A Concentrating Solar Power prototype for validating a new Fresnel-based plant design

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Abstract

A prototype of adequate scale is being built in the south campus of the Technical University of Madrid (in Getafe, Spain) to validate a number of innovations of a new Advanced Linear Fresnel Reflector featured by:

- A modular concept of receiver unit made of several tubes in a multi-pass configuration, with a size that can be made at a workshop or a factory, transported by ordinary trucks to the plant site, and assembled into the supporting structure in a simple way with a moving crane.
- A set of mirrors with the proper curvature, made of originally flat mirrors which are bent to the required distortion
- A newly developed focusing system, which will also be part of the supporting structure of the mirrors.
- The use of a gas as heat carrier fluid, notably CO\textsubscript{2}, at a working pressure close to 10 MPa.
- A number of collecting tubes which will gather the outlets of the 8 receiver modules to send it to an air-cooler for restoring the gas temperature to the value at the beginning of the thermal circuit, which includes a gas blower (or compressor-circulator) for restoring the pressure level.

The purpose is to minimize the amount of total mass of the different materials used in the capture of solar thermal power, which is sent to the power block for its valuation. It is expected to provide a significant reduction of costs compared to the complexity of the current methods to capture high temperature solar energy.

In two years, the goal is to develop this type of solar field up to industrial and commercial scale using the prototype as a guarantee for that quest.

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1. Introduction

Solar Thermal Energy for electricity generation is set up by the integration of a Solar Field (SF) and a Power Block (PB), featured by a thermodynamic cycle and some ancillary systems. In the interconnection between those blocks a third component can be placed: Thermal Energy Storage (TES), which allows to manage the plant load according to the demand, and extend the electric supply beyond the sunset.

Despite the higher capital cost than conventional technologies, it is worth pointing out that no fuel is needed to run a CSP plant, because energy is provided by solar radiation. This advantage may be obvious in the environmental aspect, but it is also a benefit regarding long-term saving and logistics, as it makes it easier to build them in remote sites like deserts with the best Direct Normal Irradiance (DNI). In turn, the size of the Solar Field must be increased proportionally to the size of the TES which is not an essential component of the plant but should be considered as such for the sake of operating the plant without instant solar energy. Thus, the cost of electricity generated by CSP plants mainly depends on the investment cost of the SF. On the contrary, the technology of the PB is, to some extent, mature and presents clear economies of scale. Nevertheless, specific cycles have been proposed to meet better the most convenient working points of the CSP solar heat, particularly, its temperature range and working pressure.

Therefore, it is necessary to reduce the cost of the SF with a much lower investment than those of the current technologies, where Parabolic Trough technology (PTC) is the reference.

A previous systemic approach [1] was carried out to identify the most promising line for cost reduction, taking into account the essential features of the different structures of the SF. PTC has the longest receiver and the shortest distance from the mirror to the receiver tube. On the contrary, Central Tower (CT) conveys the shortest length of the receiver, which in turn is located very close to the PB. It also conveys the longest distance from mirrors to receivers, and this implies a strong limitation in the power level per tower unit, because focusing onto the receiver becomes very inefficient with longer distances. The Linear Fresnel Reflector (LFR) is in the middle of that range. The distance between mirror and receiver is around 12 m, while it is 2 m for PTC and 200 m for towers. Regarding the receiver size, a 50 MW e PTC plant (without TES) would need almost 50 km of receiver tubes (and associated mirrors covering around 300,000 m$^2$) with an absorber area of 3,000 m$^2$ which implies a concentration factor of 100. A CT plant would need a 160 m tall and 20 m wide tower, with a total mirror surface close to the
previous value and a receiver surface close to 300 m\(^2\), which conveys a concentration factor of 1,000. Finally, a LFR plant will have around 20 km of receiver tubes, presenting a receiver surface of 6,000 m\(^2\), with a mirror surface around 330,000 m\(^2\), which means a concentration factor of 55. For the working temperatures such those that are reached in CSP (typically below 550ºC), where the heat absorption efficiency is high enough [2], a concentration factor of 55 is sufficient, while the solar field architecture can be simpler, lighter and cheaper. Also, LFR presents more degrees of freedom in the geometry definition and the materials to be used. This could be either an advantage or a drawback: should a decision be mistaken, that option will likely be very far from the optimum, and cost reduction would not be meaningful.

![Fig. 1. A 3D view of the mirror array of the prototype & receiver supporting](image)

An account of the total mass of the materials used in each SF model was done, in relation to their essential features. Current PTC has a linear power density in nominal conditions ranging between 4 and 5 kW\(_{th}\)/m, having a pending weigh of up to 200 kg/m plus some additional masses for the fixed part and foundations. If all the mass is accounted for in equivalent economic terms, all materials such as construction steel, concrete and mirrors can be modeled in cost-equivalent mass, with conversion factors from a given type of materials to the reference one, which should be something as an average of the materials involved. With a set of conversion factors, it is found that we need more than 300 kg per meter in each PTC collector, which can be expressed in terms of mass per unit of thermal power, which would be around 75 kg/kW\(_{th}\). This refers to the nominal operation, but there is another feature of CSP that must be accounted for, namely, the daily and seasonal variations of solar radiation intensity as it is received on the mirrors of the SF. If an average value of the linear power density is used for qualifying the plant, previous values change to 2.5 through 3.5 kW\(_{th}\)/m, and correspondingly we obtain a range of mass of 80 through 120 kg/kW\(_{th}\).

Our analyses [3-5] identified Fresnel longitudinal collectors as the type of solar radiation concentrator with the best performance/cost ratio for the range of working conditions to power a standard Rankine cycle; this is because a radiation level of 40 kW\(_{th}\)/m\(^2\) is good for that goal. Meanwhile, PTC reaches up to 80 kW\(_{th}\)/m\(^2\) and CT can arrive to 300 kW\(_{th}\)/m\(^2\), which goes far from the optimum in terms of global performance coming from solar energy.

Moreover, higher concentrations, such as those obtained with a central receiver, cause thermal-mechanical stress on the receiver, which reduces its useful lifetime and jeopardizes the plant reliability.
In this paper, an Advanced LFR-based prototype is presented and a 3D scheme is depicted in figure 1. Its main innovations are briefly explained afterwards, aiming to improve thermal performance and to reduce construction costs. In order to do that, a task force has been put in operation, joining synergies between the Research Group on Thermal Energy Systems of the Technical University of Madrid (UPM, embodying some professors from UNED University, also in Spain) and OHL Industrial, the industrial division of OHL Group, a large corporation mainly acting in the fields of Civil Works and Concessions internationally.

2. Overall description of the prototype

Solar field components need new materials for getting better cost/performance results, but the main dependence is the system morphology. Linear Fresnel has the lowest capital cost in the solar field, which can give sense to the Thermal Energy Storage (it needs a solar multiple which in the case of TCP technology, increase the LCOE).

The project will rely on gases, such as HCF, especially CO$_2$ and air; although air has some problems related to oxidation. On the contrary, CO$_2$ is an inert gas without any safety problem until reaching volume concentrations in the air above 8%, with very positive heat transfer features at high operational pressure levels. High P (higher than 75 bar) is needed for:
- High values of the heat transfer convection coefficient
- Low pressure drop values and therefore low values in pumping power
A positive previous experience in thermal performance using CO$_2$ in parabolic through collectors was accomplished by the UPM team; however, this experience was negative regarding gas leakage through rotating joints [6]. This problem could be completely avoided in brazed multi-tube receivers, with free dilatation, as the ones explained hereafter.

Figure 2 shows the layout of the plant, which will work with CO$_2$.
The mirror field is made of 12 stripes of 32 meters long each. Each mirror is 1.36 meters wide, except the latter which is wider since the chosen embodiment has been East-West instead of North-South.

Each reflecting module is composed of 4 individual mirrors, and the corresponding pillars have 8.30 meters of separation (between axes). A particular rotating device with a smart lock structure placed
on top of each pillar of the series which allows to follow a very simple procedure to fix the mirrors on the rotating structure without needing a crane because each part of the system is lighter than 50 kg and can be safely and easily managed by two workers. The main beam of the mirror frame is just an 8.20 meters long square hollow tube, and it is assembled to the outer frame of the mirror, which is a simple rib made of four pieces connected in the corners. They are also very light because they do not have a supporting function. The real support is done by the ends of the main beam as it goes into the rotating cap of each pillar plus a special innovation depicted in figure 3, which is made of two arms connected to a rotating grip placed in the middle of each of the long ribs of the mirror frame. Those arms come vertically from below, where a multi-cycle array rotates at the same speed as the mirrors; the arms being vertically fixed to the lower cycle array, although each arm tip rotates around an axis. So, the mirror does not need a very robust and heavy supporting structure rotating on two points in the ends of the main beam, because each mirror is kept in its middle cross section by a moveable system which keeps the mirror inclination just in the angle required for a perfect focusing on the receiver central line.

Fig. 3. Cycle system for structural support of the mirrors and sun tracking

Although all mirrors rotate at the same speed when they track the Sun, and therefore a unique cycle system would be enough to move all the mirrors; in this prototype it has been decided to use two different cycle systems, to improve reliability and operational availability (the system could work only with half the mirrors).

Receivers are placed on top of two upper beams which are supported by transversal arches. The separation between the arches faces is 12 meters, and two independent receivers are placed in this length. Concentrated radiation across the receiver is not uniform, with a lower intensity in the outermost strips and the maximum value in the central axis, where radiation can reach over 55 kW/m². If those radiation beams are absorbed in a single tube, entropy increases: the higher the intensity is, the higher the exergy is. Hence, it is advisable to absorb the impinging radiation in several parallel tubes laid inside the receiver box. Receivers selected for the prototype will be composed by a specific rack of tubes. The flow of all receivers, as depicted in figure 2, merges into a single stream headed to the air-cooler, where the absorbed heat is rejected into the atmospheric air. An auxiliary system compensates the variations suffered by the CO₂ pressure. Once cooled to the required temperature, the gas flows into a blower which gives the thrust to overcome the pressure loss along the full circuit.

The control system will have two fundamental parts: sun tracking and thermal performance. The former is done based on astronomical data and experimental verification, and it actuates on the tilt of the mirrors, which is governed by the cycle system. Additionally, the thermal control takes the map of temperatures and mass flows as main input, and acts on the fine control valves in order to reduce or to
increase the pressure loss in the corresponding branch of the circuit, so that the temperature map coincides with the sought values. Instrumentation also includes the temperature of the tubes in some specific points, as well as information on the pressure inside the receiver box, which can be evacuated by a vacuum pump if that option is selected. The receiver box is reinforced to withstand such a pressure difference.

3. Expected results

A broad range of new results is expected almost in every part of the Solar Field under investigation, from the mirror array and mirror tracking system to validation of CO₂ as HCF with LFR, as well as assessing the behavior of different coatings as far as absorbing solar radiation is concerned.

The thermal output of the prototype will be around 400 kWth, distributed in several receivers. The gas will aim a temperature close to 500ºC. Maximum efficiency in a receiver is expected to reach 85%, mainly for gas flows coming in at 150 ºC and going out at 400ºC, but the efficiency will remain over 80% for the other cases with inlet temperature of 250ºC and outlet temperature of 500ºC (which will have an exergy efficiency higher than that of lower temperature cases).

Other expected results should be kept confidential within the task team, until they are processed by a larger team to prepare the design of the commercial plant that should contribute to make CSP really competitive with the classical energy sources. In order to achieve that goal, we rely on a number of innovations such as:

- mirrors truly rotate around axes that correspond to the central line of the mirror surface, and so, it is avoided any additional optical errors produced by the eccentricity of the axes
- mirror width is limited by the maximum lateral drift that it is admitted when the sun position changes from the zenith to sunset, what is given by a own theorem [3]
- receiver unit is designed for being very short, what implies a very fast feedback from the control system. This is possible by selecting an optimum L/D pipe aspect ratio [4]

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References


Biography

Ricardo Muñoz is in charge of Research, Development and Innovation and Corporate Social Responsibility in OHL Industrial. He has a Higher Degree in Industrial Engineering and two Master’s Degrees: MBA in Energy, Industry and Environment and another Master on Renewable Energies. Currently, he is enrolled for Ph.D. studies in Technical University of Madrid (UPM).