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CST Receiver tube qualification, Phase 1, Investigation

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Contents

Abstract

In this report the different application possibilities for concentrated solar thermal (CST) systems are studied. Further, the possible methods for characterising and qualifying the receivers with their embedded absorber tubes are investigated.

The investigations show, CST systems can be used as an environmentally friendly alternative to fossil fuels in many applications. The most known is the generation of electrical power, but concentrated solar energy can also be used for desalination, industrial process heat, and for cooling of buildings. Industrial process heat is a large field situated in the temperature range of 120° C to over 400° C. Heat below 400° C can be provided by different parabolic trough and Fresnel systems, which are optimised for the temperature needed.

In order to further increase the usage of the CST systems, it is of great importance to provide standards for the qualification and characterisation of the different components of the CST systems. Huge efforts are currently made to define a standard for evacuated receiver tubes. For the characterisation of the black absorber tubes the development is still at the beginning, although the need here is also given.

Zusammenfassung

In diesem Report werden die verschiedenen Anwendungsmöglichkeiten von konzentrierter solarer Wärme (CST) untersucht. Des Weiteren werden mögliche Methoden zur Charakterisierung und Qualifizierung von Receivern mit ihren schwarzen Absorberröhren analysiert.

Die Untersuchungen haben gezeigt, die Anwendungsmöglichkeiten von CST Systemen, als umweltfreundliche Alternative für fossile Brennstoffe, ist vielfälltig. Die bekannteste Anwendung ist die Produktion von elektrischem Strom, aber auch im Bereich der Wasserentsalzung, industrieller Prozesswärme und Gebäudeklimatisierung kann konzentrierte Solarenergie verwendet werden. Industrielle Prozesswärme ist ein breitgefächertes Gebiet, das im Temperaturbereich zwischen 120° C und über 400° C angesiedelt ist. Wärme unterhalb von 400° C kann mit Parabolrinnen und Fresnelkollektoren, die für einen bestimmten Temperaturbereich optimiert sind, erzeugt werden.

Um die Nutzung der CST Systeme weiter voranzutreiben, ist die Qualifizierung und Charakterisierung der verschiedenen Komponenten von großer Bedeutung. Derzeit wird viel Energie in die Erstellung eines Standards für evakuierten Receiver-Röhren gesteckt. Die Charakterisierung der schwarzen Absorberröhren hingegen steht derzeit noch ganz am Anfang, obwohl die Nachfrage groß ist.

Résumé

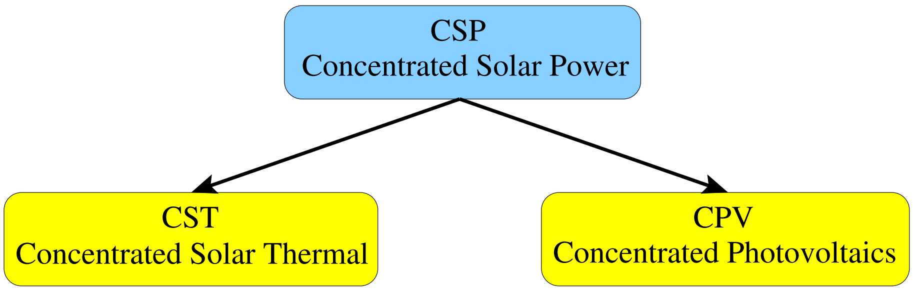
Les différentes possibilités d'application de l'énergie solaire à concentration (CST) sont étudiées ici. Par la suite, les différentes méthodes de mesure et de certification des tubes absorbeurs sont explorées et analysées.

Cette recherche montre que les systèmes CST peuvent être une alternative avantageuse à l'utilisation d'énergies fossiles dans de nombreux cas d'application. L'exemple le plus connu est la génération d'électricité, mais l'énergie solaire à concentration est également appropriée pour le dessalement, la production de froid et la chaleur industrielle. Cette dernière application est un domaine très vaste, en particulier dans la gamme de 120° C 400° C. Ces températures peuvent aisément être produites par les capteurs cylindro-paraboliques et les capteurs de type Fresnel.

Une utilisation extensive des systèmes CST ne pourra se faire que sur la base de standards reconnus de qualification et de certification de leurs différents composants. Des efforts importants sont actuellement faits afin de définir les méthodes de mesure et d'homologation des tubes receveurs. Cependant, en ce qui concerne les tubes absorbeurs proprement dits, cette démarche, bien qu'indispensable, n'en est qu'à ses débuts.

1 Introduction

Concentrated Solar Power (CSP), a rapidly developing field, includes all systems using lenses or mirrors and tracking systems to focus a large area of direct sunlight onto a small area. The efficiency of converting solar radiation into heat and/or electricity can be increased by concentrating the solar radiation. The group of concentrated solar power systems can be divided into two main subsystems, as shown in the schematic below, due to the different usage of the concentrated solar radiation.



Concentrated solar thermal (CST) systems include all CSP systems that transfer solar radiation into heat, independent of the usage of the heat afterwards. This therefore includes the production of electricity by using turbines driven by steam generated in the CST system, as well as the direct usage of the heat as process heat or for cooling of buildings. Depending on the operation temperature, CST is again divided into three subgroups. Systems operating at temperatures 150° C $< T <$ 250° C are characterised as low temperature, systems between 250° C $< T <$ 350° C as medium temperature, and systems with $T >$ 350° C as high temperature.

In a concentrated photovoltaic (CPV) system the solar radiation is focused by mirrors or lenses on photovoltaic (PV) cells, which then transform it directly into electricity. By concentrating the solar light on a PV-Cell the efficiency of the cell can be increased, if the temperature of the cell is kept low through appropriated cooling.

All these systems using concentrated solar radiation to gain heat or power will become more and more important in the future as we have to find alternatives to fossil fuels to prevent further climatic changes.

The aim of this report is to give an overview of CST systems and their components. The main focus is on applications for parabolic trough and Fresnel systems, and especially on the testing and qualification the receivers, the heat collecting element, and their absorber tubes.

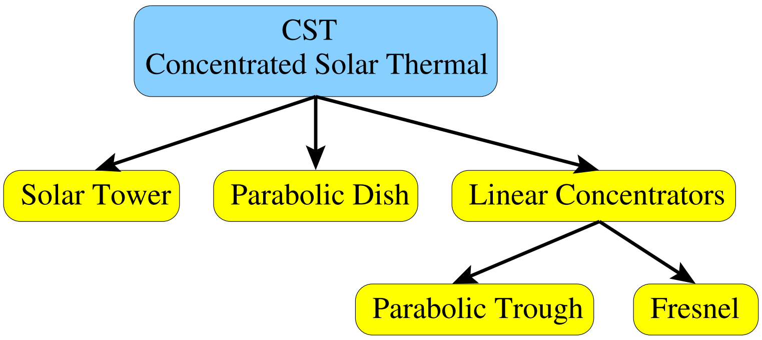
1.1 Historical Overview

Besides the legend telling that Archimedes already used concentrated solar power to beat the Romans in Syracuse, concentrated solar power (CSP) has a long history, although it only became commercially important during the last years. Already in 1866 the French scientist Augustin Mouchot presented the first parabolic trough collector to Napoleon III. Mouchot used the collector to produce steam for driving a steam engine. In 1912 a parabolic trough system, with 62 m length and 4 m aperture, was constructed by Frank Shuman near Cairo to produce direct solar steam. But as oil and coal got cheaper the development of solar power usage slowed down, but research in this field never ended [1]. Only the oil crises in the seventies could reactivate the construction of new solar plants. Two parabolic trough pilot plants for process heat were developed and constructed in the USA between 1977 and 1982. In 1981 the first European pilot plant was build at Plataforma Solar de Almería (PSA), Spain producing 500 kW of electrical power. The first commercial plant SEGS I (Solar Electricity Generation System I) was build in 1984 in the Mojave dessert in southern California by Luz Ltd.

Since the focus on renewable energy systems and the climatic changes have increased, new pilot and commercial concentrated solar power plants have been built. Furthermore there are new projects planned and under construction all over the world, and with projects like DESERTEC concentrated solar power will also play an important role in the future.

1.2 Concentrated Solar Thermal Systems

Concentrated solar thermal is divided into three subsystems, as indicated in the schematic below, depending on the shape of the receiver or the mirror. Whereas the names solar tower and



linear concentrators relate to the shape of the receivers, the parabolic dish describes the shape of the mirrors. The linear concentrators can further be divided into parabolic trough and Fresnel systems, depending on the shape of the mirrors. The different systems will be described in the following sections.

1.2.1 Solar Towers

In the case of solar towers (Figure 1 a)) a central receiver, which is located at the top of the central tower, and an array of reflectors surrounding the tower are used. The flat mirrors need each an individual two axis tracking system to focus the direct solar radiation on the central receiver. Due to the huge amount of solar radiation focused on the working fluid in the receiver, temperatures of $500°$ C to over $1000°$ C can be reached. Solar power towers are therefore used for power generation by using directly the generated steam or by combining it with a heat storage. Further they are used, due to their high concentration ratio and achieved temperatures, for a thermochemical production of hydrogen [2, 3].

1.2.2 Parabolic Dish

A parabolic dish concentrator (Figure 1 b)) consists of a parabolic reflector that concentrates light on to a central receiver, which is positioned at the focal point of the reflector. To always

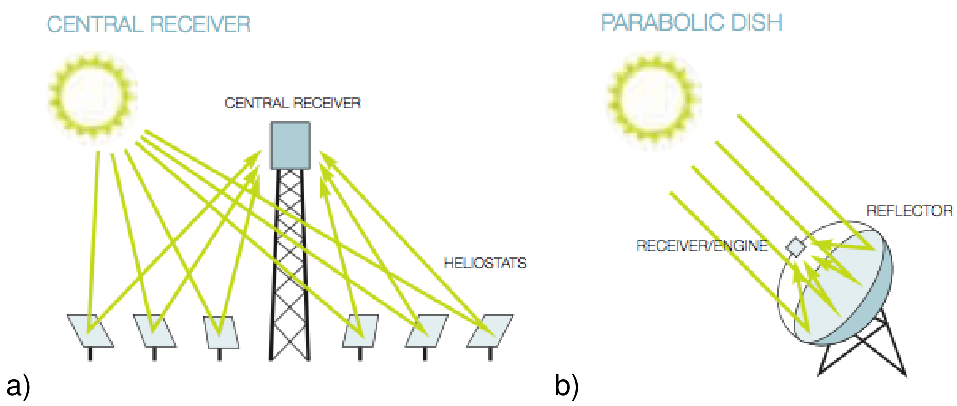


Figure 1: Schematic drawing of a solar tower (a), also called central receiver system, and a parabolic dish system (b) [2].

focus the direct solar radiation on the receiver a two axis tracking system for the dish-receiver-system is needed. Since the solar radiation of a large area is focused in one spot the concentration ratio of those systems are very high and therefore temperatures between $250°$ C and $750°$ C can be achieved. By combining the parabolic dish concentrator with a Stirling engine in the focal point, it is possible to generate solar electrical power with a relative good efficiency. The other possibility is to use the gained heat to drive a conventional steam turbine/generator system to generate electrical power [2, 3].

1.2.3 Parabolic Trough Concentrators

A parabolic trough (Figure 2 a)) consists of an elongated parabolic reflector that focuses the direct solar radiation on a linear receiver, which is located at the focal line of the parabolic reflector. The receiver consists of an absorber tube and a glass tube surrounding it. The absorber tube is a coated steel tube, with a black selective coat having a high solar absorptance and a low thermal emittance at elevated temperatures. The volume between the glass and the absorber tube can be evacuated, as some coatings are not stable in air at elevated temperatures and to reduce heat losses. The reflectors are either glass mirrors or thin polished and coated metal sheets with a high solar reflectance. During the daylight hours the reflectors follow the sun by using a single axis tracking system. Through the absorber tube a working fluid is flowing, which is heated by the concentrated solar radiation to $150 - 750°$ C [2]. Water, synthetic oil, or molten salt are used as working fluids depending on the application and the temperatures reached. Since there is a large variety of components for parablic troughs, a wide temperature range $(150°$ C to over $750°$ C) can be reached. This leads to numerous applications for parabolic troughs. This goes from electrical power generation with a conventional steam turbine over organic rankine cycle (ORC) power generation to process heat and building cooling, going from high temperatures to low ones. Using large fields of parabolic trough collectors is the cheapest way to transfer solar radiation into electrical power. The biggest advantage of parabolic trough concentrators compared to other systems is, that they are already commercially used over 20 years [4].

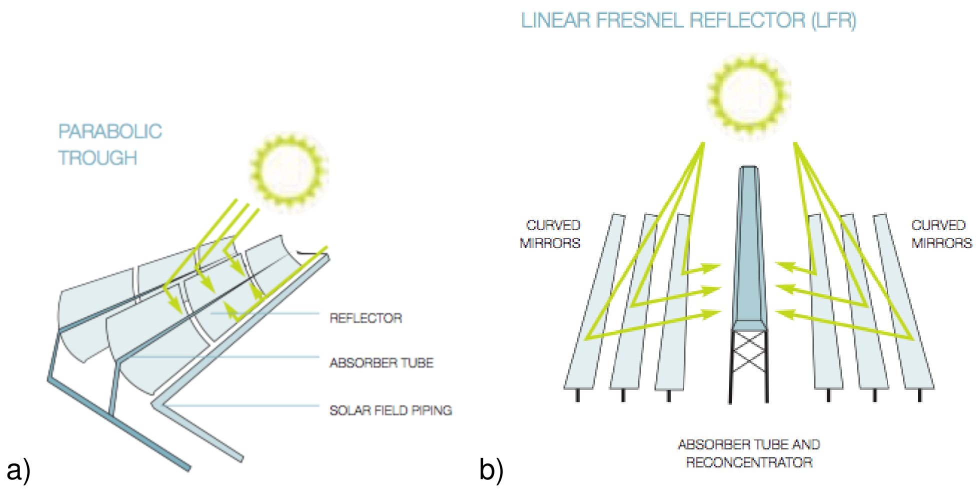


Figure 2: Schematic of a parabolic trough collector (a) and a linear Fresnel concentrator (b) [2].

1.2.4 Linear Fresnel Concentrators

Linear Fresnel concentrators (Figure 2 b)) focus the direct solar radiation on a linear receiver similar to parabolic trough systems. Instead of using the parabolic mirrors to focus the light, they use an array of long, narrow, shallow-curvature or even flat mirrors. Those mirrors are also tracking the sun along one axis. The advantage of shallow-curvature or flat mirrors is, they are much cheaper, less sensitive to wind loads, and more reflectors can be placed on the same area, as they are not shading each other. A further advantage is the receiver is not moving, which simplifies the connection of the heat fluid system.

1.3 Applications

Concentrated solar thermal (CST) can be used for different industrial applications, depending on the temperature of the working fluid, which is achieved. The high temperature range ($T > 350°$ C) is used to produce electricity by driving a steam turbine/generator system by the steam produced by the concentrating solar collectors, or the heat can be used to generate hydrogen. The low and medium temperature ($150°$ C $< T < 350°$ C) range has also a great impact, but is not yet as established as the high temperature range. Heat at those temperatures can be used as process heat and for solar cooling of buildings, or by using a Stirling engine or an organic ranking cycle (ORC) to produce electrical power.

Since CST systems only convert the direct solar radiation into heat, it is of great importance to take this in to account while dimensioning a system. The amount of direct solar radiation is larger in the sun belt of our Earth.

1.3.1 Solar Power Generation

In the public the most known way to use concentrated solar radiation is to generate electrical power with it. For this all of the above described CST systems can be used, but due to the high temperature, $T > 350°$ C, needed mostly parabolic trough and solar towers are used. In figure 3 a schematic drawing of a power plant with a parabolic trough collector field is shown. The collector field consists of a large field of single-axis-tracking parabolic trough collectors.

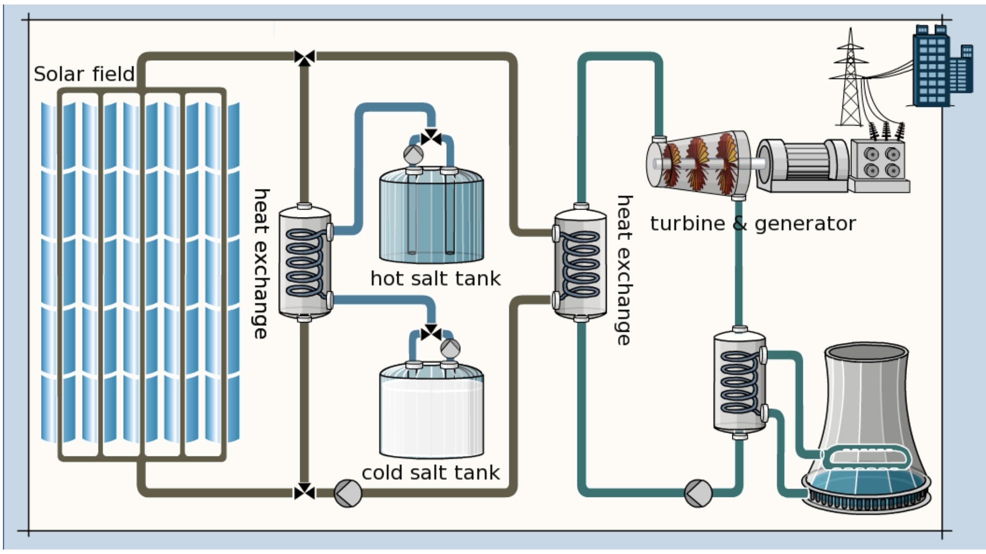


Figure 3: Schematic drawing of a CST plant using a two tank molten salt system for heat storage [5].

The field size is proportional to the gained electrical power. For example to generate 150 GWh a parabolic trough collector field of 342000 m^2 is needed. The parallel rows of the collectors are usually aligned on a south-north horizontal axis and track the sun from east to west during the day to ensure that the sunlight is always focused by the parabolic mirrors on the linear receivers [6]. The working fluid circulating through the absorber tubes of the receivers is heated up to about $400°$ C. By running through a series of heat exchangers in the power block the hot fluid is used to generate high-pressure superheated steam (100 mbar, $370°$ C) [6]. The generated superheated steam is then fed to a conventional steam turbine/generator system to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchanger. After passing through the working fluid side of the heat exchanger, the cooled working fluid is recirculated through the solar field [6].

In order to be able to achieve an electrical output with these plants during overcasts or nighttime periods a thermal storage system is integrated to the plant design. The stored solar energy can be then be dispatched when power is required. For this two large salt tanks are added, that are attached to the working fluid cycle by another heat exchanger. During times with enough solar radiation, late morning to early afternoon, salt from the cold tank is pumped through the heat exchanger, where it is heated, to the hot tank. When extra heat is needed to generate the superheated steam the flow between the two salt tanks is reversed.

If the available temperatures from the solar field are lower, then there are two other ways to generate electrical power. One is to use an organic ranking cycle (ORC); the other is to use a Stirling engine. In the case of the organic ranking cycle, micro turbines are driven by vapour of an organic liquid instead of water steam. Organic liquids used in ORC have a lower evaporation temperature than water, as well as a high latent heat and density. With these systems already at temperature around $200°$ C electrical power can be produced efficiently [3]. When a Stirling engine is used for the electrical power production it is usually placed in the focal point of a parabolic dish. This is why parabolic dish systems are also often called dish Stirling systems. The Stirling engine converts the solar radiation into mechanical work, which then is converted into electrical power by generators.

1.3.2 Solar fuels

For the production of solar fuels solar towers, with their high concentration ratio, could be used as they can achieve the high temperatures ($T > 1000^\circ$ C) needed for those processes. The development concerning solar fuels, especially hydrogen (H_2), is now rapid as the cutting of greenhouse gases becomes more and more important. Hydrogen, if produced by solar energy, is a clean alternative to fossil fuels, especially in transport uses [2]. Clean hydrogen production would be based on water H_2O and energy from renewable sources. An advantage of solar fuels compared to solar electricity is, it can be stored and transferred over long distances. Further, they are solar energy carriers that can be used for heat and electricity generation to match the customer's energy demands [7].

1.3.3 Solar Sea Water Desalination

Freshwater scarcity is increasing in several regions on Earth. The only way to overcome this situation is the desalination of seawater and/or brackish water. Currently desalination is performed in large scale depending only on the combustion of fossil fuels. Using solar power instead will provide, on one hand, a clean solution not pushing the climatic changes that are also responsible for the scarcity. On the other hand it would provide the opportunity for small and rural communities to also construct desalination plants. Besides this, desalination is an issue in areas with high solar impact, so using the solar radiation for desalination is self-evident [2].

For the industrial desalination process two principle categories are available [8]:

- Thermal-based multi-effect desalination, which needs thermal energy to vaporise water from the brine followed by condensation of pure water. This can be achieved by the following processes: Multistage Flash (MSF), Multi-Effect Boiling (MEB), and Vapour Compression (VC).
- Membrane-based processes involving selective flow of brine components through semi-permeable membranes. Energy in this case is mainly required for pumping and applying high pressure. The used processes are: Reverse Osmosis (RO) and Electodialysis (ED).

The necessary heat and electricity for those systems could be provided by concentrated solar power systems according to a study of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) [9]. Three different configurations are possible for the combination of CST and desalination. The first one would be to use only the heat for multi-effect desalination. The second is to use only electrical power for membrane-based desalination. And the last would be to combine heat and power usage to produce electrical power and at the same time fresh water by multi-effect desalination.

1.3.4 Solar Cooling

Solar cooling is becoming more and more important, as the number of buildings with large glass facades is increasing. Further the need of cooling in warm climates is also increasing. The biggest advantage of solar cooling is cooling load and availability of solar radiation are approximately in phase.

The heat generated by the solar radiation is used in conjunction with absorption chillers to provide a renewable source of industrial cooling. Absorption chillers are refrigerators that use heat to provide the energy needed to drive a cooling system. The basic thermodynamic process is based on evaporation of molecules that are absorbed by another material.

In the classical gas absorption chillers liquid ammonia is evaporated into hydrogen gas, providing the cooling. Then the gaseous ammonia is transferred to a water container, which absorbs the ammonia. The water-ammonia solution is separated into water and ammonia gas by heating. The ammonia gas is then condensed into its liquid to close the cycle. The needed heat for separating the water-ammonia solution is provided, in case of solar cooling, by CST systems. A similar system uses lithium bromide salt and water, where the water is evaporated under low pressure.

1.3.5 Process Heat

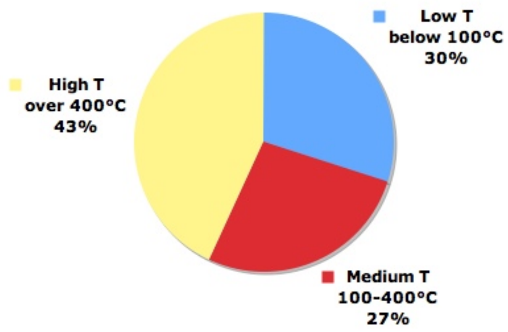


Figure 4: Share of industrial heat demand by temperature level [10].

Comparing the energy consumption in industry, transportation, household, and service shows that approximately 30% is consumed by industry [10]. And only one third of the total energy used by industry is related to electrical power, whereas two thirds are related to heat. The industrial heat can be again divided into the three temperature levels, high-, medium-, and low-temperature [11]. Figure 4 shows, that 43% of the heat needed has temperatures over $400°$ C, whereas 30% are below $100°$ C and the remaining 27% are in the medium temperature range of $100°$ C to $400°$ C. Heat in the low temperature region can be provided by flat plate and vacuum tube absorbers. For temperatures higher than $100°$ C it is more efficient to use small parabolic trough or Fresnel collectors, although they need a tracking system. The CST systems in this temperature range can have smaller apertures for the mirrors, which is equal to a small concentration ratio. Further they work with non-evacuated glass tubes surrounding the black selective absorber tubes, as the heat losses at those temperatures are much smaller. For temperatures over $300°$ C all CST systems available can be used efficiently. In this high temperature region it is important to achieve a high concentration ratios and to reduce the thermal losses. Therefore large apertures for the mirrors and evacuated receiver tubes are used.

From numerous studies on the industrial heat-demand, several industrial sectors have been identified with favourable conditions for applying solar energy. The most important industrial sectors in the lower and medium temperature range are food, including wine and beverage, textile, transportation equipment, metal and plastic treatment, chemical processes, wood, and paper. The areas of application for solar process heat are cleaning, drying, evaporation, distillation, bleaching, pasteurisation, sterilisation, cooking, melting, and surface treatment [11]. In addition to this one should keep in mind the huge amount of space cooling for factory and office buildings. In the following table the typical temperature ranges for the different industrial sectors working in the low and medium temperature range are listed [12, 13].

Industry	Process	Temperature
Food & Tobacco	Cleaning, cooking, pasteurisation, sterilisation, drying	$30 - 300°$ C
Textile	Bleaching, dyeing, degreasing, fixing, washing, drying	$20 - 180°$ C
Chemical	Distillation, pressing, cooking, coagulation, flocculation, melting	$50 - 300°$ C
Wood	Drying, pressing	$50 - 200°$ C
Pulp & Paper	Drying, bleaching, pulping	$50 - 200°$ C
Metal	Galvanisation	$50 - 100°$ C
Buildings	Cooling, heating	$50 - 180°$ C
Plastics	Preparation, distillation, separation, drying, blending	$120 - 220°$ C

Although the potential market for solar process heat seems large and the discussion of usage is not new, there are very few installations until now. Already during the first oil crises some installations were realised, for washing and drying of crops and wood [14]. The difficulties for the usage of solar radiation, the high investment costs, and the long pay-off times, due to very low industrial fossil fuel prices, have now started to become less important. But the challenges still remain the same. For an industrial process it is of great importance that the desired temperature for a given process can always be provided and is not changing with time [15]. This means it is necessary to find solutions to overcome the daily and yearly changes in solar radiation. This could be realised with very large storage systems, or by combining the solar system with a fossil fuel driven system. Both systems have their pro and cons. In the case of thermal storage, tanks will be needed, which occupy extra space and still bare a rest risk of not being sufficient in some extreme situations. In the case of fossil fuel support, two heating systems, solar and fossil, are needed so that the possible financial gain is only achieved due to the reduction of fossil fuel usage. As fossil fuel is very cheap, this will result in long pay-off times for the investments [16].

In order to make the use of solar process heat more attractive to the industry, it is therefore necessary to reduce the price of solar systems, as well as to provide investment subsidies and maybe even lower the taxes for companies using solar energy. Further, an increase of the fossil fuel price for industrial usage would increase the interest of using solar process heat [13]. To achieve a price reduction for solar systems bears some kind of problem: Solar systems will only get cheaper, if the market will grow. But the market will only grow, if the solar systems get cheaper. This leeds to a sort of dead lock, which could be solved by political forces by providing subsidies or tax reductions for the usage of solar process heat.

Although the market and interests for solar process heat is very slowly growing, several companies, like Alanod-Solar GmbH & Co. KG, Energie Solaire SA, Himin Solar Co. Ltd., Mirroxx GmbH, NEP Solar, Novatec Biosol AG, PSE AG, Solitem GmbH, and Sopogy Inc., are specialising on providing systems or components for solar process heat.

2 Components of Parabolic Trough and Fresnel Collectors

Parabolic trough and Fresnel collectors consist of mirrors focussing the direct solar radiation on a central linear receiver. The receiver is responsible to transferring the incoming solar radiation into heat. The main difference between the two systems is the shape of the mirrors. The parabolic trough systems use mirrors having a parabolic shape, whereas the Fresnel systems use several flat or shallow-curved mirror strips. The receivers of both systems contain a black absorber tube, which is responsible for the conversion of the solar radiation into heat. Parabolic troughs have a glass tube surrounding the absorber tube. This glass tube can be evacuated, depending on the application. Fresnel systems need secondary mirrors to re-concentrate the solar radiation on the absorber tube. The heat gained by the absorber tubes is transported to a storage, turbine, or other potential usage by a working fluid flowing through the tubes.

2.1 Mirrors

The mirrors independent of the collector shape focus the incoming radiation on the linear receiver and are therefore responsible for the concentration ratios that can be achieved with each system. The concentration ratio depends on the size, the aperture, and the reflectance of the mirror itself, as well as how good the mirrors focus the incoming solar radiation on the linear receiver. The efficiency of the system is further influenced by the tracking of the movement of the sun.

In the case of the Fresnel collectors the mirrors are long, narrow, shallow-curvature or even flat strips that are mounted parallel to each other. The mirror size is determined by the sum of the strip areas. In order to be able to focus the incoming solar radiation on the absorber tube, the mirror strips have to be independently turned to track the path of the sun during the day. The absorber tube of Fresnel collectors is imbedded in a reconcentrator, see figure 5, with a

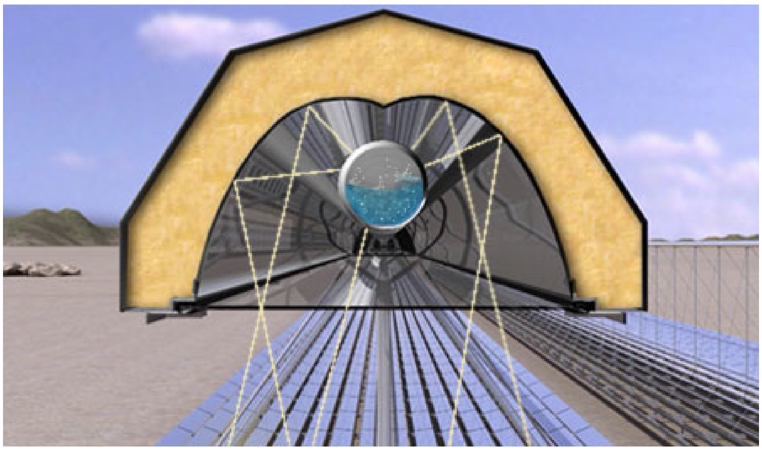


Figure 5: Schematic drawing of the reconcentrator of Fresnel concentrators [17].

secondary mirror. The secondary mirror, also called Compound Parabolic Concentrator CPC, is needed to further concentrate the incoming radiation on the absorber tube, as the mirror strips reflect the light back in a broader field than the diameter of the absorber tube.

For parabolic trough collectors the mirrors have a parabolic shape that is focussing the incoming radiation on the receiver, which is located in the focal line of the parabolic mirror. In order to always focus the direct solar radiation on the receiver the mirrors have to track the movement of the sun.

The parabolic shape of the mirrors can be obtained through different methods. The glass mirrors of Flabeg Solar International, for example, are made from a low-iron 4-mm float glass with a solar-weighted transmittance around 94% that is heated and sag-bended into the parabolic shape. Afterwards it is covered with a silver film and several protective layers [6]. Saint-Gobain has glass mirrors that are press-bended into shape, then silvered and protected by paint coatings. Laminated mirrors made of two glass sheets joined by a PVB-foil are manufactured by Guardian Industries Corp. A different technique is used by Skyfuel Inc., which uses multiple layers of polymer films with a silver reflective layer, which are then laminated to aluminium substrates that are edge guided on the collector to obtain their parabolic shape [18]. Alanod-Solar GmbH & Co. KG are using aluminium bands, where the reflectance is enhanced through a multilayer coating system and an additional nano-composite layer.

2.2 Working Fluid and Storage

Depending on the application and the temperature needed different working fluids and pressures are used in the CST systems. This also determines the maximum power cycle efficiency, which can be achieved with the different systems [6]. For operation at low temperature ($T < 250°$ C) water can be used as working fluid, which has the advantage of being cheap and of bearing no environmental risks. A water and steam mixture can also be used up to temperatures of $500°$ C but then high pressure, leading to thicker absorber tube walls, is required. An alternative is to use mineral or synthetic oil, which can be heated up to $400°$ C. The main problem of using oil as working fluid is, it is flammable and environmentally harmful. Therefore safety and environmental protection requirements have to be fulfilled. For the usage of the gained heat a heat exchanger is needed to transfer the heat to a fluid that can be stored or can be converted into steam to drive the turbines. Molten salt (60% sodium nitrate $\mathrm{NaNO_3}$, 40% potassium nitrate $\mathrm{KNO_3}$), with which temperatures up to $500°$ C can be reached, is an alternative as working fluid, leaving the testing phase. Archimede Solar Energy SpA, Italy, is currently building a plant to produce receivers working with molten salt [6]. Due to its large heat capacity molten salt was first, and still is, used as a heat storage medium. When using it as working fluid, it has to be assured, that the temperature in the absorber tubes is not decreasing below the frizzing temperature of $225°$ C during periods of low radiation, like during clouds and nights. This can be realised by continuously pumping warm molten salt through the collectors or by emptying the field.

In order to guarantee a continuous heat flow even during short cloudy periods and over night either an additional heat source or a heat storage is needed. In a hybrid solar/fossil system a backup system using fossil fuels to heat during low solar radiation is installed. For the generation of process heat wood pellets or gas can be used as alternative to fossil fuels. This additional heater starts operation, as soon as the desired temperature is no longer provided by the solar field.

Different technologies for storing the heat generated by the concentrated solar system exist or are investigated. The first CST plants used huge oil tanks to store the generated heat. But oil is no longer used as the safety and environmental risk is far to high, as they tend to explode. An alternative with no risks is to heat large concrete blocks, but the efficiency of transferring the heat from the working fluid to the concrete and back is not satisfying. Nowadays molten salt is used as storage material for the heat gained, due to its favourable combination of density (1880 kg/m^3), specific heat (1500 J/kg K), chemical reactivity (very low), vapour pressure (< 0.01 Pa), and cost ($ 0.40 - $ 0.90/kg) [19]. For the heat storage with molten salt usually two tanks are used one for the cold ($290°$ C) and one for the hot ($390°$ C) salt. During heating the salt is pumped from the cold to the hot tank through a heat exchanger, which is fed by the working fluid arriving from the concentrator field. In the schematic in figure 3 the configuration for a power plant using a two tank storage system is shown. To gain heat during low solar radiation periods the process is reversed and the solar field is disconnected by closing valves. A current research topic is to use phase-changing media for the storage of heat [2]. During the phase transformation solid-liquid, liquid-gas, solid-gas, or solid-solid latent heat is stored in the system. This heat can be gained again, if the process is reversed [20]. Only the solid-liquid and solid-solid systems are feasible, because the gas systems require far to large volumes. Latent heat storage (LHS) is based on the heat absorbed or released when a storage material undergoes a phase change. During the phase change the chemical bonds within the material break up or form, depending on the process direction. Breaking up is a heat-seeking (endothermic) process, which begins, as soon as the material begins to melt. Forming the bonds in contrast is an exothermic (heat gaining) process, which is performed during the solidification. The main advantage of those systems is, that large amounts of heat can be stored with only a small temperature change. Therefore they have a high storage density [20].

2.3 Receiver

The receiver, which is also called the heat collecting element, is the heart of each CST system and is positioned at the focus of the mirrors. For the Fresnel systems different receiver configurations are used, but they all consist of a black absorber tube and re-concentrating mirrors. Some systems use an evacuated or non-evacuated glass tube around the absorber tube to protect it and to reduce heat loses. Others close the reconcentrator with a glass at the bottom, as shown in figure 5. Responsible for the conversion of the solar radiation into heat is the absorber tube with its black selective coat. The properties and the deposition of the black selective coat will be discussed in detail in the following sections.

The receiver for parabolic troughs consists of the absorber tube and the surrounding glass tube, which is sometimes evacuated. As the configuration for the evacuated receiver tube is more difficult, it should be described here in detail. A schematic drawing of an evacuated receiver tube is given in figure 6. The steel absorber tube with the black selective coat is embedded

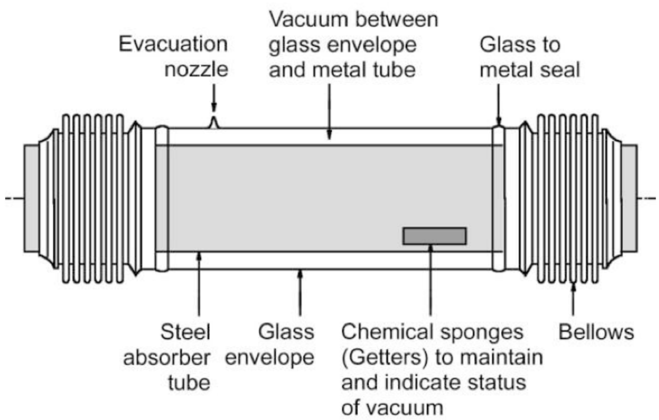


Figure 6: Schematic drawing of an evacuated receiver tube [21].

in the glass envelope. Those two tubes are joined by glass to metal seals and two bellows. The volume between the tubes is then evacuated. The bellows are needed since glass and steel have different expansion coefficients. Therefore, the bellows compensate the different length changes by stretching or shortening depending on the temperature. In the case of non-evacuated tubes the differences in expansion coefficients have to be taken into account, but they do not cause glass breakage, as long as the glass and steel tube are not connected and can expand independently.

First vacuum receivers, similar to the ones described above, were already used by Luz Ltd. (later Solel Solar Systems Ltd.) in their parabolic trough plants. Those early receivers were facing huge problems with the glass to metal seals and glass breakage due to expansion stress. The evacuated receivers of Archimede Solar Energy SpA, Schott Solar AG and Solel Solar Systems Ltd. (now Siemens Concentrated Solar Power, Ltd.) are not facing those problems anymore.

3 Solar Selective Coating

3.1 Solar Absorptance α_{sol} and Thermal Emittance ε_{therm}

The performance of a solar absorber can be characterised by its solar absorptance α_{sol} and thermal emittance ε_{therm}. For the determination of those values the optical properties like the spectral reflectance and the spectral absorptance of the absorber have to be measured.

The fundamental equation in optics, the radiation distribution equation,

$$\tau + \rho + \alpha = 1 \tag{1}$$

indicates that the sum of the light transmitted τ, reflected ρ, and absorbed α is equal to the amount of incoming light. In the case of solar absorbers, which are opaque, the transmitted radiation is equal to zero [22]. Due to this the spectral absorptance $\alpha(\lambda, \varphi)$ can be expressed in terms of the total reflectance $\rho(\lambda, \varphi)$,

$$\alpha(\lambda, \varphi) = 1 - \rho(\lambda, \varphi) \tag{2}$$

where $\rho(\lambda, \varphi)$ is the sum of both collimated and diffuse reflectance, λ is the wavelength, and φ the incident angle of light. The emittance ε at a given temperature T is defined as:

$$\varepsilon(\lambda, T) = \alpha(\lambda, T) \tag{3}$$

The spectral reflectance of flat surfaces can be measured with photospectrometers equipped with an integrating sphere at near-normal ($\varphi = 0$) angle of incidence and from this the spectral absorptance and emittance can be derived.

Usually the solar absorptance α_{sol} and thermal emittance ε_{therm} of a coating is given, as it is more convenient to compare two values different of products than their spectral behaviour. The solar absorptance α_{sol} is the integrated value of the spectral absorptance weighted with the solar spectrum $S_\lambda(\lambda)$ for a given angle of light incidence, usually perpendicular incidence ($\varphi = 0$) is used [23, 24]:

$$\alpha_{sol} = \frac{\int_{0.3\mu m}^{2.5\mu m} S_\lambda(\lambda)\ (1 - \rho(\lambda))\ d\lambda}{\int_{0.3\mu m}^{2.5\mu m} S_\lambda(\lambda)\ d\lambda} \tag{4}$$

The thermal emittance ε_{therm} is defined as the weighted fraction between the emitted radiation and the Planck's black body distribution $u(\lambda, T)$ at a given temperature T [23]:

$$\varepsilon_{therm} = \frac{\int_{2.5\mu m}^{15\mu m} u(\lambda, T)\ (1 - \rho(\lambda, T))\ d\lambda}{\int_{2.5\mu m}^{15\mu m} u(\lambda, T)\ d\lambda} \tag{5}$$

The Planck's black body distribution for the spectral irradiance is defined as

$$u(\lambda, T) = \frac{8\pi hc^2}{\lambda^5} \frac{1}{e^{(\frac{hc}{\lambda kT})} - 1} \tag{6}$$

where h is the Planck constant, c the speed of light, and k the Boltzmann constant. This shows, the thermal emittance ε_{therm} strongly depends on the operating temperature of the absorber, even if the emittance $\varepsilon(\lambda, T)$ does not change with temperature. Another property of the Planck's curve is, it shifts with increasing temperatures T to smaller wavelengths λ.

3.2 Ideal Absorber Coating

An ideal absorber coating should absorb, if possible, all the incoming solar radiation. At the same time the thermal emittance at the operating temperature should be as small as possible, in order to minimise the losses through heat emission. This means in other words, the absorptance α of solar radiation ($\lambda \leq 2.5\,\mu$m) should be closed to one (100%), whereas it should be zero (0%) for larger wavelengths ($\lambda \geq 2.5\,\mu$m). The position of this cutoff of absorptance maybe has to be higher or lower depending on the working temperature of the absorber. This shift is based on the fact that the Planck distribution $u(\lambda, T)$ shifts with change of temperature T. This shifting of the Planck curve can be seen in figure 7 where the Planck's distribution $u(\lambda, T)$ for

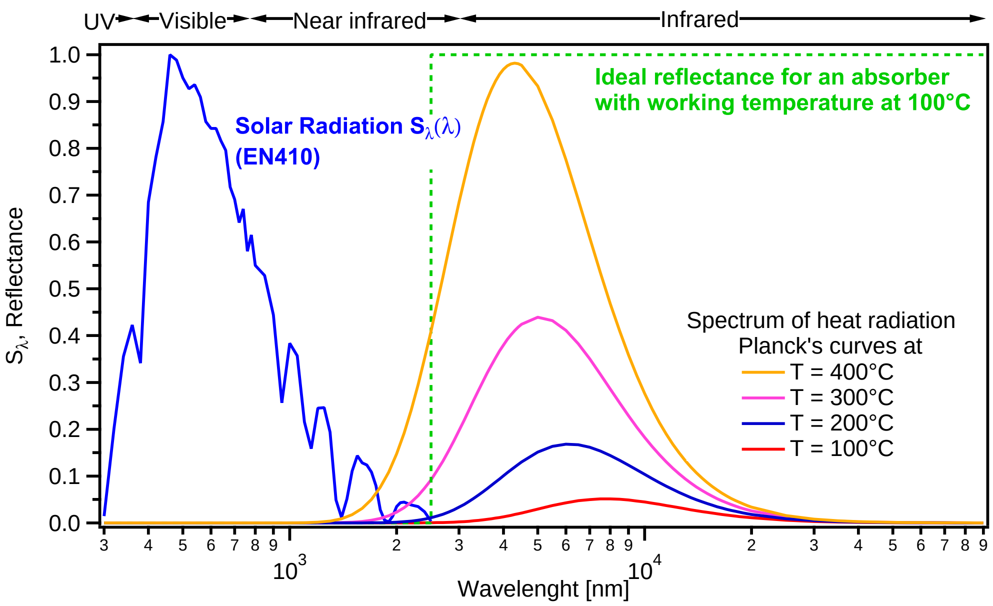


Figure 7: This graph shows the solar radiation $S_\lambda(\lambda)$ and the Plancks curve for different temperatures. An ideal absorber with a working temperature of 100° C would have the given reflectance, as all solar radiation is absorbed and nothing is emitted.

different temperatures is given. Besides the Planck curves the solar spectrum S_λ, as defined in the EN410 norm, is plotted in this figure. Further given is the theoretical ideal reflectance of an absorber with working temperature 100° C. If the working temperature would be higher, the change of the reflectance has to be shifted to smaller wavelength ranges. This means a reduction of the solar absorptance as part of the incoming solar radiation is reflected. In general the position of this cutoff has to be chosen in such a way that the overall performance of the absorber is maximised.

In practice an abrupt change of reflectance, as the one shown, will never be reached with an affordable coating. Abrupt changes can be obtained with coatings containing 30 to 50 layers with very precise layer thicknesses, like they are used in filters for high precision optics. The reflectance will in reality change with a slope from one extreme to the other. The steepness of this slope depends on the number of layers and materials used in the multilayer coating.

Different types of coatings are shown in figure 8, which illustrates the different approaches to obtain selective coatings [25]. The easiest way is to use an intrinsic selective material having intrinsic properties that result in the desired spectral selectivity. Using textured surfaces needs a very defined production technique to produce the texturing which is needed to obtain a desired

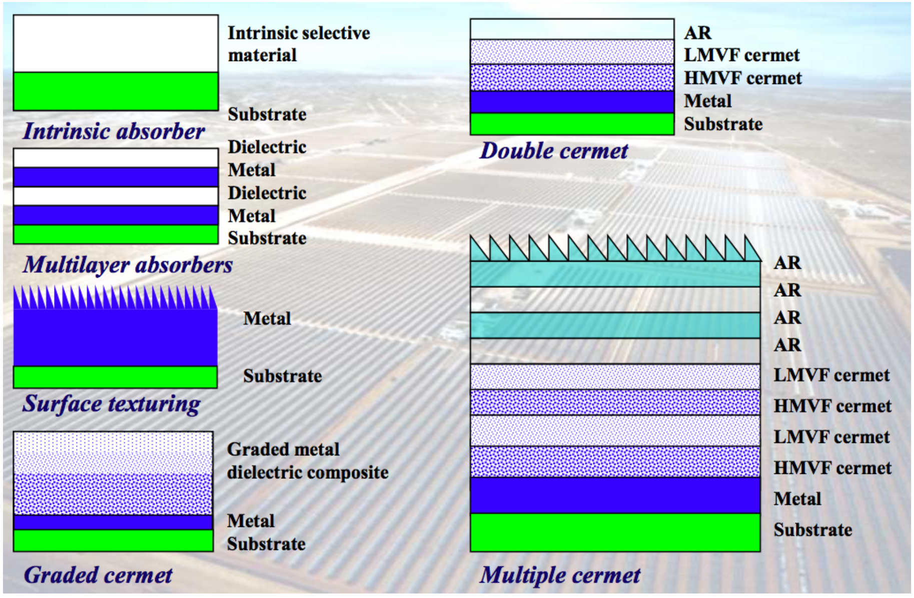


Figure 8: A coating with selective properties can be achieved by different approaches. The different types are sketch in this graphic [25].

absorptance [1]. The most common is to use multilayer systems that use multiple reflections between the layers to absorb light [26]. They can be tuned to be effective selective absorbers by varying the thickness of the individual layers or by exchanging one or two layers. Another way is to use metal-dielectric composites, so called cermets, that consist of fine metal particles hosted in a dielectric or ceramic material [27]. The small metallic particles enhance by multiple scattering the absorption of short wavelength photons, whereas the reflectance of the infrared radiation is maximised by interference effects. Therefore the exact thickness, the volume fraction of the metal content in the layers, and the size of particles determine the optical and thermal performance - solar absorptance and thermal emittance [28]. And of course a combination of the different types is possible. However, there is a discrepancy between highly absorbing coatings and ones with low emittance. Highly absorbing coatings are rough, porous, and absorb solar energy. Coatings having a low emittance are very smooth, dense, highly reflecting, and mirror-like to thermal energy [25]. But by combining several concepts solar-selective coatings for different temperature ranges can be obtained.

3.3 Deposition

The above described selective solar coatings can be produced by very different methods. The choice of technique is often correlated with the materials, which should be deposited. The different techniques can be generally classified under two main categories: Vapour deposition and wet chemical deposition. Sputtering and chemical vapour deposition belongs to the first category, whereas electrodeposition, sol-gel and painting belong to the second.

3.3.1 Sputtering

The general setup for sputtering deposition consists of a target, the material that should be deposited, a substrate, and a sputtering gas, in general argon, in a vacuum chamber. The target is negatively charged by a dc power supply, in order to build up an electric field between target and grounded substrate. The electric field is needed to accelerate electrons, which in turn collide with the argon atoms. Some of the argon atoms break up into argon ions and more electrons, producing a glow discharge. The charged particles thus produced are accelerated by the electric field. The electrons tend towards the anode (substrate) causing more ionisation on their way and the argon ions towards the cathode, the target. From the target, due to the bombardment with the argon ions, atoms are ejected. The atoms are ejected in random directions and therefore can strike and condensate on the surface of the substrate or on the walls of the vacuum chamber [29].

With this technique all kind of thin films can be produced. The easiest way is to sputter metallic films as only a target of the metal, which should be deposited, is needed. Metallic compounds like oxides or nitrides can be deposited by reactive sputtering. For this a metal target is sputtered in a gas mixture containing argon, as sputtering gas, and other gases like oxygen or nitrogen as reactive gasses. The atoms ejected from the target react chemically with the reaction gases on their way to the substrate or the chamber walls.

Sputtering is widely used for the deposition of black absorber coatings [22, 30]. The advantage is, it is relatively simple to produce different multilayer systems or to deposit metal clusters in a dielectric matrix (cermet) in a very clean and controlled environment. A disadvantage is the need of an expensive vacuum system.

For the production of black absorbers with a solar absorptance between $94 - 98\%$ often aluminium oxide $\mathrm{Al_2O_3}$ is used as cermet where different metal clusters like nickel Ni, cobalt Co, molybdenum Mo, or tungsten W are embedded. Those aluminium oxide based coatings are stable in vacuum up to 500° C [22].

The black selective coats on the absorber tubes of Archimede Solar Energy SpA, Himin Solar Co. Ltd., Schott Solar AG, Solar Power Group GmbH, and Solel Solar Systems Ltd. (now Siemens Concentrated Solar Power, Ltd.) are sputtered multilayer systems. Sputtering is also used by Fraunhofer-Institut für Solare Energiesysteme (ISE) and National Renewable Energy Laboratory (NREL) for the development of new selective coatings.

3.3.2 Chemical Vapour Deposition

Chemical vapour deposition (CVD) is a technique, where the coating is deposited by means of chemical reaction on a hot surface. Here the coating material reacts with certain reagents, like air, oxygen, or water vapour, to form a layer. For the deposition the gaseous or vapourous coating material, also called 'precursor', glides over the heated substrate with an even flow [31]. The deposition rate of CVD is compared to other techniques very low.

A related technique is the plasma enhanced chemical vapour deposition (PECVD), also called plasma-assisted CVD (PACVD), where the deposition at low pressure is combined with a gas discharge process to raise the deposition rate. PECVD is used at the University of Basel, Switzerland for the production of cermet films, like a transition metal containing hydrogenated carbon film (a-C:H/TM) or a transition metal containing silicon-carbon film (a-Si:C:H/TM) [27, 32, 33]. By incorporation of silicon into titanium-containing amorphous hydrogenated carbon films (a-C:H/Ti) the stability of the layers is strongly enhanced [32]. Those carbon films are stable under air up to 250° C and have a solar absorptance up to 87.6% and a thermal emittance greater than 6.1% [22].

3.3.3 Electrodeposition

Electrodeposition, also often called electroplating, is the process of depositing a thin film coating on a surface by the action of electric current. For the deposition of the coating on the substrate, it is dipped into a solution containing a salt of the material to be deposited. The coating is achieved by putting a negative charge on the substrate, in other words make the substrate the cathode of an electrolytic cell. The positive ions of the salt are thus attracted by the substrate. When they reach the negatively charged substrate, it provides electrons to reduce the positively charged ions and the coating is formed. In order to close the electrical cycle an anode, hanging in the salt solution, is also needed. There are two types of anodes. One is made of the same material, which should be deposited and therefore is used to replace the positive ions in the solution. This kind of anode is called a consumable anode. In the other case the anode is made of lead and the positive ions have to be constantly replenished in the solution by adding new salt to the solution. Some times a reference electrode made of platinum is used to stabilise the process. The advantage of this method is, the properties of the layers are very reproducible. The disadvantage is the risk of leakages of the electrolytes that will be environmentally harmful.

Typical materials deposited by electroplating for solar absorbers are Black nickel ($\mathrm{NiS-ZnS}$), $\mathrm{Ni{-}Sn}$, Black copper ($\mathrm{BlCu{-}Cu_2O:Cu}$), Black chrome ($\mathrm{Cr{-}Cr_2O_3}$), $\mathrm{Mo/Cr_2O_3}$, and CuO [22]. Black nickel has a solar absorptance up to 96% and a thermal emittance, which is similar to that of the substrates. The main disadvantage is, black nickel is in air only stable up to $200°$ C, if no protection layer is applied [22, 34, 35].

Black chrome coatings are an electrodeposited $\mathrm{Cr_2O_3}$ cermet containing metallic Cr particles. Coatings with a solar absorption up to 97% and a thermal emittance down to 4.6% can be achieved, depending on the substrate or the underlaying layer [22]. Further the temperature stability of black chrome in air is very high, it does not change up to $350°$ C. Electrodeposition of black chrome is used by Energy Solaire SA to produce air stable absorber tubes for non-evacuated CST applications and flat plat absorbers.

3.3.4 Sol-Gel

The sol-gel process, also known as chemical solution deposition, is a wet-chemical technique widely used in the fields of materials science and ceramic engineering. The name sol-gel describes the composition of the solution used for the deposition. A sol is a dispersion of colloidal particles in a liquid, where colloids are solid particles with a diameter of $1 - 100$ nm. Gels are interconnected, rigid networks with pores of sub-micrometer dimensions and polymeric chains whose average length is greater than a micrometer [36].

The advantage of sol-gel is, it is a cost effective technique because the cost of capital equipment is much less compared to other techniques, such as sputtering used mainly for industrial production. It also offers the opportunity to adapt and utilise industrial applications such as spray-painting, already used for larger surface area coatings [37].

A very simple coating, developed at the University of Zimbabwe, consisting of carbon nanoparticles embedded in silica. It has a solar absorptance of 88% and a thermal emittance of 41%, which is very high compared to other solar absorbers [37]. By sol-gel deposition of multilayers on stainless steal a coating with a high solar absorptance (94%) and a low thermal emittance (11%) is obtained at the LESO-PB at EPFL (Laboratoire d'Energie solaire et de physique du bâtiment at Ecole Polytechnique Fédérale de Lausanne). It is not showing any changes after a 28 hours heat treatment at 360° C [38]. A personal note of LESO-PB states that the newest values for solar absorptance and thermal emittance of their stable sol-gel coating are 96.1% and 11.7%, respectively.

3.3.5 Paint

Thickness-sensitive spectrally selective (TSSS) and thickness-insensitive spectral selective (TISS) paint coatings are a low-temperature alternative for high quality solar selective coatings [22]. TSSS coatings consist of absorbing particles in binders that have to be applied onto a highly thermally reflecting substrate. The particulates may be a semiconductor, metal oxide, black pigment, or any combination of these [39–41]. The thickness-sensitive coatings have to be either fabricated by dip-coating or by spray-systems. For thickness-insensitive coatings low emittance flakes have to be included in the paint. A widely used material for this are aluminium flakes that can be either coloured by pigments or left bare [23, 39]. By adding different pigments to the paint different colours of absorbers can be achieved. The main problem with absorbers created by painting is, that their solar selectivity is quite low. It is possible to reach high absorptance values between $83 - 96\%$, but most of them, especially if coloured, have an emittance greater 45% [22, 23, 39]. Due to the low selectivity the stability in air is of small importance, although some layers can be heated in air up to 700° C without showing any changes.

4 Characterisation and Qualification

Characterisation and qualification of the different components of CST plants is of great importance during their development as well as for their operation. Optical properties, durability, and geometrical precision of the components and the assembly have very strong influence on the overall performance, energy efficiency, and profitability of every CSP installation.

The characterisation methods for the mirrors and how well they focus the light on the absorber tubes are discussed elsewhere [42, 43]. Here the different approaches to investigate the optical and thermal properties of the receiver and the absorber tube will be discussed. Currently there are mainly two strategies, depending on the focus of interest, which are followed. One is to investigate the whole receiver tube, which includes the absorber tube and the surrounding evacuated or non-evacuated glass tube. In this case the thermal and optical efficiency is determined. The other is to directly investigate the optical properties of the absorber tubes with the black selective coating and to determine the quantities solar absorptance α_{sol} and thermal emittance ε_{therm} from an obtained spectral distribution.

The research centres DLR (Deutsches Zentrum für Luft- und Raumfahrt) in Germany and NREL (National Renewable Energy Laboratory) in the USA and the German receiver manufacture Schott Solar AG have specialised in investigating the whole receiver concerning its thermal efficiency. The characterisation is completed by the investigations concerning the optical efficiency at DLR. The Spanish research centre CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) and the German Fraunhofer-Institut für Solare Energiesysteme (ISE) have specialised on the characterisation of the coatings on the absorber tubes. The methods applied by CIEMAT are not covered in detail in this overview, as no detailed information was available. ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile), Sandia National Laboratories, DLR, CIEMAT, and PSA (Plataforma Solar de Almería) develop testing methods to investigate the properties of the different components of parabolic trough and Fresnel systems on the actual operating system. These methods are not covered here either. All the testing methods described here can be used by suppliers and costumers to qualify receiver and absorber tubes, although they are yet official standards.

4.1 Thermal efficiency

For the determination of the thermal efficiency the Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany has constructed a testing equipment, the ThermoREC shown in figure 9, where steady-state equilibrium measurements of whole receiver tubes, absorber tube in evacuated glass tube, can be investigated [44, 45]. The National Renewable Energy Laboratory (NREL), USA and the receiver manufacturer Schott Solar AG, Germany have rebuilt this testing equipment in its basic function but have added changes to it [21, 46]. One advantage of this testing method is that the receiver can be investigated in the same configuration as it will be used during operation. Another advantage is coatings, that are only stable under evacuated conditions at elevated temperatures, can be invested as they remain in their evacuated working surrounding. The disadvantage is no spectral information of the absorber tube is obtained.

The test stands are located inside to avoid any uncontrollable influence like wind or solar radiation. This ensures, that in the steady-state the power losses are equal to the power consumed by the heaters, as the power input through solar absorption is zero. The test stands consist of electric resistant heaters in a copper pipe that will be inserted into the absorber tube of the receiver, power transducers, and thermocouples. In figure 10 a technical drawing of the setup used at NREL is shown. In the centre of the absorber tube the electric resistance heater is

Figure 9: ThermoREC: Thermal loss measurement test bench of DLR, where the absorber tube of the receiver is heated to a desired temperature and the thermal losses are determined [44, 45].

inserted, which heats the absorber tube over its full length. In order to guarantee an even temperature distribution a copper pipe is surrounding this heater. To control the losses at the two ends of the receiver tube two additional heater coils at each end are installed on the setup of NREL [21, 46]. One heater coil is located just at the end of the absorber tube and one just outside it. Further the two ends are very well insulated. The setup of DLR omits these additional heaters at the ends and the losses are taken into account during the evaluation of the measured results [44]. For monitoring the different temperatures of heater, copper pipe, absorber tube, and enveloping glass tube several thermocouples are installed at different points [21, 44, 46].

The electric resistance heaters bring the absorber surface up to desired temperatures, which are measured by several thermocouples to monitor the temperatures of the copper pipe, absorber tube, and glass tube. Once a steady-state temperature is reached, power transducers measure the electrical power required to keep the absorber temperature constant. Steady-state is achieved when the glass and absorber temperature remains constant (variation $\leq 0.5^{\circ}$ C) over a period of at least 15 minutes. The temperature is measured every 5 seconds [21, 46]. The power required by the heaters is the heat loss of the receiver at the investigated temperature.

With this measuring setup the heat loss at different temperatures are determined for the whole receiver consisting of the stainless-steal absorber tube and the surrounding glass tube, which are connected by bellows and a glass to metal seal, and the vacuum separating the two. In the case of the evacuated receivers the heat losses are dominated by radiation, as convection and conduction are zero due to the evacuated space between the glass and the absorber tube. With increasing temperature of the absorber tube also the heat losses increase. This was theoretically predicted as the Planck's radiation distribution function is shifting with temperature. If the spectral reflectance of the coating is changing with temperature, this further influences the heat losses.

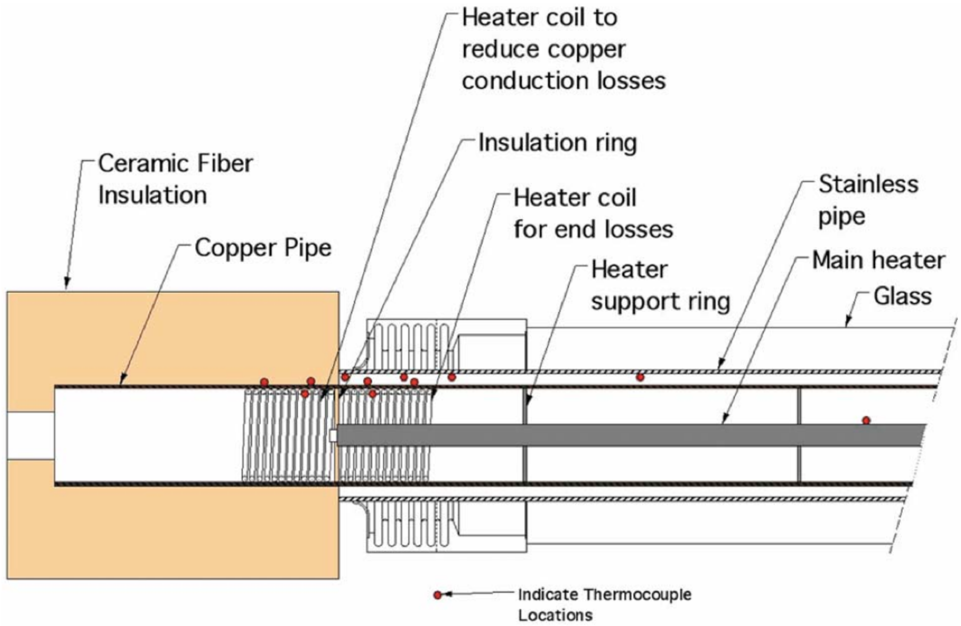


Figure 10: Design of the receiver loss test bench at NREL. It shows the heater and the copper pipe that are inserted into the absorber tube of the receiver. The red dots mark the positions of the used thermocouples [21, 44, 46].

4.2 Optical efficiency

With the thermal testing method, described above in chapter 4.1, only the thermal losses are investigated. A full characterisation of the energy balance of a receiver has to take the thermal losses and the opto-geometric efficiency $\eta_{opt,geo}$ into account. The opto-geometric efficiency describes how well the incoming solar radiation is transformed into heat by absorption. For this the DLR has developed and build a solar receiver bench working at outdoor conditions, the SolaREC shown on the left hand side of figure 11, and the ElliREC (right hand side of the figure) working at controlled conditions in the laboratory.

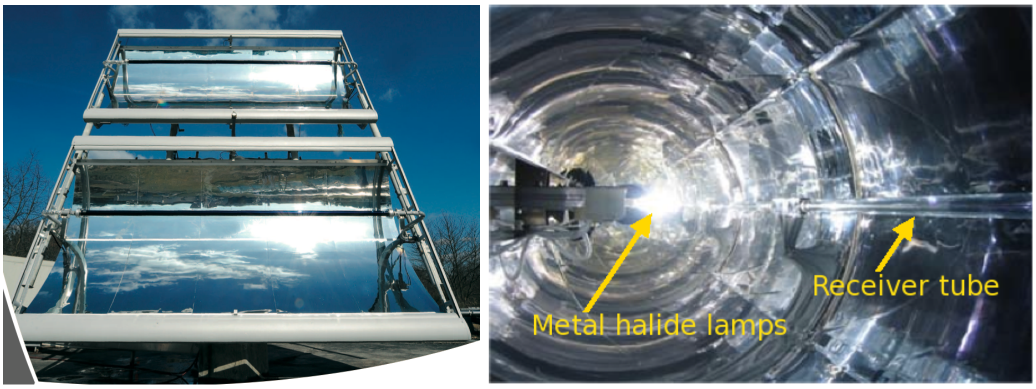


Figure 11: On the left hand side the SolaREC of DLR is shown, where two receivers can be compared concerning their opto-geometric efficiency under real conditions. On the right hand side the ElliREC is shown, where the same parameters can be investigated under laboratory conditions [45, 47].

The SolaREC consists of two parabolic trough collector modules tracking the sun by two axis.

The used troughs have an aperture width of $2.3\,\mathrm{m}$, $5\,\mathrm{m}$ module length, and a focal length of $0.80\,\mathrm{m}$ [47]. Like this receiver tubes of $70-100\,\mathrm{mm}$ diameter can be investigated. Further, a shutter mechanism enables to partially cover the aperture area, to be able to automatically control the incident solar power P_{in} onto the receivers. For this purpose, the beam irradiance is constantly monitored. There are two types of tests performed under those conditions [47]:

1. **Cold test:** In the cold test the receiver is kept near ambient temperature by having water running through the absorber tube. In this test thermal losses can be neglected and the measured temperature increase of the water ($4-10\,\mathrm{K}$) in combination with the measured flow rate can be used to determine the absorbed power. As the incident solar power P_{in} is known, the optical efficiency of the receiver near ambient temperature and perpendicular incident ($\theta = 0°$) can be calculated.

2. **Hot test:** In the hot test the absorber is heated P_{used} to a steady-state elevated temperature at constant incoming power. Since there is no heat fluid running through the absorber tube, there is no power extracted. There are two ways to evaluate this test [47]:

    - If the thermal losses for the testing temperature are known from measurements on the ThermoREC, then the optical efficiency $\eta_{opt,geo}(T)$ at this temperature T can be calculated by dividing the used power P_{used} through the incoming solar power P_{in}.
    - It the optical efficiency $\eta_{opt,geo}$ is known from the cold test, the thermal losses $P_{loss}(T)$ can be calculated form the incoming solar radiation P_{in}.

The SolaREC consists of two identical troughs that operate under the identical conditions, in order to be able to use one known receiver for the calibration of the measurements performed at different weather conditions. The disadvantage of the SolaREC test bench is that it is limited by the availability of sunshine.

In order to be weather independent another test bench, the ElliREC, for the optical efficiency was developed at the DLR [47]. The ElliREC is an elliptical mirror cylinder with flat end reflectors. The view inside, with a mounted receiver tube in the right focal line and the light sources on the left focal line, is shown in figure 11 on the right hand side. The light source are metal halide lamps, which have solar-like spectral properties. The optical efficiency is obtained by performing the same hot and cold tests as described above for the SolaREC.

The above described tests for the thermal and optical efficiency can only be performed with receiver tubes consisting of the absorber and the surrounding evacuated glass tube. Since the demand for testing and qualification of the absorber tubes without a surrounding glass tube has increased during the last years, the DLR is planning to adopt their testing equipment. One way would be to use a well characterised glass tube in which the absorber tube would be mounted for the investigations. The critical point here is, that the influence on the measurements by the air surrounding the absorber tube and the air exchanged with the surrounding, as the ends of the glass tube are open, have to be considered and determined. In this case losses due to heat radiation, convection, and conduction have to be taken into account for the standard thermal evaluation. Further the influence of the glass tube has to be quantified.

4.3 Optical Properties

Another approach towards the quantification of absorber tubes is to investigate directly the optical properties like spectral reflectance and spectral absorptance. This approach is used for characterisation and controlling of the qualities of flat plate absorbers, as well as for the characterisation during optical coating development. This is of especial interest, as the solar absorptance α_{sol} and the thermal emittance ε_{therm} can be calculated from those measurements with the relations described in chapter 3.1. Spectral transmittance and reflectance are measured with spectrometers. Here light, with a defined and calibrated intensity relation over a given wavelength range, is focused on the sample to be investigated. The transmitted or reflected light of the sample is then detected. Here three approaches are feasible:

a) The light is first focused on a monochromator before it reaches the sample. With this method the sample is always illuminated by just one wavelength at time. By scanning through the whole wavelength range the spectral transmittance or reflectance can be obtained.

b) The sample is illuminated by one wavelength at time as the light is monochromised by a Michelson interferometer in a FTIR.

c) In this case the light over the whole spectral range reaches the sample and a diode array measures the transmitted or reflected light wavelength dependent.

Depending on the wavelength range spectrometers are equipped with different integrating spheres, so called Ulbricht spheres. An Ulbricht sphere is a hollow sphere with a diffusive reflecting internal surface, an entering port for the incoming light, a sample port, and a detector. For transmittance measurements the sample is mounted in front off the port for the incoming light, whereas the sample port is blocked with the material of the Ulbricht sphere. For reflectance measurements the samples are mounted on the sample port. For measurements in the solar spectral range ($\lambda = 0.2 - 2.5\,\mu$m) the surface of the Ulbricht sphere can be coated with a highly diffusive white coating of MgO or $\mathrm{BaSO_4}$ or the walls of the sphere are made of Teflon. These coatings/walls have a very high and diffusive reflectance. Whereas for measurements in the infrared range ($\lambda \geq 2.5\,\mu$m) the inner surface of the sphere is covered with highly reflecting and rough gold.

The Fraunhofer-Institut für Solare Energiesysteme (ISE) at Freiburg, Germany uses for the optical investigations of selective absorber coatings the Fourier interference spectrometer IFS 66, shown in figure 12, with two integrated spheres for the different wavelength ranges. A very

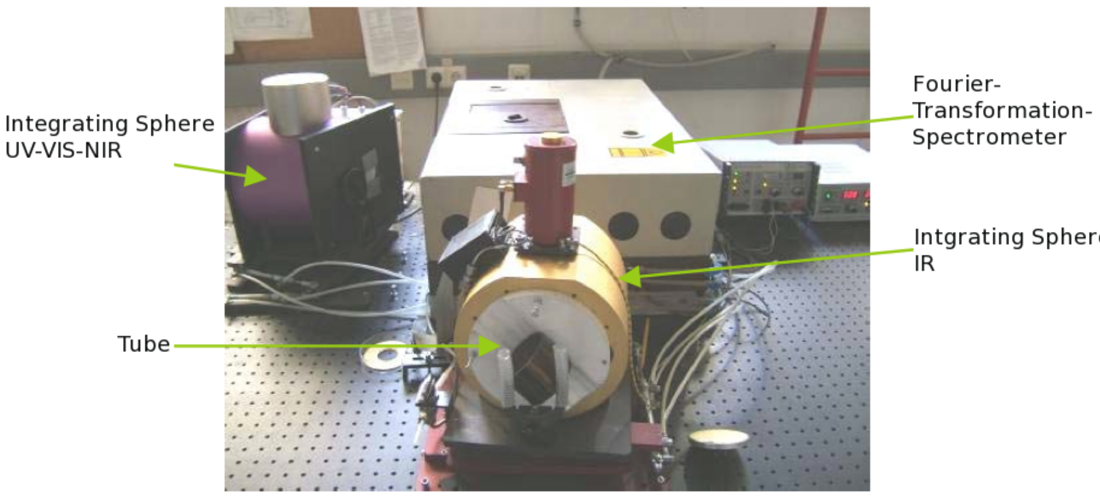


Figure 12: The Fourier-Transformation-Spectrometer of the Fraunhofer-Institut für Solare Energiesysteme (ISE) with two integrating spheres for the different wavelength ranges. With it the transmittance and the reflectance can be measured over the wavelength range $\lambda = 0.32 - 17\,\mu$m [28, 48].

similar system is used by the Institut für Solartechnik Prüfung Forschung (SPF) in Switzerland. The two systems were developed in a close collaboration of those institutes. With this spectrometer they can investigate from $\lambda = 0.32 - 17\,\mu$m the spectral reflectance and transmittance of samples [28, 48]. The National Renewable Energy Laboratory (NREL) use a PE 883 IR spectrometer for their investigations between $\lambda = 2.5\,\mu$m and $\lambda = 50\,\mu$m at their FTIR laboratory [4, 25]. The Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain is using a Perkin Elmer 950 spectrometer with a spectralon integrating sphere to investigate the optical properties of black selective absorber tubes [49]. The problem with those spectral measurements on tubes is the uncertainty introduced by the curvature of the tube surface, as described at the end of this chapter. Therefore, only relative values, but not absolute values, can be obtained for the investigated coatings.

A low resolution spectrometer was developed by Optosol GmbH, Germany, to measure the reflectance on flat and tubular absorbers. This setup consists of the alphameter and the emissiometer shown in figure 13. The measuring configuration is optimised to assure reproducible

Figure 13: The alphameter (upper two pictures) from Optosol GmbH is a low resolution spectrometer that measures the reflection of selective absorbers in the wavelength range from $0.3\,\mu$m to $1.9\,\mu$m. The emissiometer (lower picture) measures the reflected thermal radiation at $70°$ C [50].

measurements with an easy and fast handling for control measurements. The spectral resolution of this system is low and not optimised for qualification measurements.

The alphameter consists of a white integrating sphere and spectral selective light sources. Opposite of the sample port are two collimated detectors, which measure the light reflected by the sample. The light sources illuminate the whole sphere to ensure a good homogeneous illumination of the sample by the diffuse reflection of the sphere walls. Therefore they are mounted near the sample port to reduce the direct illumination of the sample. The four LED light sources in the blue, green, red, and infrared wavelength region illuminate the sphere subsequently. The reflected signal is measured by a Si-detector. For wavelengths $\lambda \geq 1.2\,\mu$m a tungsten halogen lamp in combination with a filtered Ge detector is used. The emissiometer of Optosol GmbH consists of a black tunnel, heated to 70° C. It serves as a source of thermal radiation. The attached detector, looking through a hole in the tunnel, is measuring the thermal radiation reflected by the investigated sample. The infrared detector is sensitive in the wavelength range from $8\,\mu$m to $14\,\mu$m. This covers most of the heat radiation spectrum of an emitter at 70° C. The tunnel is a diffuse radiation source, which is, especially due to its shape, suited for measurements on tubes. In order to obtain reproducible values it is important to have the samples always in the same position. To assure this, Optosol GmbH provides adapters depending on the diameter of the tubes investigated [50].

The critical point for spectral measurements on tubes is the uncertainty introduced by the curvature of the tube surface. The problem is, a beam of a given diameter is broadened if it is reflected of a curved surface. This as shown schematically in figure 14 a). Therefore, special

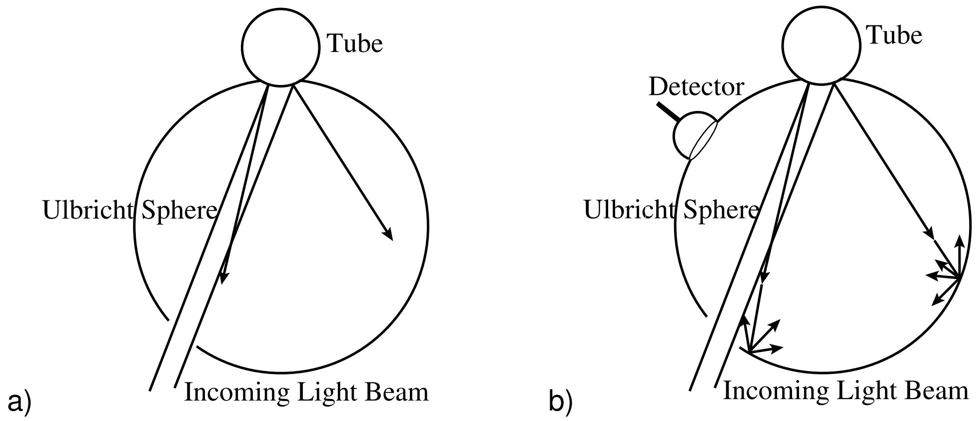


Figure 14: a) Schematic drawing of the beam broadening when it is reflected from a surface with curvature. b) Schematic of the measuring configuration used by ISE for the investigation of absorber tubes.

care has to be taken to assure that all the reflected light will be focused on the detector. This difficulty can be avoided by not measuring the reflected beam. Instead the diffuse reflection of the reflected beam at the sphere wall is measured, as shown in figure 14 b). Here all the light reflected by the sample is impinging the wall of the sphere, where it is then reflected diffusively. The detector then measures the increase of diffusive light. This configuration is used in the measuring setup used by ISE and SPF. In the measuring system of Optosol the light path in figure 14 b) is inverse and the tube is illuminated by diffuse light and the detector is measuring the light reflected by the sample. It is further important to assure that the measuring spot and the position of the sample is always the same, to guarantee a high reproducibility of the performed measurements. With the system described it is not possible to obtain absolute values, as the influence of the curvature is not known, if standard flat calibration samples are used. Using curved standards could lead to absolute values. But the problem is to calibrate those standards and they are not yet available on the market. Another problem is, it is necessary to have a standard for each possible tube curvature.

4.4 Mechanical Stability and Ageing Tests

Certified mechanical stability and ageing tests for flat plate collectors are performed for example by the Swiss Institut für Solartechnik Prüfung Forschung, HSR Hochschule Rapperswil (SPF), the German Fraunhofer-Institut für Solare Energiesysteme (ISE), and the Swedish National Testing and Research Institute (SP) [51]. The mechanical stability, the adhesion of the black coating to the substrate, is tested by two tests. In the simple test a scotch tape is pressed on the coating, which is then torn off very quickly. The more sophisticated test is described in ISO 4624, where a controlled adhesion of 0.5 MPa is applied [51].

Ageing tests are performed to assure that the quality and optical properties of the different products are not changing drastically during the lifetime of the absorber. With a lifetime of several decades (25 years for flat plate absorbers), the ageing has to be accelerated, in order to be able to predict the performance in a shorter time. In the case of glass covered flat plate collectors degradation tests due to oxidation, hydration, and hydrolysis are performed by increasing the operation temperature [51]. Further a test with an increased sulphur dioxide $\mathrm{SO_2}$ concentration is occasionally performed to investigate the influence of air pollution on the collector's performance [51]. The tests to qualify flat plate absorbers are summarised in ISO/CD 12592.2 "Solar Energy – Materials for flat plate collectors – Qualification test procedure for solar surface durability" and two publications [51, 52].

For receivers and absorber tubes no standards, neither for the mechanical stability nor for an accelerated ageing are available. They are of great importance, as the working temperature and the solar concentration on the coatings are much higher than in the case of flat plate collectors. First investigations were performed by SPF with respect to accelerated ageing tests on different absorbers (flat samples and steel tubes), for different working temperatures (from $160°$ C to $600°$ C) and for different receiver principles (i.e. evacuated or in atmosphere) [53, 54]. A simulation and extrapolation concerning the long term stability of absorber tubes based on coating data obtained on flat absorbers were performed, but this can not replace stability tests [55]. Tests concerning the durability of coatings at elevated temperatures under vacuum and in air would also be of great interest. The accelerated ageing tests performed of flat plate collectors with increased temperature are not sufficient for CST applications. Since the absorptance and emittance are changing with time, it further stresses the importance of finding standards to determine those quantities.

5 Conclusions

This report shows CST systems can be used as an environmentally friendly alternative to fossil fuels in numerous applications. They can be used to generate electrical power and solar fuels or to provide heat for desalination of water, cooling, and for various industrial processes. Although, only the generation of electrical power has gained great importance in political and economical respect, the other applications will become more and more important in the near future. This also shows in the number of operating and planed plants for electrical power production in the United States and Spain in comparison to the few micro-CST pilot plants constructed for the generation of process heat. Just now the first commercial projects for process heat are planed. The need and interest for micro-CST usage is there, but it still has to deal with long pay-off times and a low publicity. Those pay-off times could be minimised by price reductions for the systems and political support in form of subsidies and/or tax reductions. Although the market is just starting to grow, already several companies have specialised in providing components for micro-CST systems. Based on the per-formed study, there are three companies that have specialised on the production of evacuated high temperature receivers, and only two that can produce air stable selective coatings for medium temperature applications.

In order to further increase the number of installed CST systems it is necessary to define standards to qualify and with it compare different CST components. This will lead to a levelling of the playing fields of the component suppliers and a cost reduction as different products can be compared. Further standards will make it easier for financiers to access the quality of CST systems. This means in detail, it is important for suppliers of CST components to have standards in order to be able to give references to their costumers. References can reduce the doubts concerning a product. Further a quality proof can convince costumers that there is also a quality divergence between two products and not only a price difference. For costumers standards would provide the assurance that different products claiming the same quality also are of same quality. Ageing tests provide costumers and financiers the security of being able to estimate investigation costs, pay-off times, and gain.

Great effort to define standards for parabolic troughs and evacuated receivers is made by DLR (Deutsches Zentrum für Luft- und Raumfahrt) in close collaboration with NREL (National Renewable Energy Laboratory) and CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) [42–47]. They are currently defining a set of quality criteria and test procedures, but no official standard is yet defined. Their tests and qualification procedures standardise how to evaluate and specify technologies, but do not standardise components. The different testing facilities can already be used by customers and suppliers to evaluate the performance of components and systems, although they are not yet official standards [45].

Concerning the qualification and testing of non-evacuated receiver tubes or absorber tubes no standards exist or are in development. The measurements performed at ISE (Fraunhofer-Institut für Solare Energiesysteme), NREL or CIEMAT, with different photospectrometers and integrating spheres, give reproducible results for comparing different products, but they are only relative and not absolute. This is due to the fact that the standards for the calibration of the spectrometers are made for flat surfaces and not for surfaces with curvature.

This shows, standards for evacuated parabolic troughs receivers, not including durability, will be available in the near future. The prediction is that they will be ready by end of 2011 or beginning of 2012. However, with regard to the selective coating of the absorber tube very little is done. In this matter everyone relies on the performance measurements as well as durability tests that have been performed on flat plate collectors. This information is not reliable, as the geometry of the absorber is completely different (flat and cylindrical) and the working temperatures are much higher.

In the 90ties accelerated life testing and qualification test procedures were defined in the framework of the IEA Task X by the SPF (Institut für Solartechnik Prüfung Forschung, HSR Hochschule Rapperswil) along with ISE and SP (Swedish National Testing and Research Institute) [52–54]. The same tests and qualifications should be set up without further delay for CST absorber tube coatings. This phase 2 of the ”CST Receiver Tube Qualification” project should, though, fall predominantly within the competence of SPF.

6 Mentioned Companies and Institutes

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), www.enea.it
Alanod-Solar GmbH & Co. KG, www.alanod-solar.com
Archimede Solar Energy SpA, www.archimedesolarenergy.com
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), www.ciemat.es
Deutsches Zentrum für Luft- und Raumfahrt (DLR), www.dlr.de
Energie Solaire SA, www.energie-solaire.com
Flabeg Holding GmbH, www.flabeg.com
Fraunhofer-Institut für Solare Energiesysteme (ISE), www.ise.fraunhofer.de
Guardian Industries Corp., www.guardian.com
Himin Solar Co. Ltd., www.himinsun.com
Institut für Solartechnik Prüfung Forschung, HSR Hochschule Rapperswil (SPF), www.spf.ch
Laboratoire d'Energie solaire et de physique du bâtiment at Ecole Polytechnique Fédérale de Lausanne (LESO-BP at EPFL), http://leso.epfl.ch
Mirroxx GmbH, www.mirroxx.com
NEP Solar, www.nep-solar.com
Novatec Biosol AG, www.novatec-biosol.com
National Renewable Energy Laboratory (NREL), www.nrel.gov
Optosol GmbH, www.optosol.com
Plataforma Solar de Almería (PSA), www.psa.es
PSE AG, www.pse.de
Saint-Gobain, www.saint-gobain.com
Sandia National Laboratories, www.sandia.gov
Schott Solar AG, www.schottsolar.com
Siemens Concentrated Solar Power, Ltd., www.energy.siemens.com
SkyFuel Inc., www.skyfuel.com
Solar Power Group GmbH, www.solarpowergroup.com
Solel Solar Systems Ltd., www.solel.com
Solitem GmbH, www.solitem.de
Sopogy Inc., www.sopogy.com
Swedish National Testing and Research Institute (SP), www.sp.se
Universität Basel, www.physik.unibas.ch

6.1 List of Contacted Persons

Alanod-Solar	St. Brändle, S. Steuer
Ausra, Inc.	D. Mills
Angelantoni Industries	M. Zenobi
CIEMAT	A. Morales, E. Rojas
DLR	P. Heller, N. Lichtenthäler, E. Lüpfert, J. Pernpeintner, B. Schiricke
ENEA	V. Sharma, M. Vignolini
EPFL-LESO	M. Joly, A. Schüler
ETHZ	A. Steinfeld
FERA	A. Toro
Himin	J. Ma
ISE	Ch. Hildebrandt, W. Platzer
Mirroxx	Ch. Zahler
NEP	A. Milloud, St. Minder
Novatec	M. Mertins
NREL	F. Burkholder, Ch. Kennedy, Ch. Kutscher
Optosol	W. Graf
PSE AG	A. Häberle
Planair	St. Giamboni, P. Renaud
PSI	A. Meier
SolarPACES	P. Heller, Ch. Kutscher, A. Meier, A. Steinfeld
SPF	St. Brunold, M. Rommel
Xeliox	M. Vettori

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