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Direct steam generation in linear solar concentration: Experimental and modeling investigation – A review

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ABSTRACT

The present work gathers the main studies in the field of linear solar concentration operating at direct steam generation and gives a comprehensive state of the art. It discuss the direct steam generation operational strategy and advantages, and presents a brief introduction to the two-phase flow phenomena. This review shows an overview of the main experimental studies performed in the area, alongside models found in the literature. It presents the main considerations and conclusions of each model. The type of work performed by the authors is divided into sections: experimental, one-dimensional models, light water reactor evaluation software, among others. Even though direct steam generation in solar concentrators is a relatively new concept, it has been properly studied and proved to be a viable operational strategy for both new solar power plants and to generate steam for industrial heating. However, further studies on this subject must be performed. All the works here gathered may serve as a basis for these new studies.

1. Introduction

1.1. Context

Our society faces a serious environmental problem. The majority of the energy produced nowadays comes from sources environmentally unsustainable. Energy production through these sources is directly associated with greenhouse gas emissions, which leads to environment degradation and global warming. These environmental concerns have forced governments and agencies to study alternative approaches and actions that must be taken in order to change this bleak outlook. The solution requires political action, research and development of sustainable energy production. All of those reasons reinforce the relevance of clean and viable renewable energy sources, and among them, solar energy is one of the most promising option, due to its immense potential and increasingly lower production costs.

There are two main technologies to harness solar radiation. One is the photovoltaic cells, which generate electricity directly via the photovoltaic effect. This type of generation suits small-scale production, such as housing generation and off-grid installations in remote areas and industrial scale plants. One major drawback of this technology is the lack of economically feasible, large-scale energy storage technologies.

The other way to harness solar radiation is by Concentrating Solar Power plants (CSP), which make use of the thermal energy of solar radiation. This can be considered the most probable technology to provide a considerable part of the future demand of renewable energy [1]. The International Energy Agency has made two technologies roadmaps for CSP generation. The goal set in the 2010 roadmap was for CSP to reach about 11% of global electricity generation in 2050. In the revisited roadmap of 2014, that goal was maintained, which is a positive indicator towards CSP development [2]. Considering CSP and photovoltaic, solar power could generate 27% of the global electric demand by 2050. This roadmap aims to suggest actions in order to restrain the global warming limit to 2 °C in the long term [2].

Solar radiation is the most abundant energy resource available on earth. The radiation energy reaching the surface of earth is 3500 times the global energy demand estimated for 2050. However, solar radiation is a resource of relatively low density, and harvesting it efficiently is not a simple task. For that, CSP systems usually use glass mirrors or reflective film to concentrate radiation on a receiver element, in order to harness it more efficiently. Since the diffused radiation cannot be concentrated, only the direct portion of the solar radiation is useful in these systems. The concentrated radiation allows the receiver to reach higher temperatures than a flat plate collector would achieve, due to its smaller surface area, which considerably reduces heat loss to the environment. Flat plate solar collectors usually do not exceed 100 °C of operating temperature, while CSP systems can reach temperatures

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above 400 °C. Inside the receiver flows the Heat Transfer Fluid (HTF), responsible for absorbing the thermal energy from the concentrated radiation. This heated HTF can be used in several ways besides electric energy production, such as cooling, salt-water desalinization, steam production for industrial processes, among others. Usually, for electrical energy production, the heated HTF is responsible for steam generation in a Rankine Cycle.

CSP technologies can be hybridized to operate with conventional fuel burners, which increases its dispatchability and reduces the investment risk. Solar fields can also be installed in already operating thermal power plants, reducing fuel consumption. Another way to improve the dispatchability of solar thermal plants is by adding a Thermal Energy Storage (TES) system, allowing them to overcome solar transients such as the passing of clouds and even producing electricity for hours into the night. This represents a great advantage of CSP over other renewable energy sources such as photovoltaics and wind power. In 2014, the global deployment of CSP electric energy production was approximately 4 GW, while for photovoltaics was roughly 150 GW. The dispatchability on demand that CSP with TES system have, may change this panorama [2].

Although it looks like CSP and photovoltaic are competing in the solar generation market, they are, ultimately complementary. To maintain a larger solar matrix, the energy demand must be supplied during the whole day. Photovoltaic generation is higher in the middle of the day, while CSP can use TES systems to generate energy in early mornings, late evenings, and hours into the night. The greater the share of photovoltaic in the global energetic matrix, the greater the importance of TES in CSP.

Most CSP power plants operate with thermal oil as HTF. The heated oil passes through heat exchangers in the power block, where it preheats, boils and in most cases superheat water/steam, in order to feed a turbine. For these cases, there are two distinct circuits working with two distinct fluids, the solar field operating with thermal oil and the power block operating with water/steam. This review focuses on a relatively new concept, a process called Direct Steam Generation (DSG) where steam is generated directly on the solar field. This steam can be either saturated or superheated, and is directly routed to the turbine. DSG can also be used to generate steam for industrial processes.

The designs possibilities for CSP are many. They can be used in both large and small-scale installations, in solar only and hybrid configurations, using thermal oil or water/steam as HTF, etc. However, several questions still need to be answered, and processes must be perfected to guarantee the success of this technology, especially in relation to the DSG operation.

1.2. Objectives of the review

This review discusses CSP generation by linear solar concentrators operating in DSG. This technology is still in its early stages, with very few industrial applications. Therefore, it is important to use previous works and researches when developing new DSG concepts, designs or components in order to save time and to work based on verified conclusions and experiments. Here, a large number of works performed in this subject are gathered, in both experimental and theoretical analysis. The works are reported briefly, however the main considerations and conclusions of each are highlighted. The goal is to facilitate the bibliographic review for researchers working with DSG. In addition, it is always useful to have a wider view of what has been done on the subject, which may aid when choosing a study topic. The review can also give a different perspective on how to approach a problem, by showing how other researchers' works were carried out.

This extensive review addresses the most important issues regarding the two-phase flow in DSG process in linear solar concentrators. In Section 2 the main CSP technologies and the DSG topic are discussed. In addition, it presents a brief introduction about the physics of the two-phase flow.

Section 3 presents the main experimental works performed in the area of DSG using CSP linear technologies. The conclusions drawn from these works are discussed.

Section 4 gathers the models developed in the DSG context, regarding the hydrodynamic aspects of the two-phase flow and the thermal distribution on the receiver, highlighting their respective breakthroughs.

The models developed to describe the DSG processes are separated in one-dimensional models and three-dimensional models. Inside the one-dimensional models, the ones performed with Modelica are separated in a subsection, due to the quantity of works and to a specific library created in this language to treat DSG in solar fields. The other subsection discusses the works performed in light water reactor evaluation software, adapted to study DSG.

In addition to the discussions mentioned above, this section approaches some works performed in instabilities on DSG solar fields, and works performed in temperature homogenization due to metal insertions inside the absorber tube. Solar linear concentrators generate a non-uniform profile of concentrated radiation on their receivers, and this profile can affect the two-phase flow phenomena, therefore a few works are reported and discussed to give an overview on the subject.

In Section 5 the concept of thermal energy storage systems for DSG solar fields is introduced, and some works are presented. Finally, some discussions and perspectives for the DSG technology are presented in Section 6.

2. Technology background

2.1. Main CSP technologies

The four main CSP technologies are represented in Fig. 1. Of these, there are two of punctual concentration, the solar dish and solar tower, and two CSP of linear concentration, the Parabolic Trough Collector (PTC) and Linear Fresnel Collector (LFC).

Punctual concentration systems have higher concentration ratio and therefore are able to reach higher temperatures. Among the punctual concentration technologies, there is the dish systems (Fig. 1(d)). Solar dishes look similar to parabolic antennas, with a receiver mounted on its focus and a two-axis tracking system. The parabola follows the movement of the Sun, concentrating the radiation on the receiver.

These relatively compact systems are characterized for very high solar concentrated ratios. Because they are more expensive and more difficult to manufacture when compared to other CSPs, this technology is not expected to supply any relevant amount of electric generation in a global context. Solar dishes have a specific niche market, normally recommended for off-grid installations or military application. The receiver is usually a motor generator but even high-quality triple layer photovoltaic cells can be used in these systems. In the majority of cases, the motor generator is a Stirling engine or a small gas turbine. A cost-effective 10 kW Dish-Stirling engine has been developed by the European consortium inside the EURO-DISH project [1].

The other punctual concentration technology is the solar tower (Fig. 1(c)). These systems are composed by a central tower with the receiver mounted on its top, built on the middle of a field of mirrors called heliostats. The heliostats have two-angle individual solar tracking which redirect the solar radiation to the receiver. This technology has high concentration ratios, and can achieve temperatures above 800 °C. The high temperature HTF from solar tower can be used to drive a steam cycle or for gas turbine and combined cycles. This is the most commercially viable punctual concentration technology. There are some grid-connected solar towers in operation around the world.

This review studies linear CSP technologies operating with DSG. There are two main types of linear concentrators. One is the parabolic trough collector, which is the most commercially proven CSP technology in the market nowadays. Several operational power plants use