**Revista Internacional de Investigación e Innovación Tecnológica**

Página principal: www.riiit.com.mx

# Software SOLEEC optimization methodology for direct steam generation parabolic trough solar collectors designing

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**Technological innovation:** The software SOLEEC is a computational tool for designing parabolic trough solar collector as well as assessment of solar resource for any location on the planet.

**Industrial application area:** Software SOLEEC can be used for designing applications in power generation industry and for industrial process involving heating fluids.

Recibido: 02 de febrero 2016
Aceptado: 29 de febrero 2016

## Abstract

The present work describes the methodology carried out for software SOLEEC upgrading (registered to Copyright National Institute with the number 03-2012-070510302900-01). Software SOLEEC is a computational tool for designing of parabolic trough solar collector (PTC) and assessment of solar resource for any specific place where solar technology is intended to be used. In the first version, Software SOLEEC had some limitations, for mentioning some of them: heat transfer fluid does not have phase change, it means, liquid state is maintained along the collector, the rim angle is 90°, only one concentric coating tube is considered and space between the coating and absorber tubes is evacuated.

The tasks to upgrade the software SOLEEC version are basically three. First, the solar system will become a direct steam generation system (DSG), considering the absorber tube in three different sections: the first for preheating, where water enters to ambient temperature and at the exit reaches saturation temperature, at the second section a evaporative process occurs passing from saturated liquid state to saturated steam state. Finally, at the third section, superheated steam is reached at the temperature imposed by the software user.

**Keywords:** Direct steam generation system, upgrading, parabolic trough solar collectors, solar energy, SOLEEC.

## Resumen

El presente trabajo describe la metodología que se está llevando a cabo para realizar la optimización del software SOLEEC registrado ante el Instituto Nacional del Derecho de Autor con número 03-2012-070510302900-01. El software SOLEEC es una herramienta computacional para diseño y evaluación de concentradores solares de canal parabólico (PTC por sus siglas en inglés) y también evalúa el recurso solar para un lugar específico donde se pretenda utilizar esta tecnología. En la primera versión, el software SOLEEC tiene algunas limitantes, las cuales son: el fluido de trabajo no cambia de fase, es decir, se mantiene en estado líquido a lo largo del tubo absorbedor, el ángulo de borde de la parábola es de 90°, solo se considera un tubo transparente concéntrico al tubo absorbedor y el espacio entre ambos tubos se encuentra evacuado.
Las principales tareas en las que se centra la optimización del software SOLEEC son básicamente tres. Primero, se utilizará el sistema de generación directa de vapor (DSG por sus siglas en inglés), considerando que el tubo absorbedor será dividido en tres secciones: la primera de precalentamiento, donde el agua entra a temperatura ambiente y llega hasta la condición de saturación, en la segunda sección ocurre el proceso de evaporación pasando del estado de líquido saturado al estado de vapor saturado. Finalmente, en la tercera sección, el vapor es sobrecalentado llegando a la temperatura final impuesta por el usuario.
**Palabras claves:** Concentradores solares de canal parabólico, energía solar, Generación directa de vapor, optimización, SOLEEC.

## 1. Introduction

For the last 20 years, a considerable effort has been exerted in the design of solar thermal power plants with parabolic trough solar collector (PTC). Commercial plants currently working in USA has been using synthetic oil as heat transfer medium. The outlet of the solar field is connected to a heat exchanger that generates steam to feed a turbine. As the primary energy source, solar irradiation is not controllable, the main control parameter is the temperature of the oil at the outlet of the solar field, and the variable controlled is the mass flow at the field inlet.

The biggest application of this type of system is the Solar Electric Generating Systems (SEGS) at the southern California which is compound of SEGS I (14 MW), SEGS II-VII (30 MW each), and SEGS VIII

and IX (80 MW each), resulting in a total installed capacity of 354 MW. [1].

The direct steam generation (DSG) in PTC systems is a promising option for the improvement of the reliable parabolic trough technology for solar thermal energy. This technology can be used in any process involving steam generation applications for the power generation and for any heating fluid process.

Another example of power plant to produce DSG in a solar field using water through the collectors as the heat transfer medium was implemented in Almería, Spain. This plant started in 1996 and nowadays is used as pilot experimental plant in which different combinations are tested in order to find the best configuration for solar system´s commercialization [2].

INDITEP Project is another example, promoted by a Spanish-German consortium of engineering companies power equipment manufacturers, research centers and businesses involved in the energy market. The 5MW plant is composed of a DSG system using PTC collectors connected to a superheated steam Rankine power cycle. The solar field produces superheated steam at 410 ℃ for a working pressure of 70 $bar$ [3].

Some research about this topic have been carried out in México. The UNAM has a PTC collector system, which had been tested for analyzing and evaluating the feasibility of steam generation for electric power energy generation. The study also had been focused at the absorber tube [4].

The computational tools have become very important in the designing processes, due to its accuracy and precision as well as having the advantage of low cost and faster results, offering to the designer the capability of carry out simulations which are closer to the reality considering the effects of many variables under different conditions.

For PTC design, some computational tools have been developed for different purposes, such as Dymola/Modelica, used for evaluating a PTC for DSG, where water enters to the collector for being partially evaporated, after that is transported to a separator where condensed water is recirculated to the inlet of the solar field while saturated steam is conducted towards the superheating section, which basically is another PTC solar field [5].

A tool is been developed based on a spreadsheet to size solar collector fields for heat generation in industrial processes, the tool requires the geographical position of the collector, time data, solar irradiance and ambient temperature, the tool can select whether it is flat or concentrating solar collectors, tilt and orientation to the collector toward the south. The tool allows forming series-parallel arrangements, also determine the mass flow, the solar fraction and fuel in monetary value [6].

Considering the national strategies in the development and application of sustainable energy technologies, in the Instituto Politécnico Nacional it has been developed a software called SOLEEC, which is a computational tool for PTC systems designing and assessment. Software SOLEEC has been concluded at the first stage, and is copyrighted to the Instituto Politécnico Nacional. The second stage is the methodology for applications to DSG systems and is in development, being the principal topic in the following sections of this paper [7].

## 2. Software SOLEEC description

A PTC is made of a sheet of high reflectance that is conformed in a parabolic profile that is extended in an axial axis. At the axis of the parabola a tube is placed that must be of a high thermal conductivity and covered with a selective material. Surrounding the coated tube or absorber, a concentric transparent tube is placed in order to dismiss the heat losses. Inside the absorber tube, the fluid gains energy due to the effects of solar irradiation giving as a result a temperature increase at the outlet of the solar collector. Figure 1 shows a PTC collector diagram.

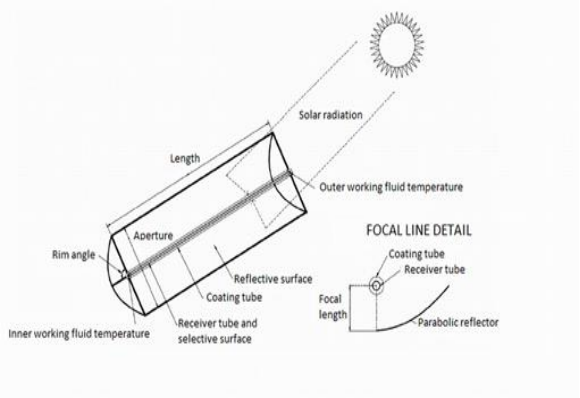



**Figure 1.** Parabolic trough solar collector diagram.

Software SOLEEC is a computational tool for designing of PTC and assessment of solar resource for any specific location, figure 2 shows the main menu and every execution option, the description of each one is exposed below.

Software SOLEEC consist of 2 main parts: the first one (at the top of the figure 2) is for solar resource assessment and has three different options:

- Data for a specific day of the year (Datos para un día específico del año).
- Data for a specific month of the year (Datos de un mes).
- Data for every month along the year (Datos mensuales a lo largo de un año).

Input data necessary for these options are: latitude (°), altitude over sea level (km), choice for a kind of climate, day (1-365) or month (1-12). Once data is introduced to the software, the execution results are organized and showed in tables and charts giving values such as: extraterrestrial solar irradiance (W⁄m^2), solar irradiance on the Earth surface (W⁄m^2) according to Hottel's model, the Earth declination along the year, the solar constant along the year, insolation hours for every day and sunrise time and sunset for every day [8].

The second part of the software SOLEEC consists of four options for PTC designing and assessment (bottom part of the figure 2):

- PTC designing for 12 solar irradiance values (Diseño del concentrador solar con 12 valores de irradiancia solar).
- PTC designing for a specific solar irradiance value (Diseño del concentrador solar con 1 valor de irradiancia solar).
- PTC assessment for 12 solar irradiance values (Evaluación de un concentrador con 12 valores de irradiancia solar).
- PTC assessment for 1 solar irradiance value (Evaluación de un concentrador con 1 valor de irradiancia solar).




**Figure 2.** Software SOLEEC main menu.

For PTC collector designing (option 1 and 2), the user must introduce some data such as: solar irradiance values, choice among many different materials for collector construction, for reflective surface, absorber tube, selective surface, coating tube and heat transfer fluid. Also some environmental conditions need to be given as input data such as air temperature (°C), air velocity (m/s), solar radiation incidence angle, (°) inner and outer fluid temperature (°C).

Once software SOLEEC is executed, results are shown and classified in tables for the geometric configuration and thermal parameters. For the geometric data are shown: aperture (m), length (m) and focal distance (m) for the parabola. For the thermal data are presented heat gain (W) , heat losses (W), mass flux (kg/s), volumetric flow (lt/s), optical efficiency (%), thermal efficiency (%), absorber tube temperature (°C) and coating tube temperature (°C).

For PTC collector assessment (option 3 and 4), the user must provide all thermal and optical characteristics for every material used in PTC construction as well as geometric values and after the software´s execution all the thermal parameters mentioned before will be computed.

The heat gain is the most important parameter about thermal performance, this parameter is directly involved by all other parameters affecting PTC designing, and therefore, software SOLEEC internally develops an iterative process until equations (1) and (2) are evenly closer.

$$Q_{u1} = \dot{m} C_p \left(T_{fe} - T_{fi}\right) \quad (1)$$

$$Q_{u2} = F_R A_a \left[ I - \frac{A_r}{A_a} U_L \left(T_{fi} - T_a\right) \right] \quad (2)$$

In (1) $\dot{m}$ represents mass flux $(kg/s)$, $C_p$ is the specific heat $(J/kg\ K)$, $T_{fe}$ and $T_{fi}$ represents exit and supply temperatures (°C) respectively, all properties for heat transfer fluid.

Eq. (2) is exclusively for PTC collectors, where $F_R$ is a flow factor, $A_a$ and $A_r$ $(m^2)$ are the aperture area and absorber area respectively, $I$ is the energy flux reaching the absorber tube $(W/m^2)$, $U_L$ represents the global losses factor $(W/m^2\ K)$ and $T_a$ is the ambient temprature (°C).

Eq. (1) represents the heat gained internally in the working fluid as a function of its thermal characteristics, while Eq. (2) represents the heat gain on solar collector taking into account the solar irradiance available, the heat losses and the collector's geometry, thus, both equations involve the same concept of energy gain, the first one as

the working fluid and the second one as the collector's performance point of view [9].

Software SOLEEC has some restrictions such as: parabola rim angle must be equal to 90°; hence the collector reaches the maximum concentration ratio, also the circulating fluid remains only in liquid phase; that is there is no phase change, and finally only considers one coating tube and the space between absorber and coating tubes must be evacuated. Software SOLEEC validation can be consulted in reference [10].

Due to the before mentioned restrictions, the SOLEEC upgrade is focused on three main tasks: direct steam generation system, parabola optimal rim angle for every case and PTC arrays assessment, serie, parallel and a combination of them. This paper is focused on methodology for DSG system which is explained in the next section.

## 3. Software SOLEEC optimization methodology

The first stage of SOLEEC upgrade is the direct steam generation system, and it was necessary to introduce the two phase change theory, after reviewing some empirical correlations for determining main parameters involved during forced boiling, the following equations were selected as will be discussed.
In the direct steam generating trough the collector, the absorber tube will be horizontal and the incident energy input can be considered uniform all along the absorber. If the feed water enters the collector at a temperature below the saturation temperature for the working pressure, the bulk temperature increases along the absorber up to the saturation temperature. After this point nucleate boiling in saturated water starts and after a small increase in quality the flow pattern changes to convective boiling or forced convective vaporization as can be seen in figure 3. The heat transfer from the wall to the water increases resulting in a fluid quality increasing. For both nucleate boiling in a saturated liquid and convective boiling the heat transfer coefficient is influenced by bubble formation and convection in the liquid film. For high energy input or long collectors, dry out occurs and the low conductivity of dry steam leads to a decrease of internal heat transfer coefficient. The maximum heat transfer coefficient in the two phase flow region has been shown to occur when the quality is $x = 0.8$ for a wide range of mass flux conditions [11].

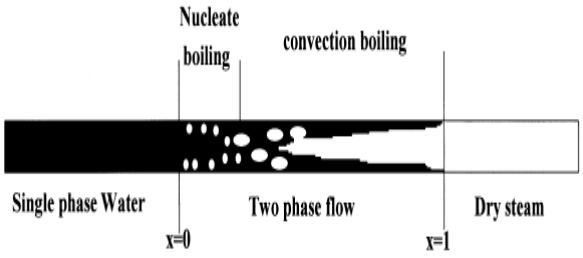



**Figure 3.** Flow patterns in the absorber of a DSG system collector.

### 3.1 Heat transfer coefficient calculation

The software upgrade for DSG system will consist of a thermal analysis of a direct boiling collector. The absorber tube will be divided into three sections to follows the phase change in the absorber.

The first section will be analyzed for fully developed single phase as can be observed in figure 3, where the heat transfer coefficient can be calculated form Dittus-Boelter correlation as follows:

$$h = 0.023 Re^{0.8} Pr^{0.4} \frac{k}{d_{ri}} \qquad (3)$$

Where $Re$ is the Reynolds number, $Pr$ is the Prandtl number, $k$ is the fluid conductivity coefficient $(W/m\ K)$ and $d_{ri}$ is the internal absorber diameter $(m)$.

Software SOLEEC will compute in an iterative procedure the needed mass flux and minimum collector length going from initial water temperature to the saturation temperature at the working pressure.

The second section of the absorber will assess the phase change, this section is characterized because of the steam quality goes from saturated liquid to saturated steam. This section is the most complex, due to flow patterns formation. As an initial guess, the mass flux will be considered as constant. As in the previous computation SOLEEC will find the minimal length for the system to change from saturated liquid to saturated steam.

The heat transfer coefficient is the most complex calculation for two phase change in order to evaluate it, the flow pattern must be determined using the Froude number as follows [12]:

$$Fr = \frac{G^2}{\rho_l^2 g d_{ri}} \qquad (4)$$

Where $G$ is the mass flux per unit of area $(kg/m^2 s)$, $\rho_l$ is the liquid density $(kg/m^3)$, $g$ represents gravity acceleration $(m/s^2)$.
If $Fr < 0.04$ stratified flow occurs and the heat transfer coefficient is given by Shah correlation [13].

$$\frac{h_{2ph}}{h_l} = 3.9 Fr^{0.24} \left(\frac{x}{1-x}\right)^{0.64} \left(\frac{\rho_l}{\rho_g}\right)^{0.4} \qquad (5)$$

The heat transfer coefficient for liquid $h_l$ can be calculated modifying Dittus-Boelter equation assuming the liquid fraction fills the tube:

$$h_l = 0.023 \left(\frac{G(1-x)d_{ri}}{\mu_l}\right)^{0.8} Pr^{0.4} \frac{k_l}{d_{ri}} \qquad (6)$$

Where $\mu_l$ is the liquid viscosity $(Ns/m^2)$ and $k_l$ is the liquid conductivity coefficient $(W/m\ K)$.

If $Fr > 0.04$ the absorber tube is completely wet due to anular flow and the heat transfer coefficient can be determined by Chan correlation. The two phase heat transfer coefficient has two independent components, bubble formation $h'_B = h_B S$ and convection $h'_l = h_l F$.

$$h_{2ph} = h'_B + h'_l \qquad (7)$$

Where $h_B$ is the heat transfer coefficient in nucleate boiling, $h_l$ is the heat transfer coefficient for saturated water, and S and F are correction and enhancement factors respectively. For determining $h_B$ the next correlation is used [14].

$$h_B = 3800 \left[\frac{q}{20000}\right]^n Fp \qquad (8)$$

$$n = 0.9 - 0.3(P_n)^{0.15} \qquad (9)$$

$$Fp = 2.55(P_n)^{0.27} \left(9 + \frac{1}{1-P_n^2}\right) P_n^2 \qquad (10)$$

$$P_n = \frac{P}{P_{cr}} \qquad (11)$$

Where $q$ is the heat flux, in this case, the solar irradiance, $P$ is the working pressure $(bar)$ and $P_{cr}$ is the critical pressure for water (221 bar). The correction and enhancement factors $S$ and $F$ are given by next equations.

$$Bo = \frac{q}{\dot{m}\Delta h_{lg}} \quad (12)$$

$$F = 1 + (2.4X10^{4})Bo^{1.16} + 1.37X_{tt}^{-0.85} \quad (13)$$

$$S = \frac{1}{1 + (1.15X10^{-6})F^{2}Re^{1.17}} \quad (14)$$

$$X_{tt} = \left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9} \quad (15)$$

Where $\Delta h_{lg}$ is the heat of vaporization $(J/kg)$, $Bo$ is called boiling number and represents a dimensionless relation between the mass of steam generated per area unit of heat transfer and the density of mass flux per cross area unit. $X_{tt}$ is the Martinelli parameter.

Equations before mentioned are going to be used into software SOLEEC codex, in order to calculate the heat transfer coefficient, due to represents the most important and complex variable on heat transfer analysis.

After water become from saturated liquid to saturated steam, the third section of the absorber is superheating. In this section, saturated steam will be superheated to the final condition and temperature prescribed by the user. Software SOLEEC will find the minimal necessary length for reaching the user´s temperature condition, also will calculate the total of steam produced. Mass flux is supposed to be constant. To evaluate the heat transfer coefficient for superheated steam, Dittus- Boelter equations is used like was presented in Eq. (3).

### 3.2 Pressure drop calculation

The two phase pressure drops for flow inside tubes are the sum of three contributions: the static pressure drop, the momentum pressure drop and the frictional pressure drop. For horizontal tubes, there is no change in static head while the momentum pressure drop reflects the change in kinetic energy of the flow.

The frictional pressure droop in two phase flows is typically predicted using separated flow models. The basic equations for the separated flow model are not dependent on the particular flow configuration adopted. It is assumed that the velocities of each phase are constant, in any given cross section, within the zone occupied by the phase.

There is some common methods for frictional pressure drop in internal flow calculation, nevertheless, the most accurate for DSG systems has been identified as the model of Friedel due fitting best the results as is showed in the figure 4 [15].

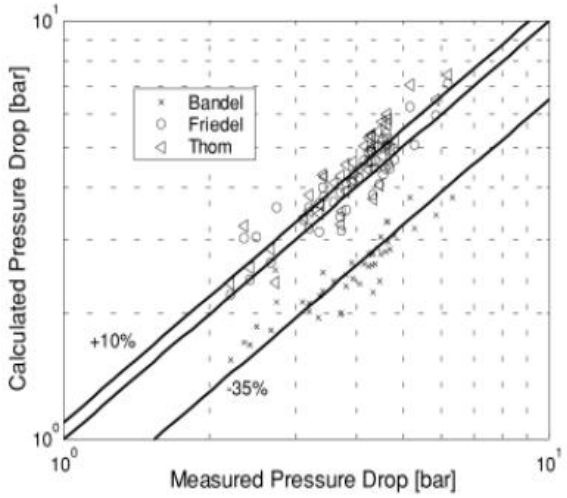



**Figure 4.** Comparison of pressure drop measured and calculated for different models.

The method for pressure drop calculation using the Friedel model utilizes a two phase multiplier.

$$\Delta P = \Delta P_L \Phi_{fr}^2 \quad (16)$$

$$\Delta P_L = 4 f_l \left(\frac{L}{d_{ri}}\right) G^2 \left(\frac{1}{2\rho_l}\right) \quad (17)$$

$\Delta P_L$ is calculated for the liquid phase and $f_l$ is the liquid friction factor, $L$ represents tube length $(m)$.

$$f_l = \frac{0.079}{Re^{0.25}} \quad (18)$$

The Friedel two phase multiplier is calculated using the next equation.

$$\Phi_{fr}^2 = E + \frac{3.24 F_{fr} H}{Fr^{0.045} We^{0.035}} \quad (19)$$

Where $Fr$ is the Froude number before mentioned, $We$ represents Weber number and the dimensionless factors $F_{fr}, H$ and $E$ are calculated as follows.

$$We = \frac{G^2 d_{ri}}{\sigma \rho_h} \quad (20)$$

$$\rho_h = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \quad (21)$$

$$E = (1-x)^2 + x^2 \frac{\rho_l f_g}{\rho_g f_l} \quad (22)$$

$$F_{fr} = x^{0.78}(1-x)^{0.224} \quad (23)$$

$$H = \left(\frac{\rho_l}{\rho_g}\right)^{0.91} \left(\frac{\mu_g}{\mu_l}\right)^{0.19} \left(1 - \frac{\mu_g}{\mu_l}\right)^{0.7} \quad (24)$$

Where $\sigma$ is the surface tension $(N/m)$, $\rho_h$ is a homogenous density depending on steam quality and the densities for every phase. This method is typically recommended when the ratio $\mu_l/\mu_g$ is less than 1000, but in the case of water, this ratio always reach below that value, also is applicable to vapor qualities from $0 \leq x \leq 1$ [16].

Once this optimization is done, the user could find the most important parameters for PTC designing and evaluation in a DSG system, including the geometrical characteristics and thermal parameters.

## 4. Conclusion

On this work, software SOLEEC upgrade methodology for parabolic trough solar collector designing and assessment for direct steam generation system was discussed.

The absorber tube will be divided into three segments, the first one for preheating, reaching the water from initial temperature to saturation temperature at the working pressure, software SOLEEC will find the minimal length for reaching that condition and necessary mass flux will be calculated.

The second stage will maintain constant mass flux, and vaporization will start from saturated liquid to saturated steam while software SOLEEC will find the minimal length for reaching the mentioned condition. The most important and complex variable for this section is the heat transfer coefficient because of flow patterns formation dominating two main phenomena, nucleate boiling and convective boiling.

Once saturated steam condition is covered, next section will superheat the steam and software SOLEEC will find the minimal length for the final temperature condition dictated by the user also the quantity of vapor produced maintaining constant mass flux condition.

Also the pressure drop phenomena is going to be considered, analyzing some methods for frictional pressure drop in two phase flow, Friedel method is recommended due to its applicability and accuracy.

When these tasks of optimization are covered, software SOLEEC will become a full, versatile and profitable computational tool for parabolic trough solar collector designing and assessment.

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