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Theoretical basis and experimental facility for parabolic trough collectors at high temperature using gas as heat transfer fluid

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HIGHLIGHTS

- Solar thermal trough collectors cooled by gas with high values of pressure and temperature.
- Experimental facility at 'Plataforma Solar de Almería' description.
- Experimental results of the gas cooled trough technology.

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ABSTRACT

The efficiency of any thermal power plant is related to the maximum working temperature that some components can reach. Examples of material constraints are the first stage blades of a gas turbine or the receiver of a solar tower plant, but there are other temperature constraints, such as the ones related with the heat transfer fluid. Nowadays, this happens in the most common solar technology: parabolic trough collectors that use synthetic oil. This fluid must work below 400 °C. This limitation affects the power plant efficiency due to a poor Rankine cycle yield. To avoid this problem and go to higher temperatures, a gas can be used as heat transfer fluid, providing at the same time other significant advantages over synthetic oil: non-flammability and no environmental threats. The purpose of this paper is to justify the theoretical basis of the gas use in parabolic troughs and the problems related, and also to describe the test loop built at the PSA (Plataforma Solar de Almería) in order to demonstrate the technical feasibility of this new technology, testing all components required to build a pre-commercial power plant. This paper describes the main features of this technology, the theoretical basis, the validation of the design tools and the results of the operation. Of them, the more important aspects are that high working pressure can reduce pumping power to adequate levels, that good controllability of the technology with hard solar transients can be achieved and that ball joints leaks problems detected appeared as the main inconvenience, but promising solution has been found.

1. Introduction

One of the most critical decisions in the design of a solar-thermal power unit is the choice of the radiation concentration geometry [1–5], which is in turn connected with the thermal flux needed in the receiver for fulfilling the ideal temperature of the power-plant. In this context, technical coherence is a major word: if a high value is chosen for the concentrated radiation thermal flux, the global heat transfer coefficient between the receiver inner surface to the heat carrier fluid must have a similarly high value [1–3]. Otherwise, the temperature difference between the receiver and the fluid will be very large, thus enhancing thermal losses from the receiver. Besides that, large temperature differences in cross sections of the receiver will convey important differential expansion effects, which can be a major cause of concern in the durability of the receiver.

In central receivers, several relevant books and papers explain the main features of concentrating solar radiation by reflecting heliostats (mirrors) [1,6–9,2,10–12].

In linear receivers (trough collectors and Fresnel) the selective coating is the radiation absorbing element, and it is the component reaching the highest temperature. The useful heat is carried by the

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working fluid and its actual energy value will depend on the temperature achieved at the collectors outlet. In some applications (e.g., with direct steam generation), boiling inside the receiver tube is considered, and the steam quality will also be a relevant parameter. In general, the increase in specific enthalpy and the mass flow are the variables characterizing the heating of the working fluid. In this context, two energy balances must be taken into account: the overall heating of the fluid, which is equal to the total energy transferred from the absorbing surface to the heat carrier fluid, and the detailed heat transfer balance, which depends on the temperature map attained in the collector due to the transmission processes among the components of the collector, with two main results:

– Heat transfer to the working fluid, which is the basis of the overall energy balance.
– Losses to the environment, mainly through convection to air and radiation to the surroundings.

Heat transfer to the working fluid depends, besides its thermal properties, on its velocity. The convection coefficient between the tube and the fluid can be increased by increasing its speed, but this fact has other effects, such as an increase in pressure drop and in pumping power [13,14]. Another important point in the system design is the actual limitations in the temperature of the different components. This is the case of the selective coating and thermal oils, which impose a limit to the maximum temperature allowed in the collector. Coatings resisting 500 °C without degradation are commercially available [15], but this is not usually the binding limitation, because in current trough collector power plants, the most popular heat carrier fluid is a synthetic oil, Therminol VP1 [16] or Dowtherm A, and its maximum working temperature is below 400 °C.

This temperature constraint implies an important limit in the achievable efficiency of the BOP, in such a way that a change in the fluid that absorbs the concentrated sunlight incident on the trough collector receivers can imply an important improvement in the overall efficiency of the plant. The use of direct steam generation is a possibility already studied some authors [17–22], not only theoretically but also experimentally [23].

If we pay attention to central receiver systems, two main options have been developed to reach temperatures higher than 400 °C: molten salts and air. Of course some projects consider direct steam generation in the central receiver.

Today, molten salts and central receivers have several interesting developments, as for example GEMASOLAR [24], a 19 MW power plant that has the honor of being the first commercial solar thermal power plant with the capacity to operate at full load 24 hours a day. The working temperature of this plant is 565 °C [25], considerably higher than the one reached with thermal oil.

Another possibility for central receivers combined with direct steam generation is the representative case of the BrightSource Energy proposal [26], with superheated steam, planning to reach supercritical steam at 650 °C and pressures between 260 and 320 bar in 2016 [26].

Some inconveniences can be found to the described technologies that want to reach temperatures above 400 °C:

– Direct steam generation: dispatchability provided by thermal energy storage (TES) is the main advantage of solar thermal power plants when compared to PV plants or wind farms. However, DSG solar plants require TES based on latent heat (i.e., phase change materials), which are still at a research stage, while TES based on sensible heat are well proven, cost-effective and efficient systems already available for large commercial solar thermal power plants.
– Trough collectors have the inconvenience of mobile parts, because they are likely to suffer from leaks [27] when the fluid pressure is considerable high, as in the case of direct steam generation at pressures around than 100 bar.
– Central receiver technologies of any type work with very high thermal fluxes in the receiver, that implies the possibility of malfunction and the dependency of the whole plant not only of the power block, but also of another unique piece in the installation, the receiver.
– In the case of molten salts, the possibility of freezing is a huge problem. Comparing the use of molten salts and CO_2 as working fluids, another benefit for CO_2 is related to the risk of freezing in the solar field piping at low ambient temperatures, because such a risk is avoided with gas and the solar field O&M is thus enhanced when ambient temperatures are below 0 °C. However, the thermal stability limit of salt mixtures currently used (600 °C) imposes a limit to the receiver working temperature. Anyway, it is important to remark that molten salts have an important advantage: thermal inertia. This characteristic can be an inconvenience in the case of gases concerning controllability, and it constituted one of the main aspects to study with the experimental facility described in Section 3.

At this point, looking at the solutions already implemented in the nuclear field, there seems to be another possibility to achieve higher working temperatures and efficiencies: trough collectors cooled by pressurized gas, for instance with carbon dioxide [28] or helium [29,30]. It is known that nuclear engineering must follow the safety parameters very carefully in every sense, and specifically in the way that thermal energy must be transferred from the nuclear rods to the heat sink. One system appears in this process, the nuclear rods cooling, not only depends on pumps and blowers, but also the stability of the coolant plays a very important role. In this sense, carbon dioxide allows the heat transfer in a safe way up to very high working temperatures [31].

With this basis, it was considered worth exploring the combination of trough collector's solar technology and pressurized gases. The initiative took shape through the CIEMAT [32] efforts at the Plataforma Solar de Almeria [33], with the initial contribution of Prof. Carlo Rubbia and some members of CIEMAT, PSA, SERLED [34] and Universidad Politécnica de Madrid [35].

The main features of this technology are presented in section two, including the theoretical basis that justifies the values of temperature and pressure of the fluid. Also the fluid selection is justified. In section three, the test facility built at the PSA is described. Section four presents some of the experimental results obtained and consequences. The paper is completed with the conclusions section and the proposed future tests and plans.

2. Main features of the technology

The main idea of the new technology is the use of a gas as heat transfer fluid on solar parabolic troughs. Some options are helium, carbon dioxide, air or nitrogen. Helium is the most expensive and air is the cheapest, but it presents, with N_2, the poorest thermo-hydraulic behavior as heat transfer fluid in the collectors.

This fact has led to the use of carbon dioxide at the first stage of development. On the other hand, CO_2 has been applied as heat transfer fluid in many fields, including gas-cooled nuclear reactors [30]. The main constraints for using gas coolants are the components temperature and pressure working limits: absorber tubes, ball joints or flexible hoses, pipes, etc., instead of the fluid degradation of oil-based coolants.

2.1. Theoretical principles

High temperature is a key point to obtain higher efficiency in the thermodynamic cycle. In the case of gas application, special