Simulation Heat Transfer Fluid Efficiency and Molten Salts in Heat Collecting Elements in Concentrating Solar Power

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Abstract

In this work, we simulate the efficiency of different Heat Transfer Fluids (HTF) and molten salts when circulating through a section of Heat Collecting Elements (HCE) in a parabolic trough system for Concentrating Solar Power (CSP). The simulation shows that the Therminol VP-1 and Dowtherm A synthetic oils are the most efficient in the solar field due to their broad range of working temperatures, their low heat loss, losses of charge and low viscosity, and all at an affordable cost. If we take into account the overall performance of the plant, the fluid that yields the best results is the Hitec XL salt due to its working temperature, which is 100 °C greater than that of the oils. Molten salts provide an alternative to the use of HTF, since they enable the total cost of running the plant to be reduced as well as improving its competitiveness.

Keywords: Concentrating Solar Power; Parabolic trough; Molten Salts; Heat Transfer Fluid; Heat Collecting Elements.

1. Introduction - The existing capacity throughout the world of Concentrating Solar Power (CSP) (Parabolic Trough Systems, Linear Fresnel Reflector Systems, Power Tower Systems and Dish/Engine Systems) increased by 50% during the period 2008 to 2013. The accumulated power of all CSP plants as of February, 2016, was 4.749 GW, with the expectation that it would reach an installed capacity of 10 GW in 2018, as compared with the 294 GW of installed capacity instalada of the the photovoltaic systems forecast for 2016 and the 450 GW estimated for 2018. CSPs with an estimated power of 1.18 GW are at present under construction and a further 4.17 GW in process of development. Of the 4.749 GW in operation throughout the world, 2.304 GW correspond to Spain, followed by the United States with 1.743 GW. Parabolic trough systems constitute the most widely used CSP technology with a deployment of 90 % in comparison with other similar concentrating solar power technologies [1-2].

CSPs have to overcome a series of restrictions, such as the need for locations with a high level of radiation, an available water supply, a flat geographical area and access to a connection with a nearby electricity grid in order to channel the electricity generated. Added to this is series of financial limitations arising from the high cost of the initial investment, the uncertainty involved, the technological risk and the regulations that must be fulfilled in some countries for the promotion, design, construction and running of these plants. For all these reasons, the opportunities for technological innovation are small and the design tends to be highly conservative.

In order to improve the competitiveness of CPS over other systems, and to increase the market share worldwide, it is necessary to research and develop new components in order to achieve greater performance of the plants. It will also be necessary to seek new innovation and technologies for increasing efficiency, as well as the incorporation of new materials, improved performance of the heat transfer fluid (HTF) and a reduction of the solar field [3].
Systems based on Renewable Energy Hybrid Systems (REHS) constitute a good choice in terms of cost, reliability and efficiency when compared with systems based on a single energy source. The optimization techniques employed in the design and development of photovoltaic and wind-powered solar energy hybrid systems are promising for their use of algorithms in order to obtain a greater precision in the calculations when compared with traditional methods [4-7].

Several studies have been devoted to research into CSP hybridization with coal [8], gas [9], geothermal gradient [10] and the use of biomass for superheating steam from a CSP at temperatures between 380 °C and 540 °C [11]. Power Tower Systems and Linear Fresnel Reflector Systems may soon be able to increase efficiency and lower the cost of generating electricity [12], so the new Linear Fresnel Reflector Systems that are about to start functioning will change the market share in their favour, although finding finance for their operation still remains more complicated than for parabolic trough systems. The DISS project (Direct Solar Steam) [13] has managed to produce superheated steam at 400 °C/100 bar in a stable manner by means of Direct Steam Generation technology (DSG), which enables performance to be increased and the cost of energy generation to be substantially reduced.

The use of molten salts obviates the use of exchangers for their storage, but they require the development of low emission, high absorbence and high durability heat collecting elements capable of operating at temperatures exceeding 500 °C.

This work proposes a useful tool for simulating the efficiency of different HTFs and molten salts when circulating through a section of heat collecting elements in parabolic trough systems for concentrating solar power. Image 1. By means of the SolidWorks® program and the FlowSimulation® complement, flow is simulated along a section under real operating conditions as well as the heat loss of the HTF when circulating through a network of tubes in the solar field. This work may prove useful for exploration of the use of new heat-transfer fluids in heat collecting elements. Different publications in the literature [14-17] have been taken into account for the simulation of the model presented herein.

2. Experimental - Parabolic trough systems employ linear collectors lined with polished mirrors curved like a parabola for the purpose of focusing solar radiation directly onto the focal point. This point is located in a heat collecting element (HCE) that absorbs the radiation reflected by the concentrator and converts into energy that heats the thermal fluid circulating inside. In order to simulate the model, the Schott PTR 70 tube has been chosen; this is the most widely employed by most of the CSP plants in Spain.

The SolidWorks® and FlowSimulation® program tools are used to simulate the real running conditions in a section of the heat collecting element.

The tube is an assembly consisting of five parts: an inner metallic Tube (DIN 1.4541), an outer envelope (Glass), a metallic bellows, and two seals at the ends of the bellows connecting it with the metallic tube (both AISI 304).

The physical properties of these materials, which are vital for the study and are included as computational values, are as follows: the thermal conductivity (m-K), density (kg/m³), specific heat (J/kg·K) and the dynamic viscosity (Pa·s). Other initial conditions of the immediate surroundings are the roughness of the tube, the heat transfer coefficient (the absolute roughness coefficient is 2.4 µm on the inside of the metallic tube), and the heat transfer coefficient with the surrounding atmosphere (0 W/m²·K is considered, due to the vacuum existing between the two tubes) [7]. The mass flow rate circulating along the tube is 6.4 kg/s [18]. The length of the tube is 4 m, and the metallic tube has an exterior diameter of 7.0 cm and that of the glass envelope is 12.5 cm. Image 2 shows this section of the heat collecting elements.

The oils chosen for the study are Therminol VP1, Syltherm 800, Dowtherm A, Therminol 59 and Marlotherm SH, which are used in most of the plants employing thermal oils as the transfer fluid. The salts chosen (a mixture of Potassium, Sodium and Calcium nitrate) are Hitec XL, Solar Salt, VP1, Dowtherm Q and Dowtherm RP.

The data of interest from each analyzed fluid are: heat loss (W), loss of charge (Pa), the heat lost by conduction at the ends of the tube (Δ°C) and the Reynolds number (Re).
The static pressure at the entrance to the tube is set to 15 bars. The temperature at the point of entry is 563 °K. Solar radiation is simulated by projecting a heat source of 15,140 W (approximate mean value of direct radiation for an affordable thermo-solar plant, 800 W/m²) onto the outer surface of the tube; a concentrator aperture length of 5.77 m, an optical performance of 82% and angle of incidence zero. The atmospheric conditions are as follows: Temperature 293 °K and atmospheric pressure 101.350 Pa.

The discretization method of the computational domain employed by FlowSimulation® is that of infinite volumes. In order to study the influence of the mesh on the results, four simulations are conducted with different sizes of the volumes in order subsequently to analyze convergence as the mesh is refined. Convergence is achieved with an order of magnitude of 5, taking into account that the difference in the results at level 6 is minimal.

3. Results and Discussion - The use of this simulation tool enables any problems to be reproduced in ideal conditions, as well as to study the influence of different variables with greater speed and at a lower cost.

The analysis shows that the fluids undergo a loss of pressure due to friction with the walls of the tube, both at the connection and in distribution. Furthermore, both density and viscosity drop as the temperature increases.

The mean velocity of the fluid is 2.3 m/seg, which increases as the temperature rises, while the density first falls and increases again at the exit to the tube.

The maximum temperature values are found at those areas of the fluid that are closest to the walls of the tube, where heat absorption by convection occurs. The increase in mean temperature at the entrance and exit is equal to 0.9965 °C. The Reynolds number indicates that this is a turbulent flow, which is important because it favours heat transfer by convection between the inner wall of the tube and the fluid.

Image 3 shows the temperature gradients and velocity in the immediate surroundings for the Therminol VP-1 in the collector-receiver tube. [Image: Authors’ Own].

The loss of charge as the fluid flows through the tube is due exclusively to friction with the walls and can be calculated by means of the Darcy-Weisbach equation, subsequent to determining the friction coefficient. The temperature increase is greater as a result of its lower specific heat, and this phenomenon, together with the lower thermal conductivity, accounts for the greater heat loss.

Table I shows the simulation variables of the fluids under study. It is observed that Dowtherm A has properties very similar to those of Therminol-VP1. The low temperature increase is the most significant difference due to the slightly higher specific heat of this fluid. The Marlotherm SH is a fluid whose maximum working temperature is 350°C, which constitutes a disadvantage when compared with the fluids previously studied. It does not require a high pressure to prevent evaporation, and its steam pressure is lower than one atmosphere at 350 °C.
Therminol 59 has a greater useful temperature range and reaches 315 °C with stability. This fluid undergoes a lower temperature increase because of a greater specific heat.

Data on the properties of the salts are obtained from the SAM (Solar Model Advisor) simulation program. The values introduced for performing the simulation are identical to those employed before, but the temperature at entry is set to 390 °C. With regard to heat loss, it is much greater in the thermal oils due to the temperature difference between the fluid and the exterior, which is 100 ºC higher. As a result of the high viscosity, the Reynolds number is some 10 times less than that calculated for Therminol VP1. Nevertheless, the fluid remains turbulent and is thus valid to function as HTF.

Relative errors are taken into account in the results obtained as compared against the simulation conducted with the Burkholder and Kutscher method, and are lower than 1% [19]. Table II.

The oils composed of aromatic hydrocarbons, such as Therminol VP-1 or Dowtherm A, are highly contaminating, as well as being damaging to health. The use of a fluid that is innocuous for the environment would mean that these types of plants would not emit any contaminating substances, thereby improving their status as a source of renewable energy. High viscosity fluids lead to greater charge losses, and thus a greater pumping power for impelling el HTF is required. Higher conductivity fluids engender lower heat losses, while fluids with a high specific heat enable enable large amounts of energy to be stored and require a lower circulation flow in order to collect a particular amount of energy.

### 4. Conclusions

- The Therminol VP-1 and Dowtherm synthetic oils are the most efficient due to their broad range of working temperature, low heat loss and loss of charge, low viscosity and an affordable cost. However, if not only the solar field but also the overall performance of the plant are taken into account, the fluid that yields the best results is the Hitec XL salt, thanks to its working temperature of 100 °C higher than that of the oils. The fluids composed of silicones, such as Syltherm 800 or the molten salts, are less prejudicial for the environment than organic oils. Syltherm 800 does not require an auxiliary heating system because of its low point of solidification.
- Molten salts provide an option for us in HTFs, where a heat exchanger between the oil and the salts is unnecessary and thereby results in a reduction of plant operating costs as well as improving its competitiveness.
- Future work includes the study of improvements in geometry and in the dimensions of the tubes in order to reduce heat loss through optical effects, because these factors exert greater influence on overall performance. In addition, where the use of molten salts such as HTF is concerned, it would be useful to do research into materials possessing a greater resistance to heat fatigue when working with a network of tubes at higher temperatures.

### 5. References


