MEDIUM TEMPERATURE SOLAR CONCENTRATORS (PARABOLIC-TROUGHS COLLECTORS)

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Contents

Summary

This Topic-level contribution provides information about parabolic-trough solar collectors, which are concentrating devices able to convert direct solar radiation into thermal energy up to 400ºC with a good efficiency. This temperature level makes this type of solar collector to be very suitable for many commercial applications of solar energy to industrial thermal processes, including electricity generation by means of a Rankine cycle. The working principle of these solar collectors is explained here, as well as the basic equations governing their thermal and optical behavior (Sections 2, 3 and 4). Different ways to couple a solar field with parabolic-trough collectors to industrial processes and an introduction to suitable thermal energy storage systems are also included in Sections 6 and 8 of this Topic-level contribution. Since direct steam generation in the receiver pipes of parabolic-trough collectors (the so-called DSG process) is seen as a promising option to reduce the cost of thermal energy produced by these collectors, a review of the state-of-the-art of this new technology is given in Section 7. Although electricity production is at present the most outstanding industrial application of parabolic-trough collectors, only an introduction to solar thermal power plants with this type of solar collectors is given in Section 9 of this contribution because this particular application is further developed and explained in other contribution.

1. Introduction

At present, the World energy consumption is based on fossil fuels, which release a huge amount of gases that provoke the well-known greenhouse effect. This is the main reason for the significant climate change and natural disasters (e.g. hurricanes, flooding, etc.) taking place more often nowadays. Most of scientific studies performed in recent years have come to this conclusion. Together with this negative impact of fossil fuels consumption on the environment, there is another important reason that must be taken into consideration when evaluating the medium and long-term perspectives of current energy market scheme: the limited fossil fuel resources. Though the size and capacity of fossil fuel resources currently available can be discussed, there is no doubt about the impossibility to meet the energy demand with fossil fuels for ever. It is therefore clear that alternative and renewable energy sources are needed to make compatible the future energy demand and a sustainable growth of the mankind. To this extent, wind and solar energies are the best candidates for massive energy production.

Solar radiation can be directly converted into electricity (by means of photovoltaic cells) or thermal energy (by means of solar thermal collectors). The temperature level achieved when converting solar radiation into thermal energy depends on the type of system used for the conversion. While flat plate solar collectors are suitable to produce hot water or air up to 80ºC (approximately), higher temperatures can be achieved when using evacuated tube collectors (125ºC), parabolic-trough collectors (400ºC), central receiver systems (1000ºC) or dish concentrators (>2000ºC). Though these temperature numbers are approximate, they give a good idea about the typical temperature range for the systems mentioned.

Market studies performed in USA and Europe have shown that energy consumption at temperatures below 400ºC represent between 15% and 20% of the total energy consumption in those places. Though this energy demand is mainly supplied with fossil fuels at present it could be met with solar concentrating systems suitable to work within this temperature range (i.e. flat plate and parabolic-trough solar collectors). While the typical temperature range of flat plate collectors is more suitable to produce hot water for domestic applications, parabolic-trough collectors are the best option nowadays for industrial applications in the range 150ºC – 400ºC. The commercial maturity of parabolic-trough collectors is clearly stated by the more than 2 x 10^6 m^2 of this type of collector installed in California (USA) and in operation since the 1980s.

2. Parabolic-trough Collectors: Working Principle and Components

Figure 1 shows a typical parabolic-trough collector (PTC), which is basically composed of a parabolic-trough-shaped concentrator that reflects direct solar radiation onto a receiver tube located in the focal line of the parabola (linear-focus concentration). Since the collector aperture area is bigger than the outer surface of the receiver tube, the direct solar radiation is concentrated. The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar radiation into thermal energy in the form of sensible heat of the fluid. This fluid can be efficiently heated up to 400ºC.

The *concentration ratio* of a PTC is the ratio between the collector aperture area and the total area of the absorber tube. Usual values of the concentration ratio are about 20, although the maximum theoretical value is in the order of 70. High concentration ratios are associated to higher working temperature. The *Concentration Ratio*, *C*, is given by (1).

$$C = \frac{l_a l}{\pi d_o l} = \frac{l_a}{\pi d_o} \qquad (1)$$

being:

d_o : outer diameter of receiver steel pipe
l : collector length
l_a : parabola width

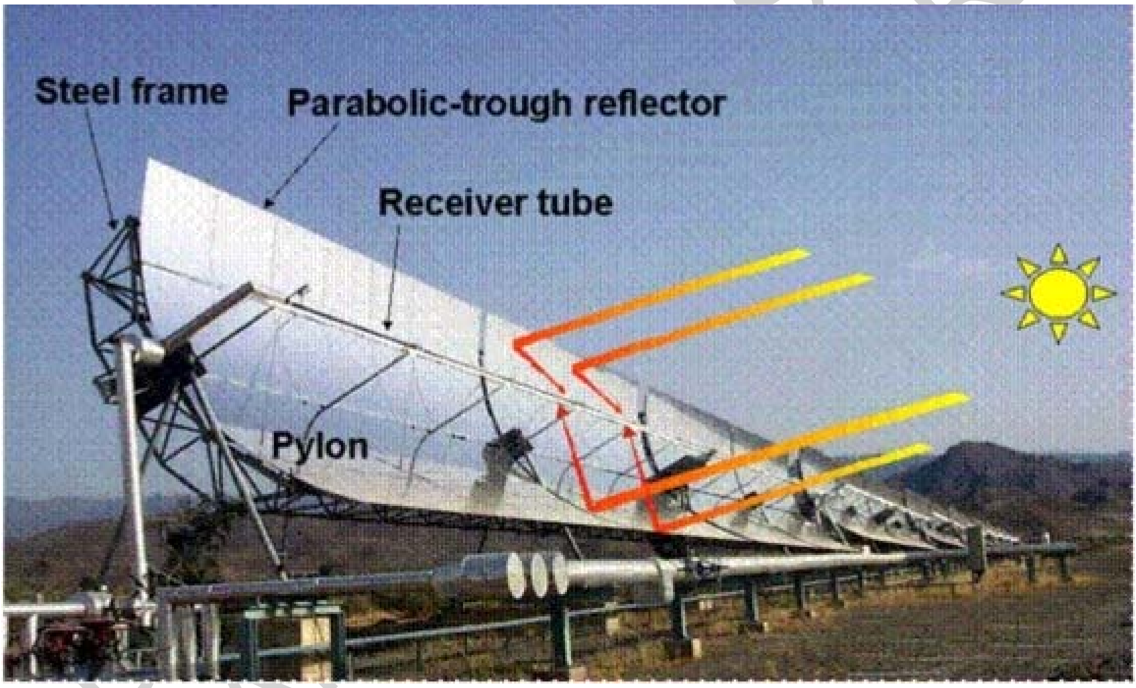


Figure 1: A typical parabolic-trough collector

Since a PTC is an optical solar concentrator it has to be positioned at every moment in accordance with the Sun position (i.e. Sun vector) so that the incoming direct solar radiation is reflected onto the receiver tube. If the concentrator is not in the right position, the reflected Sun rays will not intercept the receiver tube. Figure 2 shows the way direct solar radiation has to reach the aperture plane of the collector in order to be properly reflected onto the receiver tube. Since the diffuse solar radiation falls onto the Earth's surface at ground level without a specific direction this component of the solar radiation is useless for parabolic-trough collectors because it can not be reflected by the concentrator towards the receiver tube. This is the reason why parabolic-trough collectors are dynamic devices that change their position as Sun moves in the sky during sunlight hours.

Figure 2 refers to a PTC with a single-axis tracking system (i.e. the concentrator can rotate around one axis, the so-called "tracking axis"), which is the case of the collector shown in Figure 1. Though PTCs with two-axis tracking systems were designed, manufactured and tested in the past, evaluation results showed that they were less cost-effective than single-axis collectors. The existence of a two-axis tracking system reduces optical losses while increasing the amount of solar radiation available at the PTC aperture plane. However, the length of passive pipes (i.e., pipes not heated by concentrated solar radiation) and the associated thermal losses are significantly higher than in single-axis collectors. Furthermore, their maintenance cost are higher and their availability lower because they require a more complex mechanical design.

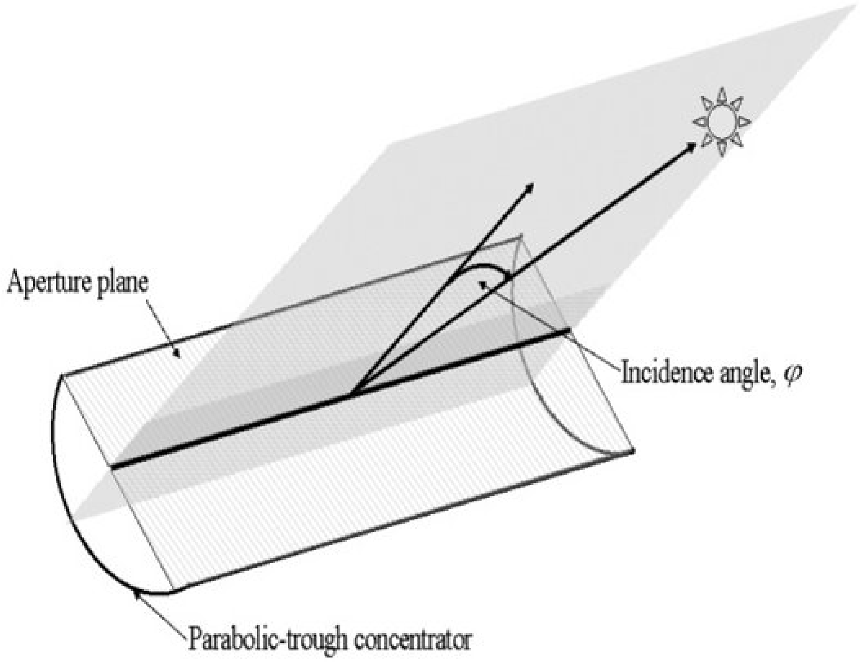


Figure 2: Correct positioning of a parabolic-trough concentrator

Parabolic-trough collectors are usually installed with their tracking axis oriented either North-South or East-West, although any other orientation may be feasible too. The orientation of the tracking axis has a significant influence on the Sun's incidence angle onto the aperture plane of the collectors which, in turn, affects the collector's performance. The incidence angle is the angle between the normal to the aperture plane of the collector and the Sun's vector— both contained on a plane perpendicular to the collector's axis (see Figure 2).

Seasonal variations in collector output for North-South oriented collectors can be quite large. Three to four times more energy is delivered daily during summer months than in winter months, depending on the geographical latitude and site weather conditions. Seasonal variations in energy delivery are much smaller for an East-West orientation. Nevertheless, the yearly thermal output of a PTC with its tracking axis oriented North-South is greater. This difference in energy output is caused by the different incidence angle of the direct solar radiation onto the aperture plane of the concentrators. Daily variation of the incidence angle is always greater for East-West orientation, having maximum values at sunrise and sunset times and a minimum value of 0º every day at solar noon.

Collector movement along the day requires a drive unit. One drive unit is usually sufficient for several parabolic-trough modules connected in series and driven together as a single collector. The parabolic concentrators are supported and connected to the foundations by pylons. The type of drive unit assembly depends on the size and dimensions of the collector. While units composed of an electric motor and a gearbox combination are used for small collectors (aperture area < 100 m^2), powerful hydraulic units are required to rotate large collectors. The drive unit is placed at the central pylon and it is commanded by a local control unit which tells the drive unit when and in which direction to rotate the collector to track the Sun. The Sun position has to be known by the control unit to decide when the collector position has to be changed. For this purpose, the Sun position can be either physically detected by means of solar cells or theoretically calculated using accurate mathematical algorithms. Both systems are commercially available nowadays.

The heart of a PTC is its receiver tube, because the overall efficiency of the collector greatly depends on the optical and thermal properties of this element (e.g. solar absorptance, thermal emittance, thermal loss coefficient, etc.). The receiver tube of a typical PTC is composed of an inner steel pipe that is surrounded by a transparent glass pipe to reduce convective heat losses from the hot steel pipe. The steel pipe is provided with a selective coating, which has a high solar absorptivity (>90%) and low emissivity in the infrared wavelength range (<30%), thus reducing thermal losses by radiation. Several types of coatings are commercially available for PTC. If the working temperature is below 290ºC, a cheap electrically deposited black-chrome or black-nickel coating can be used. For higher temperatures, sophisticated cermet coatings manufactured by physical vapor deposition (PVD) or sputtering are required to achieve a good thermal efficiency (~ 70%) of the PTC.

Receiver tubes with vacuum between the steel pipe and the glass cover, as well as glass pipes provided with an anti-reflection coating are used to achieve higher thermal efficiencies and better annual performance of the PTC, especially at higher operating temperature. Vacuum-less receiver tubes are usually implemented for working temperatures below 250ºC, because thermal losses are not so critical at these temperatures. Due to manufacture constraints, the maximum length of single receiver pipes is less than 6 meters, so that the complete receiver tube of a PTC is composed of a number of single receiver pipes welded in series up to the total length of the PTC. The total receiver tube length of a PTC is usually within the range 25 – 150 meters.

Figure 3 shows a typical vacuum receiver pipe for PTCs. The glass cover is connected to the steel pipe by means of metallic expansion bellows which compensate for the different thermal expansion of glass and steel when the receiver tube is working at nominal temperature. The glass-to-metal-welding used to connect the glass cover and the flexible bellows is a weak point in the receiver tube and it has to be protected from the concentrated solar radiation to avoid a high thermal and mechanical stress that could lead to the breakage of this welding. A aluminum shield is usually placed over the flexible bellows to protect the welding.

It can be seen in Figure 3 that several pieces called “getters” are placed in the gap between the steel receiver pipe and the glass cover. The mission of these “getters” is to absorb the molecules of gasses that pass from the fluid to the annulus through the steel pipe wall during the expected life-time of the receiver tubes (> 20 years). “Getters” are usually made of a zirconium – strontium - vanadium – manganese alloy, though the exact composition is patented and not publishable.

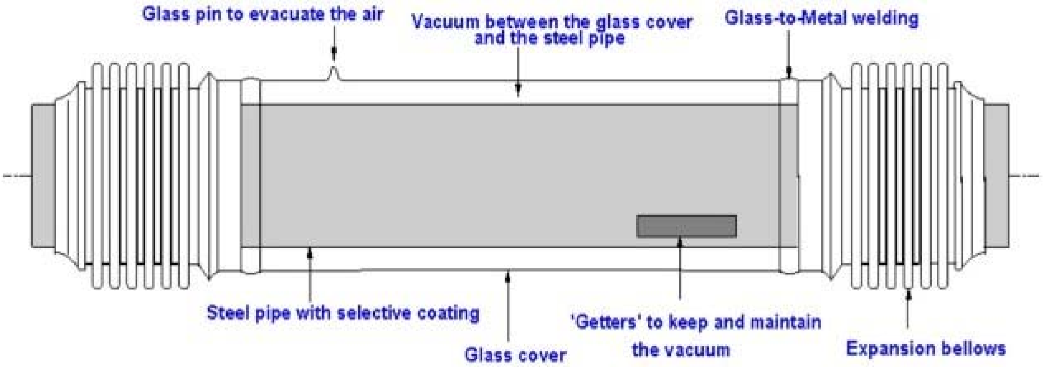


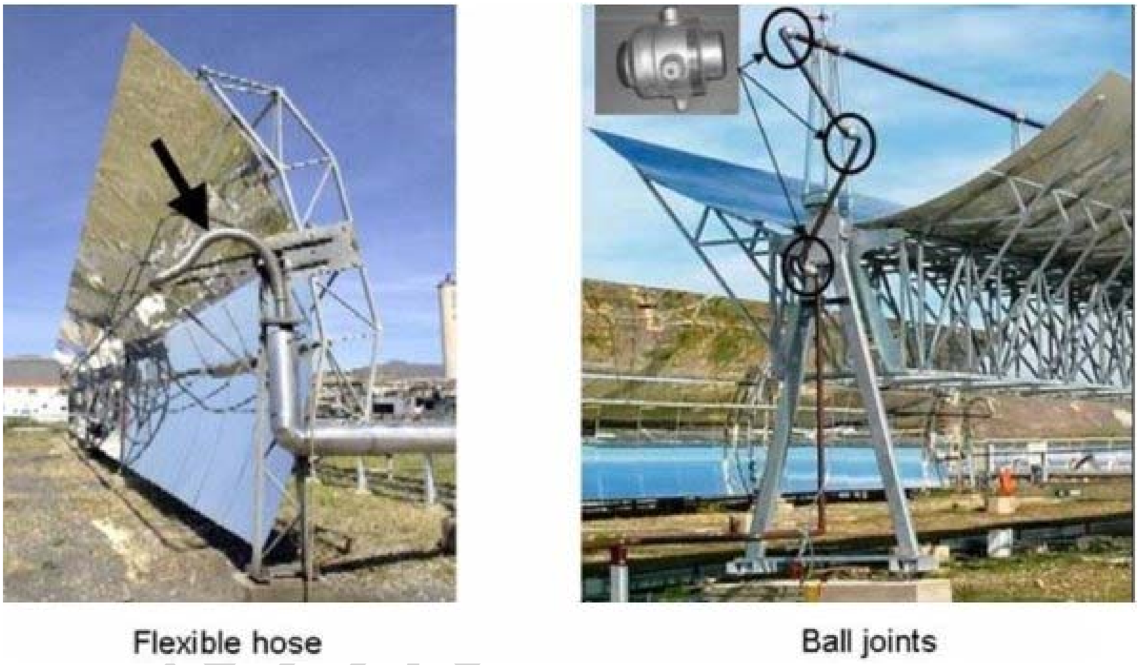
Figure 3: A vacuum receiver tube for parabolic-trough collectors

Reflectors play also an important role in the performance of a PTC because its optical efficiency is proportional to the solar reflectance of the mirrors composing the concentrators. Reflectors commonly used in PTC are made of either back-silvered glass mirrors or polished aluminum sheets mirrors. Durability and solar spectral reflectance of glass mirrors (~ 0.92) are better than those of polished aluminum sheets (~ 0.87). Since iron has an absorption band within the solar spectrum, glass with low iron content is used for the reflectors and receiver tube glass envelopes used for PTCs.

A typical solar field with PTCs is composed of a number of parallel rows of collectors, with several collectors connected in series within every row. The number of PTCs connected in series within every row depends on the temperature increase to be achieved between the row inlet and outlet, while the number of rows connected in parallel depends on the required nominal output thermal power at the design point. The higher the nominal output power, the more parallel rows are needed. Within every row of collectors, receiver tubes of adjacent parabolic-trough collectors have to be connected with flexible elements to allow independent rotation of both collectors when they track the Sun during sunlight hours. These flexible connections are also needed to allow the linear thermal expansion of the receiver tubes when their temperature increases from ambient to nominal temperature during system start-up. Two main types of flexible connections are available: flexible hoses and ball joints.

Flexible hoses for temperature below 300ºC are composed of an inner hose that can withstand this maximum temperature and an outer metal braid shield that protects the inner hose. Proper thermal insulation is installed on the outer metal braid to reduce thermal losses. For higher temperatures, stainless steel bellows are usually implemented. This type of flexible hose has a more limited flexibility and introduces a significant pressure drop in the circuit because of its high friction coefficient. The minimum bending radius defined by the manufacturer must be taken into consideration to prevent overstressing of the bellow.

Ball-joints are other option to implement a flexible connection between the receiver tubes of adjacent collectors. The main benefit of this option is a significantly lower pressure drop. Ball joints are provided with an inner graphite sealing to reduce friction and avoid leaks. Nowadays, ball-joints are most widely used for working temperatures above 300ºC and the flexible hoses installed in the 80´s of last century at the solar power plants of California are being replaced by ball joints because they have a better reliability and lower maintenance costs. Flexible hoses are likely to suffer from fatigue failures resulting in a leak, while ball-joints only require a refilling of the graphite sealing after thousands of hours of operation. Figure 4 shows typical connections with both flexible hoses and ball-joints.



Flexible hose

Ball joints

Figure 4: Flexible hose and ball-joint connections

The selection of the working fluid for a solar field with PTCs is a very important decision in the design phase. Thermal oil is the fluid commonly used in parabolic-trough collectors for temperatures above 200ºC, because these operation temperatures would produce high pressure inside the receiver tubes and piping if normal water were used. This high pressure would require stronger joints and piping, and thus raise the price of the collectors and complete solar field. However, the use of demineralized water for high temperatures/pressures is currently investigated at the Plataforma Solar de Almería (PSA) and feasibility of direct steam production at 100bar/400ºC in the receiver tubes of parabolic trough collectors has been already proven at an experimental stage. For temperatures below 200ºC either a mixture of water/ethylene glycol or pressurized liquid water can be used as working fluid because the pressure required to keep the fluid in liquid phase is moderate.

There are several thermal oils suitable for parabolic-trough collectors. One of the key parameters to be considered when choosing the appropriate type of oil is the maximum bulk temperature defined by the manufacturer to guarantee a good oil stability if such temperature is not exceeded. Above this temperature, oil cracking and rapid degradation may occur.

The oil most widely used in parabolic-trough collectors for temperatures up to 395ºC is VP-1, which is an eutectic mixture of 73.5% diphenyl oxide / 26.5% diphenyl. The main problem of this oil is its high solidification temperature (12ºC), which demands the implementation of an auxiliary heating system when oil lines run a danger of cooling below this temperature. Since the boiling temperature at 1 013 mbar is 257ºC, the oil circuit must be pressurized with nitrogen, argon or any other inert gas when oil is heated above this temperature. Blanketing of complete oil circuit with a oxygen-free gas is a must when working at high temperatures because high pressure mists can form an explosive mixture with air. Though there are other thermal oils suitable for slightly higher working temperature and with lower solidification temperature (e.g. Syltherm 800), they are unaffordable for large solar plants due to their much higher price. The use of oil as working fluid in solar fields is internationally known as Heat Transfer Fluid Technology (HTF), because the oil acts as a heat transfer medium between the solar field and the process where the thermal energy delivered by the solar field is consumed.

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