e-ISSN:2706-6800

Research Open Access

Correspondence:

SIMULACIÓN DE UN COLECTOR SOLAR CILINDROPARABÓLICO DESARROLLADO EN INGENIERÍA EQUATION SOLVER

SIMULATION OF A PARABOLIC TROUGH SOLAR COLLECTOR DEVELOPED IN ENGINEERING EQUATION SOLVER

Ernesto Ruano
Universidad Técnica Estatal de Quevedo, Quevedo – Ecuador
ernjav@gmail.com
http://orcid.org/0000-0002-7114-3792

Miguel Socasi
Universidad Técnica Estatal de Quevedo, Quevedo – Ecuador
msocasi@uteq.edu.ec
http://orcid.org/0000-0003-2339-8800

Resumen

El presente estudio trata de determinar la eficiencia térmica de un colector solar cilindroparabólico en condiciones no ideales (condiciones no muy cercanas a las del estado del arte). Es decir, se considerarán algunas condiciones como alta velocidad del viento, bajo o nulo vacío en el espacio anular del HCE (presión atmosférica o vacío parcial, 10 kPa), propiedades radiativas de los materiales inferiores a las actuales más altas, entre otras que se especificarán. Sin embargo, las dimensiones del colector, especialmente del HCE, están basadas en las medidas estándar del colector cilindroparabólico tipo LUZ LS-3. Además, a diferencia de otros estudios, no considera flujos de calor por unidad de longitud, sino flujos de calor para una determinada longitud de HCE (4 metros). La simulación se realizó en el programa EES (Engineering Equation Solver), considerando que EES tiene una gran base de datos de propiedades térmicas y físicas de muchos fluidos. EES puede incorporar tablas de búsqueda para interpolar y recuperar propiedades de fluidos no incluidos en las bases de datos (en este caso, para los HTF analizados: Therminol VP-1 y Syltherm 800). El modelo matemático se escribió en EES y se creó una ventana de diagrama para ingresar los valores de entrada y mostrar las respuestas de salida. Las ecuaciones se basan en modelos típicos de transferencia de calor [Forristal, 2003, Incropera, 2006]. Se puede afirmar, como se evidenció, que la eficiencia se reducirá a medida que aumente la temperatura del HTF debido a las pérdidas térmicas.

Palabras clave Cilindroparabólico, energía solar, colector solar concentrado, energía solar térmica, EES

Article

Abstract
The present study tries to determine the thermal efficiency of a solar parabolic trough collector under non ideal conditions (conditions not too close to the state-of-the-art). Namely, it will be considered some conditions like high wind velocity, low or no vacuum in the HCE annular space (atmospheric pressure or partial vacuum, 10 kPa), materials' radiative properties lower than the current highest, among others that will be specified. However, the collector's dimensions, specially from the HCE, are based on the standard measurements of the parabolic trough collector LUZ LS-3 type. Moreover, unlike other studies, it doesn't consider heat fluxes per length unit, it rather considers heat fluxes for a determined HCE length (4 meters). The simulation was performed on the EES (Engineering Equation Solver) program, considering that EES has a large database of thermal and physical properties of many fluids. EES can incorporate Lookup tables to interpolate and recall properties for fluids not included on the databases (in this case for the analyzed HTFs: Therminol VP-1 and Syltherm 800). The mathematical model was written on EES, and a Diagram Window was created to enter the input values and show the output answers. The equations are based on typical heat transfer models [Forristal, 2003, Incropera, 2006]. It can be stated, as was evidenced, that the efficiency will be reduced as the HTF's temperature increases because of the thermal losses.
Keywords Parabolic trough, solar energy, concentrated solar collector, thermal solar energy, EES

Introducción

A parabolic trough solar collector is a technology of concentrated thermal solar energy. It is based on a parabolic curved mirror that concentrate the rays of beam solar radiation on a focal line where is located the heat collector element (HCE). The HCE takes out part of the solar energy and transfers it to a fluid, the HTF. To allow the concentration of beam radiation on the focal line, it is necessary that the parabolic trough tracks the Sun direction. Thus, must have a continuous rotation of the parabolic trough that align the parable symmetry line to the beam radiation rays.

The absorber tube (part of the HCE), located on the focal line of the parabolic trough could suffer high thermal losses because of radiation with the surroundings and convection with the external winds, losing part of the heat gained because of the geometrical concentration. For this reason, there's an external glass envelope that encloses the absorber tube. Then, the arrange (absorber – envelope) is concentrical. Moreover, is highly beneficial that the annular space between the absorber and the envelope experiences vacuum. This characteristic reduces the heat losses.

Considering that in a solar field with parabolic trough collectors, the heat transfer fluid (HTF) circulates from collector to collector (in a series arrangement), the HTF input temperature in each individual collector will be different because the HTF heats up as it advances through the collectors arrange. For this reason, the amount of heat gained by the HTF passing through each individual collector gradually decreases and the efficiency do too.

1.1 Glossary

- HTF: heat transfer fluid. It is the liquid that is heated internally and carries the gained heat to the rest of the energy generation system. Generally, these systems work on organic Rankine cycle and have heat exchangers for refrigerants (organic fluids) get energy from the HTFs.
- HCE: heat collector element. It is the part of the parabolic trough where the concentrated solar radiation is transmitted, and “collected” as heat. The HCE is composed by a metallic tube called absorber tube inside a transparent special glass tube, called glass envelope.
- Absorber tube: is a metallic tube with a high absorptance selective surface (the HTF flows internally through this tube).
- Glass envelope: is a transparent special glass tube with high transmittance for solar radiation. The absorber tube is assembled inside the glass envelope.
- Annular space: the space between the absorber tube and the glass envelope. Ideally, it would have a high vacuum pressure.

Materiales y métodos

2. MATHEMATICAL MODEL

NOTE: not all the equations of the mathematical model are displayed on the paper, only the main equations are not shown, i.e. are not described formulas for the cilindrical areas, formulas for the nondimensional numbers (Reynolds, Prandtl, Nusselt, etc.). If they were included the extension of the paper will increase a lot. However, all the necessary equations were included on the EES calculations.

The mathematical model considers the heat transfer between the two main parts of the HCE: absorber tube and glass envelope, and the surroundings, i.e., the transfer with the HTF (internal convection), with the air and the surroundings (external forced convection and external radiation), and absorber – envelope transfer (radiation and convection in the annular space, no vacuum or partial vacuum). The conduction heat loss between the HCE and the collector’s structure or other elements is neglected because there are no exact criteria about the structure and its conduction, and the conduction losses have been estimated as low percentages. The used equations are based on known heat transfer expressions.
The simulation of the model was performed in the EES (Engineering Equation Solver) software. An energetic balance of the absorber tube was performed separately from the balance of the glass envelope, with the objective of solving not only the individual heat fluxes, but the inner and outer temperatures of both elements (absorber tube and glass envelope). It is important to state that uniform temperatures are considered on the radial surfaces, i.e., the longitudinal temperature gradients are neglected, but not the radial gradients. For example, the inner temperature of glass envelope is considered uniform for a single HCE (4 m length). Although in practice it is not entirely true, the HTF flowing through the 4 m length HCE increases its temperature in a value less than 2 °C, and for this reason it’s not generated an important longitudinal temperature gradient on the two main element of the HCE. This small

gradient could be determined in another specialized FEM simulation software for a single HCE, but in an arrangement of collectors it results complex, then, this longitudinal gradient will be neglected in the absorber and the envelope. In the same way, most properties of the absorber tube, the glass envelope, the HTF, the external air and the annular air like thermal conductivity, C_P, density, etc. will be calculated also as bulk parameters, i.e., the properties are determined with the mean temperatures, as material functions in the EES.

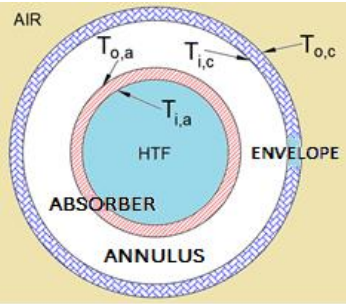

Fig. 1: HCE section view with characteristic temperatures

The characteristic temperatures of the absorber tube and glass envelope are:

T_{o_a}: absorber tube outer surface temperature
T_{i_a}: absorber tube inner surface temperature
T_a: mean absorber tube temperature

$$\mathbf{T_a = \frac{T_{o_a}+T_{i_a}}{2}} \quad \textbf{(1)}$$

T_{o_c}: glass envelope outer surface temperature
T_{i_c}: glass envelope inner surface temperature
T_c: mean glass envelope temperature

$$\mathbf{T_c = \frac{T_{o_c}+T_{i_c}}{2}} \quad \textbf{(2)}$$

The characteristic diameters of the absorber tube and glass envelope are:

d_{o_a}: absorber tube outer diameter
d_{i_a}: absorber tube inner diameter

d_{o_c}: glass envelope outer diameter
d_{i_c}: glass envelope inner diameter

2.1 Absorber tube

This tube receives radiation intercepted by the collector, reflected by the parabolic mirror, transmitted by the glass envelope, and absorbed by the absorber's outer surface ($\dot{\mathbf{Q}}_{\mathbf{r_{in,a}}}$). Thermal losses are radiation and convection heat fluxes inside the annular space toward the glass envelope ($\dot{\mathbf{Q}}_{\mathbf{r_{an}}}$, $\dot{\mathbf{Q}}_{\mathbf{c_{an}}}$), considering that in normal operation the absorber will be hotter than the envelope. The difference between gain radiation and heat losses, will be the convection heat flux gained by the HTF flowing through the absorber tube ($\dot{\mathbf{Q}}_{\mathbf{c_{int,a}}}$). The conduction heat flux between the inner and outer absorber tube walls ($\dot{\mathbf{Q}}_{\mathbf{k_a}}$) will determine the absorber tube inner and outer surface temperatures.

$$\dot{\mathbf{Q}}_{\mathbf{r_{in,a}}} - \dot{\mathbf{Q}}_{\mathbf{r_{an}}} - \dot{\mathbf{Q}}_{\mathbf{c_{an}}} = \dot{\mathbf{Q}}_{\mathbf{c_{int,a}}} \quad \textbf{(3)}$$

$\dot{Q}_{r_{in,a}}$: radiation heat flux entering absorber / $\dot{Q}_{r_{an}}$: radiation heat flux lost toward envelope (annular) / $\dot{Q}_{c_{an}}$: convection heat flux lost toward envelope (annular) / $\dot{Q}_{c_{int,a}}$: convection heat flux gained by HTF

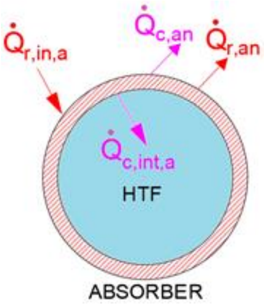

Fig. 2: Absorber tube heat fluxes

Below, the formulas of the absorber heat fluxes are detailed:

$$\dot{\mathbf{Q}}_{\mathbf{r_{in,a}}} = \mathbf{A_a} . \mathbf{G_b} . \boldsymbol{\eta}_{\mathbf{int}} . \boldsymbol{\rho}_{\mathbf{m}} . \boldsymbol{\tau}_{\mathbf{c}} . \boldsymbol{\alpha}_{\mathbf{a}} \quad \textbf{(4)}$$

A_a: collector aperture area / G_b: beam radiation received on collector aperture plane / η_{int}: collector intercept efficiency / ρ_m: mirror reflectance / τ_c: glass envelope transmittance / α_a: absorber tube absorptance

$$\dot{\mathbf{Q}}_{\mathbf{r_{an}}} = \frac{\sigma . \mathbf{A_{o_a}} . \left(\widehat{\mathbf{T_{o_a}}}^{4} - \widehat{\mathbf{T_{i_c}}}^{4}\right)}{\frac{1}{\varepsilon_a} + \frac{1-\varepsilon_c}{\varepsilon_c}\left(\frac{\mathbf{d_{o_a}}}{\mathbf{d_{i_c}}}\right)} \quad \textbf{(5)} \quad \textbf{[Incropera, 2006]}$$

σ: Steffan-Boltzmann constant / A_{o_a}: absorber tube external area / ε_c: glass envelope emittance / ε_a: absorber tube emittance

$$\dot{\mathbf{Q}}_{\mathbf{c_{an}}} = \mathbf{L} \frac{\mathbf{2{,}425 . k_{an}} \left(\mathbf{T_{o_a}} - \mathbf{T_{i_c}}\right)}{\left[1 + \left(\frac{\mathbf{d_{o_a}}}{\mathbf{d_{i_c}}}\right)^{0{,}6}\right]^{1{,}25}} \left(\frac{\mathbf{Pr_{an} . Ra_{o_a}}}{\mathbf{0{,}861 + Pr_{an}}}\right)^{\mathbf{0{,}25}} \quad \textbf{(6)}$$

L: HCE length / k_{an}: annular air conductivity / Pr_{an}: annular air Prandtl number / Ra_{o_a}: Rayleigh number at temp. T_{o_a}

$$\dot{\mathbf{Q}}_{\mathbf{c_{int,a}}} = \mathbf{h_{int_a}} . \mathbf{A_{i_a}} . \left(\mathbf{T_{i_a}} - \mathbf{T_m}\right) \quad \textbf{(7)}$$

h_{int_a}: internal convection coefficient between absorber and HTF / A_{i_a}: absorber tube internal area

The heat flux gained by the HTF ($\dot{Q}_{HTF}$) must be equal to the lost heat flux by the absorber internal convection ($\dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{int,a}}}$). In the same way, this convection heat flux must be equal to the conduction heat flux between the external and internal absorber walls ($\dot{Q}_{k_a}$), this is useful to determine the temperature difference between T_{o_a} and T_{i_a}.

$$\dot{\mathbf{Q}}_{\mathbf{HTF}} = \dot{\mathbf{m}}.\mathbf{C_P}(\mathbf{T_f} - \mathbf{T_0}) = \dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{int,a}}} \ \mathbf{(8)}$$

$\dot{m}$: HTF mass flow / C_P: HTF specific heat at constant pressure / T_0: HTF temperature at absorber inlet (for 1 individual HCE) / T_f: HTF temperature at absorber outlet (for 1 individual HCE)

$$\dot{\mathbf{Q}}_{\mathbf{k_a}} = \frac{\mathbf{2\pi.k_s}}{\mathbf{ln}\left(\frac{\mathbf{d_{o_a}}}{\mathbf{d_{i_a}}}\right)} = \dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{int,a}}} \ \mathbf{(9)}$$

k_s: absorber tube wall conductivity

The convection coefficient between the HTF and the absorber inner surface is calculated like this:

$$\mathbf{h_{int_a}} = \mathbf{Nu_{HTF}} \frac{\mathbf{k_{HTF}}}{\mathbf{d_{i_a}}} \ \mathbf{(10)}$$

$$\mathbf{Nu_{HTF}} = \left[\frac{\frac{f}{8}(\mathbf{Re}-\mathbf{1000})\mathbf{Pr_{HTF}}}{\mathbf{1+12,7}\sqrt{\frac{f}{8}}(\mathbf{Pr_{HTF}}^{2/3}-\mathbf{1})}\right]\left(\frac{\mathbf{Pr_{HTF}}}{\mathbf{Pr_i}}\right)^{\mathbf{0,11}} \ \mathbf{(11)}$$

Nu_{HTF}: HTF Nusselt number / k_{HTF}: HTF conductivity / Re: HTF Reynolds number / Pr_{HTF}: HTF Prandtl number / f: HTF flow friction factor / Pr_i: HTF Prandtl number at temperature T_{i_a}

2.2 Glass envelope

This transparent tube allows that most of the received solar radiation can be transmitted toward the absorber tube. However, a small portion of radiation is absorbed by the envelope ($\dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{in,c}}}$). In the same way, it exists a small gain of heat on the glass by radiation and convection through the annular space ($\dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{an}}}$, $\dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{an}}}$) because the absorber is at higher temperature than the glass envelope. The envelope thermal losses are generated by the forced convection of the external wind ($\dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{ext,c}}}$) and the radiation toward the surroundings ($\dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{out,c}}}$), colder than all the HCE elements. These losses are the main losses of the collector system and must be reduced to increase the efficiency. This is the main reason to have a glass envelope enclosing the absorber.

$$\dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{in,c}}} + \dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{an}}} + \dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{an}}} - \dot{\mathbf{Q}}_{\mathbf{c}_{\mathbf{ext,c}}} - \dot{\mathbf{Q}}_{\mathbf{r}_{\mathbf{out,c}}} = \mathbf{0} \ \mathbf{(12)}$$

$\dot{Q}_{r_{in,c}}$: radiation heat flux entering envelope / $\dot{Q}_{r_{an}}$: radiation heat flux gained from absorber (annular) / $\dot{Q}_{c_{an}}$: convection heat flux gained from absorber (annular) / $\dot{Q}_{c_{ext,c}}$: air – absorber convection heat flux / $\dot{Q}_{r_{out,c}}$: radiation heat losses to surroundings

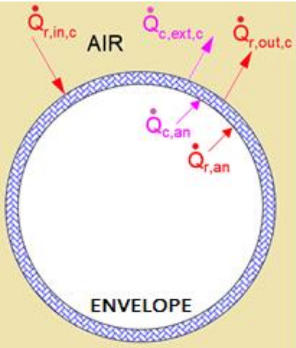

Fig. 3: Glass envelope heat fluxes

Below, the formulas of the glass envelope heat fluxes are detailed:

$$\dot{\mathbf{Q}}_{\mathbf{r_{in,c}}} = \mathbf{A_a . G_b . \eta_{int} . \rho_m . \alpha_c} \ \textbf{(13)}$$

A_a: collector aperture area / G_b: beam solar radiation received on collector plane / η_{int}: collector intercept efficiency / ρ_m: mirror reflectance / α_c: envelope absorptance

$$\dot{\mathbf{Q}}_{\mathbf{c_{ext,c}}} = \mathbf{h_{ext_c} . A_{o_c} . \left(T_{o_c} - T_s\right)} \ \textbf{(14)}$$

h_{ext_c}: external convection coefficient between air and envelope / A_{o_c}: glass envelope external area

$$\dot{\mathbf{Q}}_{\mathbf{r_{out,c}}} = \boldsymbol{\sigma} . \boldsymbol{\varepsilon}_{\mathbf{c}} . \mathbf{A_{o_c}} . \left(\widehat{\mathbf{T_{o_c}}}^{\mathbf{4}} - \widehat{\mathbf{T_s}}^{\mathbf{4}}\right) \ \textbf{(15)}$$

σ: Steffan-Boltzmann constant / ε_c: glass envelope emittance / A_{o_c}: glass envelope external area

It must be considered the conduction heat flux between the internal and external absorber surfaces ($\dot{Q}_{k_c}$) to determine the difference between the temperatures T_{i_c} and T_{o_c}:

$$\dot{\mathbf{Q}}_{\mathbf{k_c}} = \frac{\mathbf{2\pi . k_g \left(T_{i_c} - T_{o_c}\right)}}{\mathbf{ln\left(\frac{d_{o_a}}{d_{i_a}}\right)}} \ \textbf{(16)} \quad \textbf{[Incropera, 2006]}$$

k_g: glass envelope conductivity

Using the concept of thermal resistances, it's possible to relate the absorber conduction heat flux ($\dot{\mathbf{Q}}_{\mathbf{k_c}}$) with the convection and radiation heat fluxes from the glass envelope toward the surroundings ($\dot{\mathbf{Q}}_{\mathbf{c_{ext,c}}}$, $\dot{\mathbf{Q}}_{\mathbf{r_{out,c}}}$):

$$\mathbf{\dot{Q}_{k_c} = \dot{Q}_{c_{ext,c}} + \dot{Q}_{r_{out,c}}} \quad \textbf{(17)}$$

The convection coefficient between external air and envelope external surface is calculated then:

$$\mathbf{h_{ext_c} = Nu_c \frac{k_{air}}{d_{o_c}}} \quad \textbf{(18)}$$

$$\mathbf{Nu_c = C.\,Re_{air}{}^{m}.\,Pr_{air}{}^{n}\left(\frac{Pr_{air}}{Pr_c}\right)^{0,25}} \quad \textbf{(19)} \quad \textbf{[Incropera, 2006]}$$

Nu_c: external air Nusselt number / k_{air}: external air conductivity / Re_{air}: external air Reynolds number / Pr_{air}: external air Prandtl number / Pr_c: HTF Prandtl number at temperature T_{o_c}

The constants C and m are determined on the next table, as a function of the Reynolds number:

Re	**C**	**m**
1 – 40	0,75	0,4
40 – 1 000	0,51	0,5
1 000 – 20 000	0,26	0,6
20 000 - 10^6	0,076	0,7

The constant n value depends on the Prandtl number, with two possibilities:

Pr	**n**
≤10	0,37
>10	0,36

3. INPUT PARAMETERS

Because of the model's complexity and some characteristics of the operation of parabolic trough solar systems, it has been selected some typical input parameters. The values showed on the next table, has been selected based on state-of-the-art criteria, an extensive bibliographic review, and proper decisions of conservative type. The criteria that justify these selections are indicated:

INPUT CONDITIONS	CRITERIA	REF.
Flux		
$\dot{m}$ = 8 kg/s	Approximated HTF mass flow for a volumetric flow rate of 160 gpm	**[Forristal, 2003]**
T_o between 540 to 665 K (267 – 392 °C)	Operative input temperature ranges for the parabolic trough arrangements in energetic plants	**[Fernández-G. 2010]**
G_b between 500 to 1000 W/m^2	Beam solar radiation, from medium level (500 W/m^2) to high normal level (1000 W/m^2) (on aperture plane)	
HTFs		
Therminol VP-1 Syltherm 800	Most used HTF fluids on parabolic trough collectors that comply the selected temperatures	**[Therminol, DOW]**
External conditions		
v_{air} = 10 m/s	The selected air velocity corresponding to strong winds that increase the convection heat losses	
$T_s = T_{air}$ = 293 K = 20 °C	For simplification, surroundings temp. is considered the same as air temp., using standard value of 20 °C	**N/A**
Annulus pressure		
101,3 kPa / 10 kPa	It was considered the values of 101,3 kPa (P atm), no vacuum on envelope – absorber annular space; and 10 kPa, partial vacuum on annular space.	**N/A**
Convection coefficients		
h_{ext_c} ITERATIVE h_{int_a} ITERATIVE	Values for h_{ext_c} and h_{int_a} are unknown, however, approximated values are assumed. After, iterations are performed until the assumed approach the calculated values	**N/A**
Radiative properties		
Mirror ρ = 0,94 / η_{int} = 0,9	Conservative values as compared to the state-of-art η_{int} refers to the collector intercept efficiency	**[Zaaraoui, 2011]**
Glass envelope α_c = 0,02 / τ_c = 0,93 / ε_c = 0,86	Conservative values for absorptance, transmittance and emittance as compared to the state-of-the-art values	
Absorber tube α_a = 0,92 / ε_a = 0,15	Conservative values for absorptance and emittance as compared to the state-of-the-art values	
Geometry		
Mirror b = 5,76 m L = 4 m (for a single HCE)	Luz LS-3 collector geometry	**[Fernández-G., 2010, Zaaraoui, 2011, Eckhard 2001]**
Glass envelope d_{o_a}= 115 mm / d_{i_c}= 109 mm **Absorber tube** d_{o_a}= 70 mm / d_{i_a}= 66 mm	Standard diameters of the HCE elements (Luz LS-3)	

4. OUTPUT PARAMETERS

After entering the input parameters (data), the EES programing calculate the output parameters (answers). The calculations based on the mathematic model equations. The output variables are:

- Incident beam radiation energy on the collector aperture plane (E_0)
- HTF volumetric flow rate ($\dot{V}$)
- Characteristic temperatures of each HCE section (absorber external surface T_{o_a}, absorber internal surface T_{i_a}, absorber mean temperature T_a, envelope external surface T_{o_c}, envelope internal surface T_{i_c}, mean envelope temperature T_c)
- Properties and nondimensional numbers for HTF internal flow (Nu_{HTF}, k_{HTF}, Pr_{HTF}, Re, f, Pr_i)
- Properties and nondimensional numbers for air external flow (Nu_c, k_{air}, Re_{air}, Pr_{air}, Pr_c, C, m, n)
- Prop. and nondim. numbers for air natural convection inside the annular space (k_{an}, Pr_{an}, Ra_{o_a})
- Convection coefficient between the HTF internal flow and the absorber internal surface (h_{int_a})
- Convection coefficient between the air external flow and the envelope external surface (h_{ext_c})
- Pressure loss of the HTF internal flow (ΔP)
- All the mentioned heat fluxes ($\dot{Q}_{r_{in,a}}$, $\dot{Q}_{r_{an}}$, $\dot{Q}_{c_{an}}$, $\dot{Q}_{c_{int,a}}$, $\dot{Q}_{HTF}$, $\dot{Q}_{k_a}$, $\dot{Q}_{r_{in,c}}$, $\dot{Q}_{c_{ext,c}}$, $\dot{Q}_{r_{out,c}}$, $\dot{Q}_{k_c}$)
- Thermal efficiency $\left(\eta_t = \frac{\dot{Q}_{HTF}}{E_0}\right)$

Resultados

According to the calculations, the obtained results don't show contradictory values and the numbers complete the respective summations of the energetic balances, the gained and lost heat fluxes. In the same way, the obtained temperatures keep a logical relationship between them.

As an example, below is shown a screenshot with part of the results (heat fluxes, temperatures, and efficiencies), for the next data: HTF temp. at absorber inlet of 600 K, G_S 500 W/m^2, 8 kg/s mass flow of Therminol VP-1, annulus pressure of 10 kPa and another data previously indicated (including geometric data). It is important to note that the thermal efficiency was 60,77% and the HTF temperature at absorber outlet (for a single HCE) was 600,4 K (it was heated 0,4 K approx.):

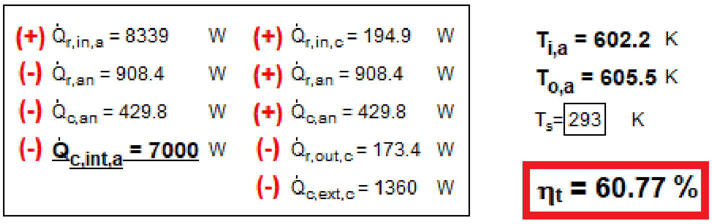

Fig. 4: Screenshot of part of the results, showing heat fluxes, temperatures, and thermal efficiency

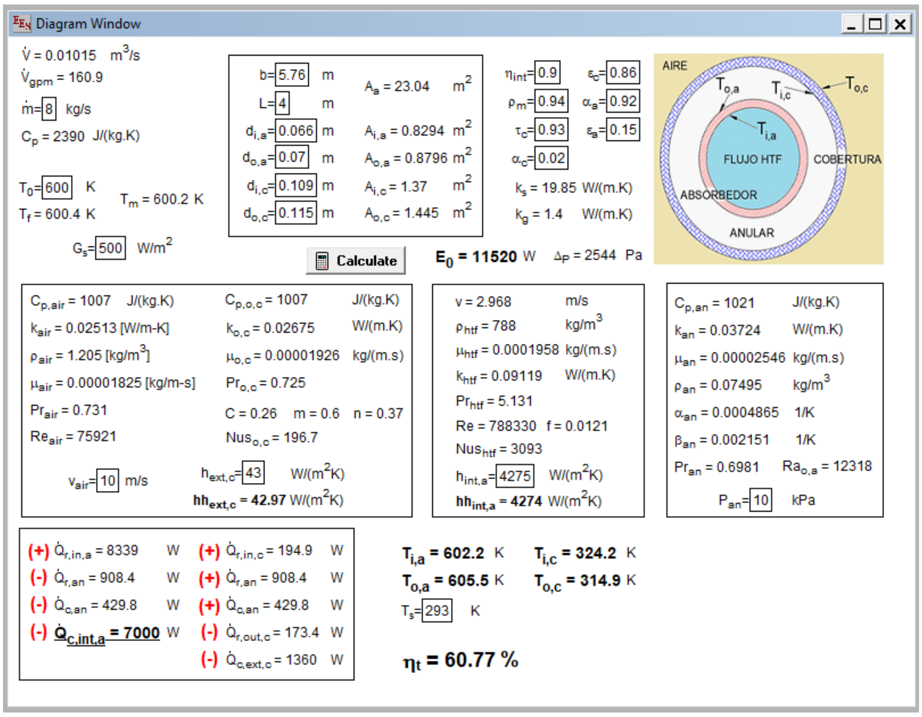

Fig. 5: Screenshot of all the EES Diagram Window, showing all the input and output parameters

In the same manner, the most important graphics generated on the EES for this case are the relation between HTF input temperatures and the thermal efficiency for the parabolic trough. Evidently, with the increase of the HTF temperature at absorber inlet, the thermal losses by convection and radiation increase too (even with the glass envelope and a full vacuum annular space). Then, is stated that the thermal efficiency will reduce as the temperature T_0 increases. Below, are showed T_0 vs η_t curves for two selected HTFs (Therminol VP-1 and Shyltherm 800) considering two annulus pressure values: no vacuum at 101,3 kPa and partial vacuum at 10 kPa:

4.1 Results for Therminol VP-1 HTF

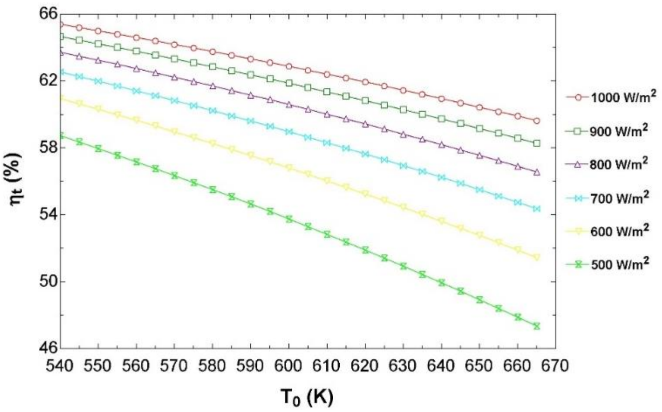

Fig. 6: Thermal efficiency (η_t) as a function of HTF input temp. (T_0) for different radiation fluxes, Therminol VP-1, annulus pressure 101,3 kPa

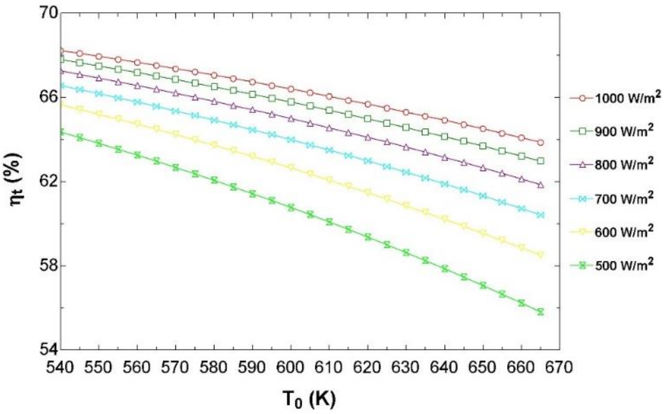

Fig. 7: Thermal efficiency (η_t) as a function of HTF input temp. (T_0) for different radiation fluxes, Therminol VP-1, annulus pressure 10 kPa

4.2 Results for Syltherm 800 HTF

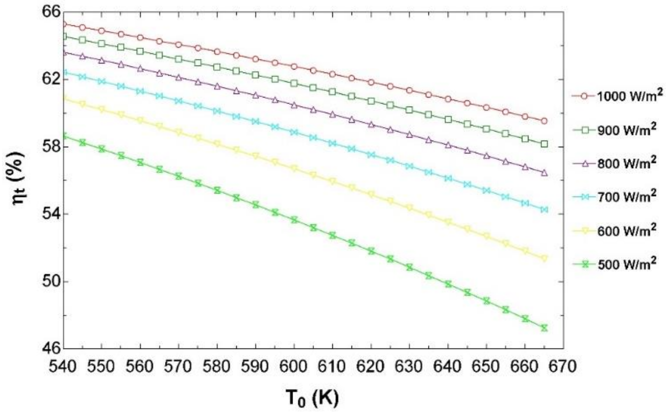

Fig. 8: Thermal efficiency (η_t) as a function of HTF input temp. (T_0) for different radiation fluxes, Syltherm 800, annulus @ 101,3 kPa

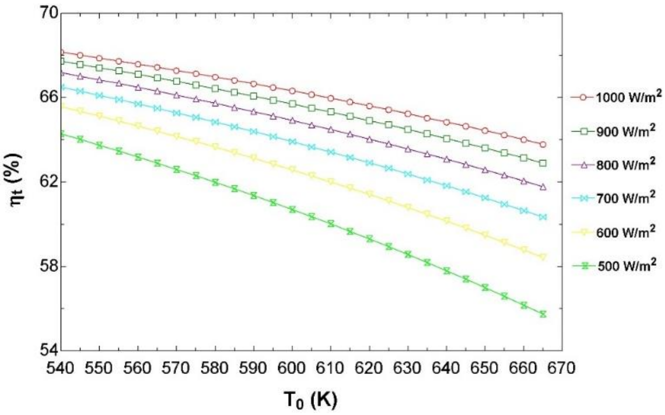

Fig. 9: Thermal efficiency (η_t) as a function of HTF input temp. (T_0) for different radiation fluxes, Syltherm 800, annulus @ 10 kPa

Discusion

It is clear that the two considered HTFs: Syltherm 800 and Therminol VP-1 had almost the same performance on the simulation. Looking for figure 6 and figure 8, seems to be almost the same graphic but the first is for Therminol and the second for Syltherm. The same situation analyzing figures 7 and 9. Considering that the data properties for the HTFs was obtained from the official webpage [Therminol, Dow] then it is possible to affirm that both fluids work in same temperature ranges with similar performances. Then the selection of the two HTFs was correct for the study.

Considering partial vacuum of 10 kPa inside the annulus, the highest calculated efficiency was around 68% for 1000 W/m^2 of beam solar radiation (on aperture plane) and HTF at 540 K (267 °C), for the same radiation value, efficiency drops to around 64% for HTF at 665 K (392 °C). For the same condition (annulus at 10 kPa) but beam solar radiation of 500 W/m^2, efficiency goes from 64% at 540 K to 55% at 665 K.

On the other hand, if there is no vacuum on the annulus and the pressure is considered the standard atmospheric (101 kPa) there is a significant drop on the efficiency values. The maximum efficiency at 540 K and 1000 W/m2 is around 65% and the minimum efficiency at 665 K and 500 W/m2 is around 47%. It is a logical effect that the efficiency experiments a drop from the case of partial vacuum (10 kPa) to the case of no vacuum (101 kPa).

Comparing the results of efficiency with other previous articles is stated that the values of the present work are smaller than the values of other articles. This is because as was explained, it was considered parameters under non ideal or conservative conditions, i.e. radiative properties not on the greater state-of-the-art values. Tzivanidis et al [2015] considers that the efficiency can be around 80%, using a 1D numerical model developed in Fortran and the use of Solidworks. The difference is that this paper show a graphic of Efficiency vs $(T_{in}-T_{am})/G_b$, the latter is HTF input temperature minus ambient temperature divided by beam radiation. Forristal [2003] in an extensive work of simulation for the NREL, also in EES, shows in the figure 6.15 a graphic of Efficiency vs Average HTF temperature (very similar to the present work's figures 6 to 9). For a HTF temperature of 100 °C and beam radiation of 1100 W/m^2 the efficiency approaches near 74%, and almost all the values of the graphic are above 65% for different temperatures and radiation values from 300 to 1100 W/m^2. It is necessary to indicate that in the present study the heat fluxes were calculated in W (a length was assigned to the HCE), in the Forristal study the fluxes were calculated in W/m, i.e. power per unit length. Hongbo Liang et al [2017] study the anual collector efficiency for some locations of variate climate types in China, in figure 4 of their work, shows that the efficiency varies from 52% in the worst location to 63% in the best location, for a north-south axis tracking (typical tracking for parabolic trough). Their metodology considers dynamic performance of parabolic trough for different sun-tracking systems considering the solar conditions for the different places in China [Hongbo, 2017].

Conclusiones

- For the two modeled HTFs (Therminol VP-1 and Syltherm 800), the thermal efficiency of the parabolic trough collector was around 60% in the case of atmospheric pressure in the annular space, decreasing the efficiency with the increase of the temperature and depending on the direct radiation level. The model considered the use of the glass envelope and the conditions described on the input parameters.
- The thermal efficiency increases to around 65% (or more) in the case of partial vacuum (10 kPa) in the annular space. Here it is obvious than make vacuum between the tube absorber and the glass envelope reduce the thermal losses for radiation and convection heat transfer. It would be even better if the pressure of the annulus reduces to less than 1 kPa (ideal condition).
- Although the simulation was not performed on a basis of heat fluxes per length unit, like other simulations [Forristal, 2003], the results were not so far away from other works. It can be considered that the results have logical values.

Referencias

Alcocer, M. y Hernández, C. (2020). Investigación en enseñanza de las ciencias en Colombia: estudio desde sus cosificaciones. *Educación y Educadores*, 23(1), 47-68. https://doi.org/10.5294/edu.2020.23.1

Asrizal, A., Amran, A., Ananda, A., Festiyed,F. & Sumarmin,R. (2018). The development of integrated science instructional materials to improve students' digital literacy in scientific approach. *Jurnal Pendidikan IPA Indonesia*.7 (4), 442-450, https://doi.org/10.15294/jpii.v7i4.13613

Bedin, E., & Claudio Del Pino, J. (2020). La Movilización De Competencias Y El Desarrollo Cognitivo Universal-Bilateral Del Aprendizaje en La Enseñanza De Las Ciencias. *Paradigma*, 360–383. https://doi.org/10.37618/paradigma.1011-2251.0.p360-383.id804

Casal, J. D. (2019). STEM: Oportunidades y retos desde la Enseñanza de las Ciencias. *Universitas Tarraconensis. Revista de Ciències de l'Educació*, *1*(2), 154-168. https://doi.org/10.17345/ute.2019.2

Casa Coila, M. D., Huatta Pancca, S., & Mancha Pineda, E. E. (2019). Aprendizaje Basado en Problemas como estrategia para el desarrollo de competencias en estudiantes de educación secundaria. *Comuni@ cción*, *10*(2), 111-121. https://doi.org/10.33595/2226-1478.10.2.383

Campos, A. A., & Aguado, A. M. (2019). Aprendizaje Basado en Problemas, Un Enfoque Diferente en la praxis de las clases de Ciencias Naturales/Biología en la Básica Secundaria para el desarrollo de Competencia Científica. *Palobra*, *19*(1), 226–242. https://doi.org/10.32997/2346-2884-vol.19-num.1-2019-2479

Castañeda, Y. (2020). La comunidad escolar: colectividad hacia la investigación transdisciplinar. (Spanish). Educación y Ciudad, 38, 14–30. https://doi.org/10.36737/01230425.n38.2020.2311

Castelblanco, A., Cifuentes, J., Pinilla, D., y Pulido, S. (2020). Prácticas pedagógicas para la aproximación al conocimiento como científico social y natural en estudiantes de secundaria. (Spanish). *Revista Praxis & Saber*, *11*(27), 1–16. https://doi.org/10.19053/22160159.v11.n27.2020.10474

Cobo, C., & Ariza, M. R. (2019). Propuesta didáctica en la formación de profesorado para trabajar naturaleza de la ciencia y pensamiento crítico. *Ápice. Revista de Educación Científica*, *3*(1), 15-28 , https://doi.org/10.17979/arec.2019.3.1.4630

Colorado, B.L., & Morales, B. (2018). Avaliação dos conhecimentos tecnológicos, pedagógicos e disciplinares no ensino da ciência. *Revista Ibero-Americana De Estudos Em Educação, 13*(3), 997-1010. http://dx.doi.org/10.21723/riaee.v13.n3.2018.11167

Chen, CM., & Wang, WF. (2020). Mining Effective Learning Behaviors in a Web-Based Inquiry Science Environment. *J Sci Educ Technol* **29,** 519–535. https://doi.org/10.1007/s10956-020-09833-9

De Sá Ibraim, S., & Justi, R. (2018). Ações docentes favoráveis ao ensino envolvendo argumentação: estudo da prática de uma professora de química. *Investigações em Ensino de Ciências*, 23(2). 311-330. https://doi.org/10.22600/1518-8795.ienci2018v23n2p311

Domènech, J., Lope, S., & Mora, L. (2019). Qué proyectos STEM diseña y qué dificultades expresa el profesorado de secundaria sobre Aprendizaje Basado en Proyectos. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *16*(2), 1–16. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2019.v16.i2.2203

Domènech, J. (2018). Aprendizaje Basado en Proyectos en el marco STEM. Componentes didácticas para la Competencia Científica. *Ápice. Revista de Educación Científica*, 2(2), 29-42, https://doi.org/10.17979/arec.2018.2.2.4524

El Nagdi, M. E., Leammukda, F., & Roehrig, G. (2018). Developing identities of STEM teachers at emerging STEM schools. *International Journal of STEM Education, 5*(1), 1-13. http://dx.doi.org/10.1186/s40594-018-0136-1

Fuentes del Burgo, J., Huertas Gallardo, P., & Torres Aranda, A. M. (2019). Promoción de la ciencia, la tecnología, la ingeniería y las matemáticas (stem). el proyecto precampus. (Spanish). *Ensayos: Revista de La Facultad de Educacion de Albacete*, *34*(2), 101–121. http://search.ebscohost.com/login.aspx?direct=true&db=eue&AN=142077137&lang=es&site=eds-live

García, F. J., Quesada, A., Romero, M. & Abril, A. M. (2019). Promover la indagación en matemáticas y ciencias: desarrollo profesional docente en primaria y secundaria. *Educación XX1, 22*(2), 335-359. http://dx.doi.org/10.5944/educXX1.23513

Gehlen, S. T., & Delizoicov, D. (2020). A função do problema: aproximações entre vygotsky e freire para a educação em ciências. *Investigacões Em Ensino De Ciências*, *25*(2), 347-368. http://dx.doi.org/10.22600/1518-8795.ienci2020v25n2p347

Gesqui, L. C. (2020). Desempenho ibero-americano nos PISA 2012, 2015 e 2018. Revista Iberoamericana de Educación, 84(1), 67-83. https://doi.org/10.35362/rie8413901

Giraldo, C. F., Caballero, M. C., y Meneses, J. Á. (2020). Una experiencia de práctica pedagógica con docentes en formación en ciencias naturales apoyada en el aprendizaje basado en proyectos (ABPy). *Uni-Pluriversidad*, 20(1), e2020102, https://doi.org/10.17533/udea.unipluri.20.1.3

Gonçalves, W. C., & Mendonça, S. (2020). O Pisa como indicador da aprendizagem de ciências. *Roteiro*, *45*. https://doi.org/10.18593/r.v45i0.20107

Intasoi, S., Junpeng, P., Tang K., N., Ketchatturat, J., Zhang, Y.& Wilson, M. (2020*).* Developing an assessment framework of multidimensional scientific competencies**.** *International Journal of Evaluation and Research in Education* **(IJERE)** 9(4), pp. 963~970, http://dx.doi.org/10.11591/ijere.v9i4.20542

Imbert, N. D. & Elósegui, E. (2020). Mejoras en el desarrollo de la competencia científica en estudiantes de primer año de secundaria en un liceo de Uruguay. *MLS Educational Research*, *4* (1), 22-40. https://doi.org/10.29314/mlser.v4i1.247

Jufrida, J., Fibrika Rahmat F., Kurniawan W., Danu, M., Fitaloka, O. **(2019).** Scientific literacy and science learning achievement at junior high school. *International Journal of Evaluation and Research in Education (IJER*E). 8 (4), pp. 630~636,doi : https://doi.org/10.11591/ijere.v8i4.20312

Kurnia, A., Ibrahim, M., Widodo, W. (2020). Scaffolding design to improve pedagogical competence of natural sciences for pre-service biology teachers, IOP Publishing Journal of Physics: Conference Series. https://doi.org/10.1088/1742-6596/1567/4/042074

Lin, P. Y., Sing C., y Siu-Yung, M. (2019). A PISA-2015 Comparative Meta-Analysis between Singapore and Finland: Relations of Students Interest in Science, Perceived ICT Competence, and Environmental Awareness and Optimism. *International Journal of environmental Research and Public Health.* 16 (1); pp.1-15. https://doi.org/10.3390/ijerph16245157

López, F., García, I., y, Expósito, E. (2019). Rendimiento en ciencias, concepciones epistémicas y vocaciones STEM en las comunidades autónomas españolas. Evidencias desde PISA 2015, políticas, y prácticas de mejora. España. Revista

Española de Pedagogía. International Journal of environmental Research and Public Health.pp. 1-15, https://doi.org/10.22550/REP77-1-2019-09

López V., Couso D. & Simarro, C. (2020). Educación STEM en y para un mundo digital: el papel de las herramientas digitales en el desempeño de prácticas científicas, ingenieriles y matemáticas. *Revista de Educación a Distancia*. 62 (20). http://dx.doi.org/10.6018/red.410011

Lupión, T., Franco, A.J., & Girón, J. R.(2019). Predictores de vocación en Ciencia y Tecnología en jóvenes: Estudio de casos sobre percepciones de alumnado de secundaria y la influencia de participar en experiencias educativas innovadoras. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *16*(3). https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2019.v16.i3.3102

Medeiros, D. R., & Goi, M. E. J. (2020). Problem Solving as an Investigative Methodology in Natural Science Teaching. *Research, Society and Development*, *9*(1), 49911579.

Menchaca, I.; Dziabenko, O.; García, J. (2020). Experiencia española en el proyecto Go-Lab. *Educar*, 2020, Vol. 56 (2), pp. 387-405, https://doi.org/10.5565/rev/educar.1067

Ministerio de educación y formación profesional (2019). PISA 2018. Programa para la Evaluación Internacional de los Estudiantes. Informe español. https://www.educacionyfp.gob.es/inee/evaluaciones-internacionales/pisa/pisa-2018/pisa-2018-informes-es.html

Minedu (2016). Programa curricular de educación secundaria. Educación básica regular. 1-229.

OCDE(2020). Resultados PISA 2018. Volumen VI. ¿Están los estudiantes preparados para prosperar en un mundo interconectado?. https://www.oecd.org/pisa/

Ortiz, C. I., & Suárez, M. (2019). guided indagation as a methodological strategy for the development of scientific competences in middle education students. *MLS Educational Research*, *3*(1). https://orcid.org/0000-0002-0188-3074 https://orcid.org/0000-0002-0188-3074

Rosales, E. M., Rodríguez, P. G., & Romero, M. (2020). Conocimiento, demanda cognitiva y contextos en la evaluación de la alfabetización científica en PISA. http://dx.doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2020.v17.i2.2302

Salamanca, X., & Hernández, C. A. (2018). Enseñanza en ciencias: la investigación como estrategia pedagógica. trilogía Ciencia Tecnología Sociedad, 10(19), 133-148. https://doi.org/10.22430/21457778.1025

Sabido, J., Sáez, I., Gracenea, M., & Santacana, J. (2019). Teaching scientific competence and the scientific method in social and natural sciences education: A project with a transdisciplinary approach. *Revista d'Innovació i Recerca En Educació, 12*(2), 1-1–16. http://dx.doi.org/10.1344/reire2019.12.227434

Sánchez, N. S. (2018). Clase invertida y aprendizaje basado en proyectos en el aula de biología: un proyecto de innovación para 1.° de eso. valoración de la experiencia. *Enseñanza & Teaching, 36*(1), 81-110. http://dx.doi.org/10.14201/et201836181110

Sepulveda, B., Castro, J., & Pavez, O. (2018). Impacto de la aplicación de una guia metodologica cientifica en proyectos de investigación escolares en la región de atacama, chile. *Holos, 34*(1), 157-169. http://dx.doi.org/10.15628/holos.2018.6595

Simonics, I. (2020) y Hetzl, A. (2020). The Status of Natural Scientific Education and its Relationship with Exam Systems. Special Focus Paper. 5 (10). 77-88. https://doi.org/10.3991/ijep.v10i5.14127

Soto, J.R., y Aguedo, K. P. (2019). Desarrollo de la competencia "uso comprensivo del conocimiento científico" en un entorno blearning. Córdoba – España. Bio-grafía. *Escritos sobre la Biología y su Enseñanza. https://revistas.pedagogica.edu.co/index.php/bio-grafia/article/view/11150*

Sosa, J. A., & Dávila, D. T. (2019). La enseñanza por indagación en el desarrollo de habilidades científicas. *Educación y ciencia*, (23), 605-624. https://revistas.uptc.edu.co/index.php/educacion_y_ciencia/article/view/10275

Sulistioning, R., Nugraha, U., Subagyo, A. Eka, Y., Sari, N. & Hidayusa, O. (2020), Investigation of Learning Science: Fun in Learning, Interest in Learning Time, Social Implications, Scientific Normality for Science Learning. *Universal Journal of Educational Research* 8(4), 1126-1134, https://doi.org/10.13189/ujer.2020.080402

Timarán, R., Hidalgo, A., & Caicedo, J. (2020). Patrones de desempeño académico de los estudiantes de educación media en la prueba de ciencias naturales del saber 11 con árboles de decisión. *Revista Ibérica De Sistemas e Tecnologias De Informação*, 190-201. Retrieved from https://search.proquest.com/docview/2452331780?accountid=37408

Tocora, M. A., & Hernández, C. H. (2020). Investigación en enseñanza de las ciencias en colombia: Estudio desde sus cosificaciones . *Educación y Educadores*, *23*(1), 47-68. http://dx.doi.org/10.5294/edu.2020.23.1.3

Tormohlen Gehlen, S., & Delizoicov, D. (2020). A função do problema: aproximações entre vygotsky e freire para a educação em ciências. *Investigações em Ensino de Ciências*, *25*(2).1-23. https://doi.org/10.22600/1518-8795.ienci2020v25n2p347

Valverde, D., De Pro, A., & González, J. (2020). La información científica en Internet vista por estudiantes de Educación Secundaria Obligatoria: Un estudio exploratorio de sus competencias digitales. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *17*(1), 1–18. https://doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2020v17.i1.1101

Valverde, D., De Pro, A., & González, J. (2018). La competencia informacional-digital en la enseñanza y aprendizaje de las ciencias en la educación secundaria obligatoria actual: una revisión teórica. *Revista Eureka Sobre Enseñanza y Divulgación de Las Ciencias*, *15*(2), 2105-1-2105–2115. http://dx.doi.org/10.25267/Rev_Eureka_ensen_divulg_cienc.2018.v15.i2.2105

Yurnetti, Asrizal y Murtiani (2020). Need analysis to develop science learning material based on thematic teaching by integrating the new literacy. Journal of Physics: Conference Series . pp- 1-11 , https://doi.org/10.1088/1742-6596/1481/1/012122