the receiver gets heated due to radiative and convective phenomenon.

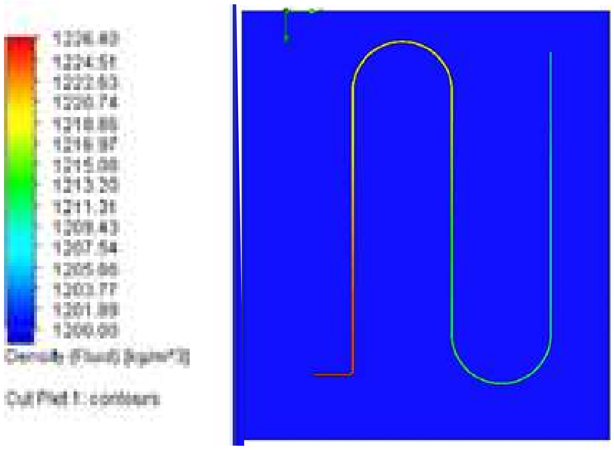

Figure 8. Refrigerant density variation (Top view). Source: own

For this case, the total density variation was about 20 KGM^3, at least four times bigger than waters density variation. This represents greater buoyancy forces driven the natural convection phenomenon, leading to greater velocities in the fluid. Figure 9 shows a velocity lateral view of the fluid in the system.

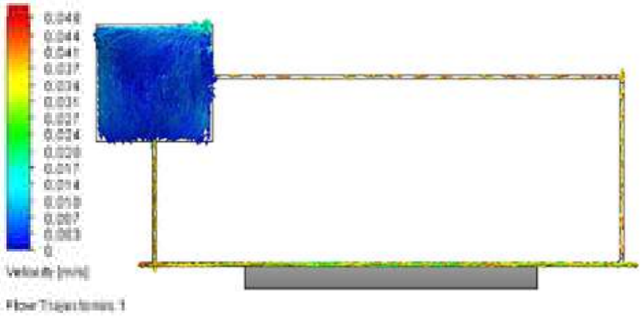

Figure 9. Fluids velocity for refrigerant system (Lateral view). Source: own.

As expected, the velocity for the refrigerant is greater, reaching a peak value of 0,048 *m/s*. To observe in which section of the system the fluid reaches that value, figure 10 is presented below.

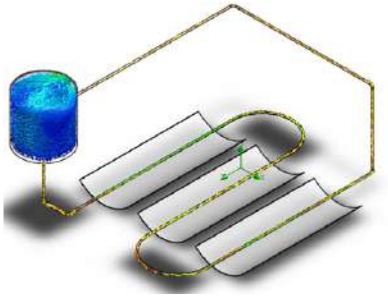

Figure 10. Velocity for the refrigerant heat transfer fluid (Isometric view). Source: own.

The maximum values of fluids velocity are presented in the heating section and the right leg, where the fluid is going up.

To compare the results explained and observe during this work, table 2 below summarizes the data acquired from simulations.

	WATER	R134A
Specific Heat	4.183 *J/Kg K*	1.412 *J/Kg K*
Δ_T	20 *K*	10 *K*
Δ_ρ	5 Kg/m^3	20,56 Kg/m^3
Velocity	0,006 *m/s*	0,048 *m/s*

Table 2. Comparison between results for water and refrigerant. Source: own.

4. Conclusions

Despite the fact both systems had the same geometric parameters, materials and initial conditions, specific properties of the fluid such as density and viscosity (temperature dependent) are the ones that will drive the natural convection phenomenon and so on the heat transport in the closed loop.

To emphasize on how thermosyphon effect occurs in thermo-solar devices such as parabolic trough collectors, two heat transfer fluids were tested, analyzing the velocities they acquire due to heating-cooling sections. As a comparison between the selected fluids, the refrigerant presented a velocity (v = 0,048 *m/s*) 8 times greater than the water (v = 0,006 *m/s*) as a result of density variations, which for the 134A was 4 times bigger than the water. With this simulation results can be concluded that, even if water is commonly used as a heat transfer fluid, there exists some other alternatives that have better performance for solar applications.

Even when this work did not study thoroughly the heat and optical losses, one of the critical factors in these kinds of applications is to reduce them, enhancing the efficiency of the entire system. Some other factors to be studied is the vortices or geysering that occurs in the fluid even when its driven by thermosyphon effect.

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