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“A review of the application performances of concentrated solar power systems”

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A review of the application performances of concentrated solar power systems

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Abstract

The global energy production model is changing from fossil fuels to renewable and nuclear energies. Concentrated solar power is one of the growing technologies that is leading this process. This growth implies the sophistication and size of the systems and, therefore, it requires an increase in maintenance tasks to ensure reliability, availability, maintainability and safety. The aim of this paper is to describe the current context of concentrated solar power, to summarise and analyse the main degradation mechanisms and the main techniques to detect, prevent and mitigate these faults. An exhaustive literature study is presented, considering the most advanced techniques and approaches. A novel qualitative and quantitative analysis of the literature is provided. Finally, the current trends and the future challenges in this field are gathered from this study.

Keywords: Concentrated solar power; maintenance; fault detection; fault prevention; survey.

Acronyms: CSP (Concentrated Solar Power); PTC (Parabolic Trough Collector); SPT (Solar Power Tower); LFR (Linear Fresnel Reflector); PDS (Parabolic Dish System); TES (Thermal Storage System); FEM (Finite Element Modelling); AT (Absorber tube); UAV (Unmanned Aerial Vehicle); NDT (Non-Destructive Testing); HTF (Heat Transfer Fluid); LCOE (Levelized Cost of Energy)

1. INTRODUCTION

Nowadays, global energy production is changing since fossil fuels are being replaced by renewable energy and nuclear power. By 2040, renewable energy is expected to be more than 20% of total energy production [1, 2]. Solar energy has played an essential role in this change as one of the most exploited technologies in recent years. In 2013, global solar energy installed capacity increased by 35%, whereas wind energy installed capacity increased by 12% and, geothermal and hydro power less than 5% [3]. The growth of solar energy production has occurred due to greater efficiency in technology.

The exploitation of solar energy can be carried out using two different technologies:

- *Photovoltaic (PV)* where energy is generated by the photovoltaic effect. This effect is produced when sunlight incises on solar cells, that generates electricity in certain semiconductors. This electricity can be stored or sent to the electricity grid [4, 5].
- *Concentrated Solar Power (CSP)* where the energy is generated from heating a fluid using concentrators and mirrors. In this field, Spain and the USA are the greatest producers of CSP with more than 4 GW [6]. Figure 1 shows the main CSP configurations.

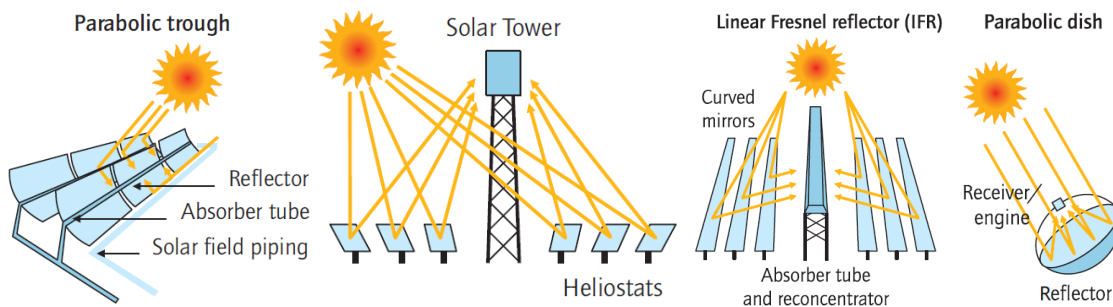


Figure 1. Current CSP configurations [7].

Table I shows a qualitative comparison between these configurations [7]:

- *Parabolic trough collector (PTC)*. This technology is based on the reflection of direct sunlight onto parabolic mirrors towards an absorber pipe containing a Heat Transfer Fluid (HTF) [7].
- *Solar power tower (SPT)*. The reflections of hundreds of mirrors, called heliostats, are concentrated into a single point [8]. Electricity is generated by a thermo-dynamical cycle.
- *Linear Fresnel reflector (LFS)*. It is based on the previous configurations. Unlike PTC, the receiver is not located within the mirrors, but in a separate tower [9]. A recent design called a compact linear Fresnel reflector (CLFR) employs two parallel receivers in each row, making it more compact than PTC. This design has already been tested in working plants, e.g. Puerto Errado, Spain [10].
- *Parabolic dish systems (PDS)*. A set of mirrors form a parabolic shape that concentrates sunlight in a focal point. This system can follow the sun in two directions, making it more efficient.

Table I shows an analysis of CSP technologies. Since PTC is one of the most developed technologies, its improvement potential is lower than others. However, LFR, SPT and PDC have great improvement potential, which makes them very attractive for research projects.

Table I. CSP technologies analysis.

	Relative cost	Land occupancy	Thermodynamic efficiency	Operating T range (°C)	Solar concentration ratio	Improvement potential
PTC	Low	Large	Low	20-400	15-45	Limited
LFR	Very low	Medium	Low	50-300	10-40	Significant
SPT	High	Medium	High	300-565	150-1500	Very significant
PDC	Very high	Small	High	120-1500	100-1000	High potential

Energy generation can also be done using hybrid plants that combine different energy sources to produce electricity. These combinations may be PV-CSP that use uniquely solar power and whose profitability has been proven, as mentioned in reference [11]; or with a thermal plant [12] that increases the energy generated from a fuel and thus the electricity generation of the plant by increasing temperature on the heat exchanger. Installation costs for CSP and PV technologies are expected to decrease in the future, making hybridization more profitable and attractive for investors [13].

The contribution of this paper is summarized as follows:

- This paper explains the main degradation mechanisms in CSP, the causes and the consequences. Some reviews in literature focus on the main characteristics of solar plants [14] or certain components [15, 16]. Other research works study certain cases, e.g. durability [17], soiling [18] or its modelling [19]. However, this paper summarizes all the faults affecting CSP energy and their influence over the affected structures.
- Fault detection and diagnosis, failure prevention and mitigation techniques are presented. The state of the art studies the research into the design of certain components, e.g. collectors of a SPT [20], the suitability of materials [21], or standardized evaluation methods for components, as solar mirrors [22]. This paper collects the main publications of failure detection for any component, and the main techniques to prevent and mitigate these faults.
- An exhaustive analysis that classifies the references about the maintenance of CSP is showed. A qualitative discussion of the principal requirements and improvement potential is provided based on the literature. A quantitative analysis is carried out to analyse the research studies on CSP and the future trends in this field.

This work focuses on application performances based on the main causes and effects of the principal degradation mechanisms in CSP technology, together with the techniques used for their detection, prevention and mitigation. There are numerous studies where new techniques are developed for enhancing the global efficiency of CSP plants. It involves keeping the degradation processes under control, i.e. by studying the effects of corrosion [23], through mechanisms for reducing soiling [24]; by optimising the cleaning strategy [25]; by modelling the thermal stress of solar receivers [26]. These advances, together with new materials and designs, allow for improvement in heat transfer [27]; increasing the efficiency of the thermal cycle [28]; improving the energy storage systems [29], reducing the operations and maintenance requirements [30] or increasing the electricity production [31]. The scope of this paper is to define the most relevant agents that can be counterproductive to the proper functioning of a CSP plant and explain the main techniques and advances to fight against them.

The structure of the paper consists of: Section 1 shows the context of solar energy and provides a brief explanation of the most usual technologies in this field. Section 2 analyses the principal failure mechanisms affecting CSP technology. Section 3 compiles the main research studies about detection, prevention and mitigation of failures in CSP. Section 4 presents a discussion of the degradation mechanisms in CSP technology and shows two tables that summarize the main literature in this field. Section 6 gives the conclusions and discusses the future challenges arising from this work.

2. APPLICATION PERFORMANCES IN CONCENTRATED SOLAR POWER

This section outlines the main studies of application performances in CSP installations. The principal causes and effects on the implied components are also analysed. This section is divided according to the type of application performances.

Some relevant degradation mechanisms in CSP are related to high temperatures and gradients, the corrosion of pipelines or a long exposure to radiation in the installation. The effects of protecting paint on mirrors related to their durability and the effects of weather conditions or their ageing are also considered.

2.1. Absorber tube deformation and cracks

The HTF circulates through pipelines along the whole installation in a PTC plant, where it can corrode or deform the inside of the pipeline [32]. The pipelines are commonly steel based with coatings to

improve the absorptance of their external surface [33, 34]. Figure 2 shows the basic scheme of an absorber tube (AT).

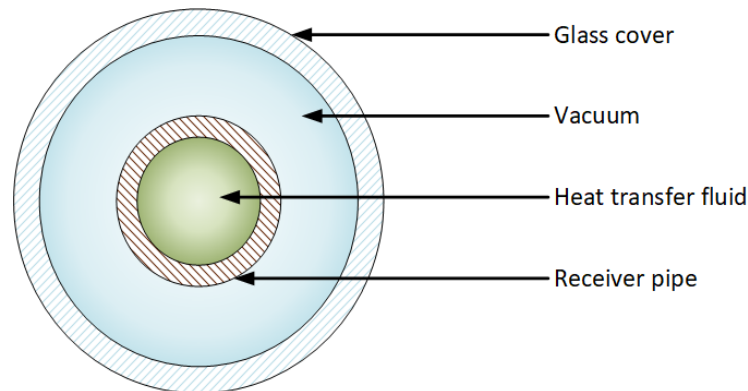


Figure 2. Absorber tube scheme.

Akbarimoosavi and Yaghoubi studied the theoretical effects of the deformation on ATs in two different CSP plants [35]. They modelled the AT using Finite Element Modelling (FEM) and analysed the concentration ratio on its surface. The results show an optical efficiency drop below 2% for a maximum deformation of 20mm in the glass cover. A correlation between the HTF convection coefficient and temperature with respect to the deformation was identified.

The bending of tubes was also studied by Tripathy et al. [36]. They employed FEM to test the behaviour of tubes under different materials, such as steel or laminated metal composites, and different mass flow rates. The results showed similar stress distributions for all flow rates, but with different temperature distributions depending on the materials. A negative correlation between mass flow and deformation was identified in all the materials.

Lu Li et al. [37] considered the use of multi-level analysis using FEM for CSP plants in two different publications. Firstly, they provided a detailed explanation of the multi-level model employed in the system. The levels are associated with system thermodynamics, the thermal properties of the AT, the wall temperature distribution of the tube and thermo-mechanical behaviour. They also considered aspects such as the communication between sub-models and computational performance. Secondly, they used the model under different conditions of temperature, system constraints or shading, among others [38]. The results showed the bending rates of the different parts of the AT and the performance efficiency reduction caused by them. The energy efficiency is, according to the models, around 18% in summer and 11% in winter. The losses due to deformation are less than 1%. These numbers should not be neglected since they can entail significant losses in large energy production plants

Regarding cracks, most studies in literature are focused on stainless steel which is an essential part of the structure. For example, Gómez Muñoz et al. [39] used electromagnetic acoustic transducers

(EMATs) to detect, locate and characterize cracks in stainless steel tubes with a small relative error for lengths up to 4 meters. Some authors employ frequency and vibration analysis to detect cracks in steel fluid-filled pipes. For instance, Murigendrappa et al. [40] formulated and checked experimentally the effects of water-filled steel pipelines on crack detection. Dilena, Dell'Oste and Morassi [41] analysed the change in natural frequencies of tubes to detect up to two cracks in a steel pipeline filled with water. Other technologies, such as the so-called 'pigs', are used in large oil and water pipelines but, because of the difficulty of their re-dimensioning, they are not applied to CSP technology.

Finally, the study of cracks is usually done through ultrasounds or frequency related Non-Destructive Testing (NDT) [42-44]. These techniques have been proved useful for locating and classifying cracks [45, 46]. However, this fault has not been studied enough in complex pipeline structures as ATs, and there are not many studies of crack detection on the whole structure of the AT.

Deformation is, together with heating issues, one of the most studied faults of ATs, because the external glass cover may break and reduce the effectivity of the components. Temperature affects deformation and can increase deflection. FEM has been demonstrated to be a widely used method to analyse deformation under different conditions. Deformation can cause focussing decreases, since it alters the position where the efficient flux is located.

2.2. Corrosion in absorber tubes and thermal storage system tanks

Corrosion is considered one of the most important degradation mechanisms in CSP. It can affect the ATs and the Thermal Energy Storage (TES) system. Most studies are dedicated to TES systems; therefore, different stainless steels, often treated with chromium, are used the most. Even in those cases, they are affected by temperature and molten salts.

Tian et al. [47] developed a characterization of early steel corrosion in marine ambient. Their work focused on coated and uncoated steel components with an exposure time between 1 to 10 months, concluding that corrosion is a convergent process and that some electric features of steel are degraded using eddy currents.

Regarding the TES, Liu et al. [48] reviewed the main storage systems, classifying them into sensible, latent and thermochemical storages. They also mentioned the most recent developments in TES, according to the materials and technologies used and their compatibility with containment materials and their corrosive effects. Some mitigation options are also mentioned.

There are several techniques used for the evaluation of corrosion in TES, spectroscopy and gravimetric analysis being the most used techniques in this area.

Ni et al. [49] evaluated the resistance of a pure aluminium coating (99.99%) and 310S stainless steel subject to corrosion at high temperatures employing spectroscopy. They compared the coating before and after it was immersed on molten carbonate for 120h, showing significant differences in the structure and composition between them. Spectroscopy was also used by Ruiz-Cabañas for material selection at high temperatures with different metals and alloys [50]. Fernández et al. [51] used both spectroscopy and gravimetric analysis to measure corrosion in steel at 390°C, and observed the generation of a protective layer on the steel surface.

Gravimetric analysis was employed by Yan et al. [52] to study structural changes in superalloy samples, most of them being composed of nickel, cobalt, chrome and titanium, etc. Fernández et al. [53] compared different steels used for energy storage in CSP plants during 2000 h. McConohy and Kruiženga [54] employed this technique to observe the evolution of thermo-physical properties, such as specific heat or heat of fusion, being in nickel alloys at 600°C and 680°C.

Hot corrosion is due to the composition of the HTF and the high temperatures reached in the installation. Most publications refer to the TES, since the HTF stays in the tanks for longer. It has been discovered that hot corrosion in steel is commonly studied. Research studies concerning ATs, or pipelines for CSP, are scarce.

Regarding the corrosion of TES, spectroscopy and gravimetric analysis are the techniques that are mainly used. They usually consider the influence of temperature, HTF composition and the material used in the installation.

2.3. Thermal issues in absorber tubes and thermal storage system tanks

Heat transfer, heat losses, and thermal stress are the most relevant conditions to consider when designing and inspecting any installation of ATs, because they work under high temperatures.

Heat transfer and heat losses depend on the relative vacuum and gas composition inside them. Conrado et al. [55] showed different approaches to study the behaviour and costs of both, e.g. thermal, exergy and energy, or numerical models. These approaches are also useful for simulating the behaviour of the tubes.

Navarro et al. [56] analysed the thermal losses of ATs in a 50 MW commercial CSP plant by evaluating the relative vacuum inside them. For this purpose, they used three devices: an infrared camera, the thermo-hook (a measurement header fixed at the end of a pole), and the annulus gas analyser (AGA), a device that allows the NDT of vacuum in any receiver, based on the spectral emission of excited gases. These devices provide a measurement of the gas composition and the relative vacuum inside the tube resulting in around 1240 out of 13000 receivers with a lost vacuum. This increases their operating temperature and adds an extra heat loss of 0.6 GWh per year.

Heat losses in PTC were also studied by Eichel et al. [57] who observed the elongation of the AT caused by temperature and the effect of emittance. Häberle et al. [58] studied the heat losses using a thermocouple. Häberle et al. [59] also simulated the optical performance and the losses of the concentrator. They correlated the heat losses with the temperature of the AT. FEM based studies are applied in this area, e.g. Patil et al. [60], who studied the thermal losses in non-evacuated ATs and the influence of convection and conduction in heat loss enhancement. Al-Ansary and Zeitoun [61] analysed thermal losses in half-insulated tubes and their temperature correlation.

Burkholder and Kutscher [62] measured losses under different temperatures and flow rates for an AT, achieving an estimation of heat losses per metre. The design of the AT was improved through dynamic vacuum while the solar field is operating in the HITECO European project. The correlation between heat losses and the air composition was measured, and satisfactory results were obtained [63].

Abedini-Sanigy [64] analysed thermal stress, AT being under quasi-steady state conditions. The solar flux is calculated to obtain the temperature distribution on the tube, deflection and thermal stresses. The analysis showed that an increasing temperature and mass flow rate cause deflection reduction. It was also seen that deformation variations were small during the studied periods and that the maximum deformation occurred in the central part of the tubes. Furthermore, Zhenjie Wan et al. [65] used FEM to study thermal stress and fatigue in the steam receiver. They obtained an important non-uniformity in the heat distribution and the flux along the panel, identifying hot spots in the elbows of the pipelines. They concluded that it is necessary to inspect regularly the welds of the structure, since they are prone to suffering thermal fatigue.

Analysing storage tanks involves measuring and mitigating thermal losses by modelling the behaviour of the system. Heat losses were observed and mitigated by Prieto et al. [66] in a pilot plant in Seville, see Figure 3. They analysed and modelled the losses and proposed the addition of a cold mesh in order to reduce them. Similar work was carried out by Prieto et al. [67], who measured the temperature distribution and the thermal losses in a pilot plant in Lleida.

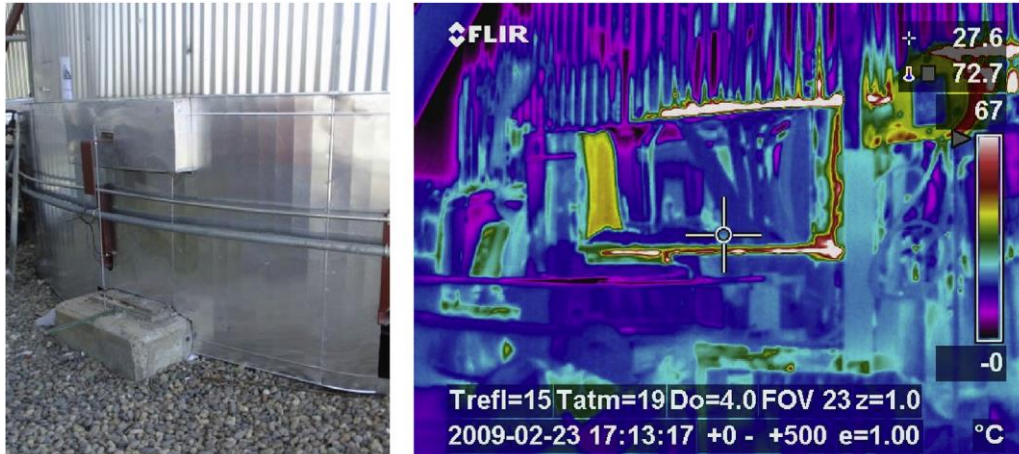


Figure 3. Thermal losses in the hot tank foundation [66].

Many studies related to thermal behaviour focus on modelling the system. Torras et al. [68] modelled the thermal behaviour of a two-tank storage system considering the geometry, materials and structure of the tanks, among other aspects. Rodríguez et al. [69] divided the molten salt tank into different parts and evaluated them separately. Fernández-Torrijos et al. [70] used FEM to simulate thermal and mechanical loads, displacement of the salts and temperature of the tanks. Peiró et al. [71] studied the influence of different HTF properties in charging and discharging processes, Zaversky et al. [72] focused on the transient modelling of a two-tank TES system during charge and discharge. Finally, Goortani and Heidari [73] modelled the effects of solar irradiance daily and yearly on a two-tank system.

It is observed that most AT studies are related to thermal behaviour. This is due to the high temperatures and the consequent problems derived from it. It is not possible to prevent heat losses because of the inherent thermal gradient between the ATs and the ambient. Hence, the studies consider vacuum loss as the most important one. Since they cannot be totally prevented, the studies are usually oriented to model them and to improve the thermal behaviour of the tubes. For this purpose, the use of coatings or the generation of irregularities in the inner surface of the tubes is a common practice, described in Section 3.2. Thermal stress and fatigue are not specially considered, since there are few studies focused on their causes and effects in CSP. The influence of temperature, mass flow and structure of the system are considered as the most relevant variables.

Research projects study the effects and the distribution of thermal losses in storage tanks and propose different procedures to mitigate them. FEM is used, analysing the transient charge and discharge states. The modelling of the entire TES system is extended and applied. This is generally done by combining real-time data from the sensors in the tanks, and by calculations and simulations of the system conditions.

2.4. Mirror soiling and dust accumulation

Deserts and arid areas are used to locate CSP plants because of solar radiation. However, these places usually suffer from natural events, such as sandstorms, presence of airborne sand or dust particles, that could cause soiling and abrasion on the mirrors. Soiling is the deposition of sand and dust on the surface of solar panels, resulting in reduced performance. Yu et al. [74] detected the main variables that contribute to dust accumulation: temperature, speed and wind direction.

Karim et al. [75] proposed a methodology to analyse the influence of some parameters on mirror degradation in two locations in Morocco. They classified the influential parameters into climatic (wind speed and direction and humidity) and geological (particle size, shape distribution and hardness). They confirmed the correlation between the wind speed and the amount of transported sand. They also highlighted the relevance of humidity to the particle adhesion process.

The effects and consequences of soiling have been analysed, for example, by Costa et al. [18], who presented an updated state-of-art that consider both CSP and PV. Picotti et al. [19] show approaches for modelling dust generation, deposition, adhesion and removal.

Merrouni et al. [76] studied the reflectance and the cleanliness of aluminium and glass mirrors over three months. These mirrors were installed in “mirror spheres”, i.e. structures that allow them to be positioned in four different directions (North, South, East and West), and four different angles (0°, 45°, 90° and 135° with respect to the horizontal plane). They obtained a cleanliness reduction of 2% in 90° and 45° in aluminium and glass mirrors, 10-16% in 135° mirrors and, 27% (aluminium) and 44% (glass) in 0° mirrors. The influence of angles was also studied by Heimsath et al. [77]. They studied, under laboratory conditions, the impact of soiling for different incidence angles on the reflectance measurements of the mirrors. They demonstrated the effect of soiling on the reflectance measurements that resulted in losses in reflectance greater than 15% in some cases.

Bouaddi et al. [78, 79] focused on the dynamic modelling of the soiling in reflectors. They studied the evolution of reflectance in different materials and created an updated model by using time series and smoothing of the oldest data. These models were then checked and compared with statistical behaviours. Pape [80] studied the precision of pyrheliometers and the correction of its measurement errors.

Bouaddi et al. [81] compared soiling on glass and aluminium mirrors over several months in two Moroccan locations by the sea. They collected meteorological data for six months and characterized the regular airborne particles of the ambient. They measured the reflectance of the mirrors and the

soiling patterns that appeared to compare soiling rates. The author concluded that aluminium is more suitable than glass for desert locations.

Merrouni et al. [82] analysed the performance of two reflectometers over 12 weeks. They measured reflectivity in several mirrors in the summer. The results showed a significant reflectivity decrease during the driest weeks up to 30%, and a substantial imprecision of the measurements in the weeks with high aerosol concentration.

It can be concluded that any fault that causes a decrease in the light transmission capacity of the mirrors is considerably important. The mechanisms that affect the mirrors are studied and modelled in literature, e.g. soiling, caused by deposition of dust, sand and other particles on mirror surfaces. Soiling is relevant in the desert, a suitable place to locate solar farms. Researchers have studied the variables, such as dust size and hardness, wind speed and orientation and materials used for the mirrors. Moreover, there are many studies that correlate the dust deposition rate with reflectivity losses. Soiling prevention and mitigation techniques are studied in Subsections 3.2 and 3.3.

2.5. Mirror erosion

Mirror erosion in CSP occurs mainly because of the impact of abrasive particles on their surface, with a reflectance reduction. These particles are usually sand or dust. Völker et al. [83] studied sand trickling, used more to study coatings, based on the fall of sand from a certain height, and sand blasting, that involves throwing sand from a horizontal pipe to the sample under several angles and speeds.

The study carried out by Karim et al. [84] focused on the effects of sandstorms on mirror surfaces. Figure 4 shows some effects. Two different locations, the ocean and the desert, were considered. Samples of real sand were simulated under laboratory conditions, considering speeds and impact angles. Two impact shapes were discovered, i.e. a ring and normal cracks, depending on wind velocity.

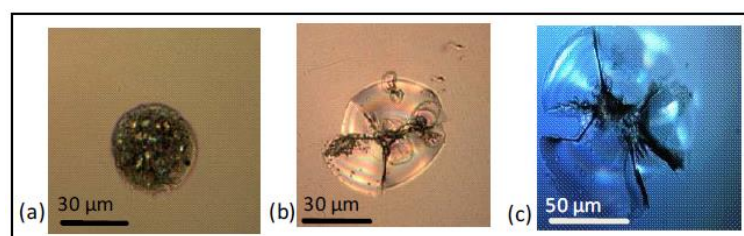


Figure 4. Damaged surfaces: (a) desert site; (b) oceanic site; (c) laboratory [84].

Wiesinger et al. [85] compared the results of laboratory tests on mirrors in the station in Zagorra (Morocco). They used silver and aluminium mirrors (in outdoor conditions) with an inclination of 45°

and a variable inclination from 0 to 90°. The results showed a correlation between degradation and sand mass impacts. They also observed a correlation on the impact angle, 90° being the worst one.

Comley et al. [86] studied the effects of sand and dust particles in CSP plants in Libya. They modelled the particles of sandstorms with respect to their size. They detected that the damaged area and a reflectance reduction depend on particle speed.

Naamane et al. [87] simulated the erosion of glass mirrors in the laboratory using data from two different sites. They considered wind speed, the impact angle and sand particles, measuring the evolution of reflectance and created a 3D sample map of the mirror. They observed that wind speed influences surface erosion and the roughness of the mirrors; the impact angle affects only the morphology of the impacts, and sand particles cause erosion.

Sutter et al. [88] analysed and compared the effects of sandstorms on mirrors in several places in Morocco and Spain. Firstly, they measured the degradation and the losses of reflectance caused by sand on mirrors after 24 months. Then, they compared the impact of sand with the reflectance losses of the three sites with the purpose of obtaining their Single Particle Momentum Distribution (SPMD). They were able to describe the erosion characteristics of both laboratory and outdoor sites accurately.

Khaldoun et al. [89] designed an abrasion chamber using a particle blower. They produced a literature review of the effects of sand and durability of the mirrors. They designed a vertical blower considering features as the flow and homogeneity of the sand particles. Finally, a machine was built and its ability to function well was certified.

The main insights can be summarised as follows: Dust and sand related faults are significant in CSP plants because of their location and environment. Erosion is a fault that that is generated by the impact of airborne particles on mirrors with irreversible damage. Erosion and soiling have been conducted under laboratory conditions, considering variables such as physical properties of dust, incidence angle and speed. The main difference with soiling is the irreversibility of this phenomenon, as it also causes permanent losses of reflectance. Erosion is an irreversible degradation mechanism, but there are not enough studies about its mitigation.

2.6. Mirror ageing, degradation and corrosion

The ageing of mirrors is considered for installations of any size and type. This is a phenomenon caused by the life cycle of mirrors and their long exposure to the weather. This may cause corrosion in the surface or the edges, and paint degradation that reduces the reflectance of the mirrors [90, 91]. García-

Segura et al. [17] classified the different materials and configurations for mirrors, grouping them into glass, aluminium, and silver-based reflectors, and the studies of durability.

Accelerated ageing is employed to measure durability and the influence of the ambient, studying the ageing effect without long-time exposures, and making it possible to model the behaviour and evolution of the mirrors. Boubault et al. [92, 93] created and tested a numerical thermal model to analyse the behaviour of absorber materials under highly concentrated light fluxes. Reference [92] describes a proposed model that is applied and validated in Reference [93]. They observed that variables such as diffusivity, effusivity or conductivity influence the lifetime of the samples.

Fernández-García et al. [94] analysed the efficacy of accelerated laboratory experiments using three commercial mirrors to test the surface and edge corrosion related to ageing and use. This study compared the degradation of real mirrors after two years with accelerated ageing cycles of up to 3000h. They concluded that some types of tests cannot be used to make life estimations, and that accelerated ageing experiments could only be used to replicate short exposure periods. Figure 5 shows the effects of corrosion and erosion in a desert environment after 3 years of exposure.

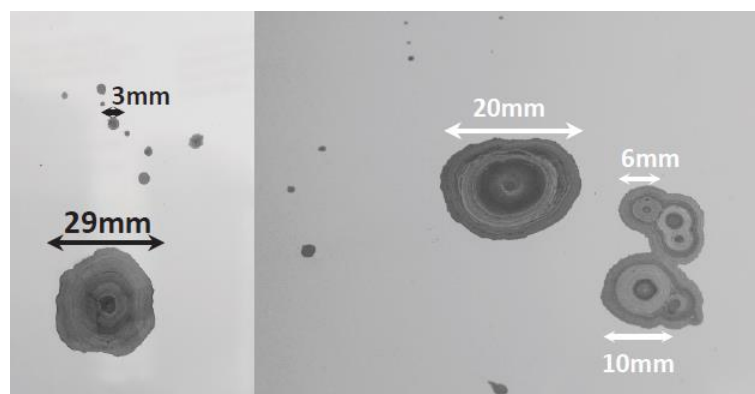


Figure 5. Pitting corrosion spots after 3 years of use [94].

Brogren et al. [95] analysed several materials in both an accelerated ageing test chamber for 2000h and outdoors over 9 months to compare the effects of ageing. They then measured the optical properties of the mirrors and displayed their results. The displays show a reflectance reduction in all the mirrors, both in accelerated and outdoor ageing. They discussed the different capacities of the materials to withstand accelerated ageing and high temperatures, and the suitability of the different materials to be tested in laboratory as compared to real exposure.

Guerguer et al. considered the degradation in glass and polymeric mirrors in two different environments: coast and desert [96]. This research briefly compared the ambient conditions and observed abrasion spots due to sand particles in polymeric mirrors, delamination caused by the thermal expansion of the different layers, larger corrosion in the coastal site and microscopic blisters

in the desert location. Regarding glass mirrors, the corrosion was slower and it only appeared in the coastal location, starting at the edges and showing some differences between monolithic and laminated mirror samples.

Delord et al. [90] studied the degradation of glass mirrors through their discoloration. They performed some tests at three temperatures (100, 150 and 200°C) until the reflectance losses were significant. The results show a two-phased degradation, a protective paint decolouring and the corrosion of the silver layer of the mirrors. They established a correlation between temperature and protective paint lifetime for the three temperatures.

The atmosphere plays an important role in the degradation of mirrors. Suspended water vapour causes small reductions in heat transmission depending on the humidity [97]. Aerosols are also relevant in this aspect, according to the study by Sengupta and Wagner [98]. Hanrieder et al. [99] reviewed the models used to estimate atmospheric extinction and its effects on plant performances.

The influence of acid atmospheres, rich in sulphur dioxide (SO₂), was studied by Fernández-García et al. [100] on a set of glass, aluminium and polymeric mirrors. They carried out laboratory tests over 50 cycles of 24 hours, collecting corrosion and reflectance measurements, and appearance after the test. They observed the lowest corrosion and reflectance reduction on the glass, staining corrosion of the aluminium and a slight degradation of the polymeric mirrors.

Related to mirrors, but hardly studied, is the effect of their weight, which may reduce the focusing quality of mirrors and affect their efficiency. Meiser et al. [101] used FEM to evaluate the deformation of parabolic mirrors. The results indicated that the stiffness of the collector and the construction design influence the shape and magnitude of deformation in two structures and three models (ideal, elastic and cantilever).

The main highlights can be summarised as: ageing and ambient exposure are degradation mechanisms that, unlike soiling and erosion, are related to long-term exposure of installations. They affect the mirrors with irreversible damage and heavily depend on the ambient and the location. Offshore and industrial environments are more harmful than desert areas, since there are more impurities and the environmental conditions for the mirrors are harsher. The main consequence of mirror ageing is the loss of reflectivity, especially at the unprotected edges. As these effects are only visible after long exposures, accelerated ageing techniques are commonly used to correlate the effects of laboratory testing and outdoor exposure. These mechanisms are irreversible; therefore, many studies focus on a classification of the best materials, addressing different aspects, such as composition, ambient conditions or structure of the mirrors, among others.

3. FAILURE DETECTION, PREVENTION AND MITIGATION TECHNIQUES IN CONCENTRATED SOLAR POWER

3.1. Failure detection techniques

Pitz-Paal [102] outlined the main problems for monitoring any CSP: large measurement surface, limited access, operation disturbance avoidance or high precision requirements. It divided the monitoring into PTC and SPT. PTC requires the measurement of the mirror focusing capacity, the adequate vacuum of the ATs or the cloud shading prediction. SPT must have an optimal optical quality for the mirror focusing on the tower or the heat transfer to the receiver, making the use of data processing systems necessary. Both technologies also require corrosion monitoring due to the features of the HTFs used in their installations.

Quoilin et al. [103] used a PTC power plant combined with a steam generation system for parameter characterization. They modelled the behaviour and studied the influence of different parameters on the performance of the plant, and thus simulated and optimized the future working conditions of the plant. Pousinho et al. [104] also modelled the behaviour of a combined CSP-fossil powered plant to forecast its production. This model maximized profits and ensured self-scheduling for up to 1 day.

Hsu and Su [105] created an adaptive chart for a thermal plant, and monitored up to 29 variables to predict the behaviour of the plant regarding failure detection. The results showed that the combination of moving averages and exponential smoothing gives better results than other time series models or neural networks. They also detected small process shifts.

The use of Unmanned Aerial Vehicles (UAVs) is spreading since their capacities to automatize and transmit information from devices on board have been successfully validated. The work published by Mesas-Carrascosa et al proposes an open hardware to monitor and send live data of the inspected area, such as position, thermographic image or ambient conditions [106]. This hardware is demonstrated to be useful in locating and identifying incidents on ATs.

Large data processing and diagnosing systems are currently advancing by Artificial Neural Networks (ANN) [107, 108]. ANN acquires and processes large amounts of data to 'learn' how to diagnose and detect system failures [109, 110]. An application to thermal plants, including CSP, was developed by Fast and Palme [111]. They used an ANN to monitor and diagnose a combined heat and power plant, with a prediction error lower than 2% in most cases. Cerri et al. [112] studied heat and cogeneration plants, and their production programming. Amozegar and Khorasani [113] used dynamic neural

networks for failure detection in turbines, and Fast et al. [114] focused on failure detection and modelling in gas turbines, similar to those used in power producing systems in CSP plants.

Cheng et al. developed [115] a numerical model using FEM techniques based on Partial Differential Equations (PDEs) to detect simulated cracks at distances varying from 18 to 50 cm in the axial direction between transducers and several different depths. The results showed an effective localization and size identification of the simulated cracks.

Regarding mirror soiling detection, Wolfertsletter et al. [116] created the Tracking Cleanliness Sensor (TraCS). They applied the method in two different stations, one daily maintained and the other sporadically maintained. TraCS measures the reflectivity of the mirrors and relates it to the cleanliness of them. Also, the soiling on the sensor itself is measured to determine accuracy changes. They concluded that the accuracy of measurements cannot be guaranteed in dusty environments, and that the TraCS accessory is useful for monitoring soiling rates of a mirror online.

Infrared thermography is common in the monitoring of heat losses in ATs, since it is the easiest method of measuring their temperature. The Spanish National Renewable Energy Centre (CENER) used a terrestrial mobile device to determine the temperature of glass tubes, and a self-developed algorithm to classify tubes [117]. The methodology ensures that the signal can be received and analysed online with a high accuracy rate of up to 15 km/h. It could be further used as an indicator of power plant efficiency.

There are different methods for filtering thermal images to facilitate fault detection [118, 119]. Pfaender et al. [120] used infrared thermography and two different filters to reduce the influence of background temperature. It was discovered that, even when using the filters, temperature measurements are slightly affected by solar radiation, but the usage of both filters allows the temperature of the absorber surface to be determined more accurately.

The corrosion in ATs and HTF storage systems was studied by Aung and Liu [121], who developed a sensor for online monitoring at high temperatures. Hamlaoui et al. [122] monitored galvanised steel coatings using electrochemical spectroscopy and observed its evolution after more than 30 days. Eliaz et al. [123] focused on the corrosion in turbine components at high temperatures, and Ahmad and MacDiarmid [124] referred to steel corrosion inhibition with different polymers.

Long-term feasibility was considered for condition monitoring by Boubault et al. [125], employing a formula for the levelized cost of energy (LCOE, [\$/MWh]). The formula divides the sum of the costs of a component by the energy produced and compares coatings depending on a set of characteristics.

The study shows graphics with LCOEs depending on variables such as reapplication interval, initial costs, temperature or cost reduction.

New technologies have been demonstrated to be useful for condition monitoring and failure detection of CSP installations [126, 127]. UAVs to inspect large power plants can be enhanced using image recognition and processing [118]. ANNs allow automatic inspection and detect faults with accuracy, where some faults, e.g. soiling, can be detected faster and treated with more efficiency [128, 129].

Condition monitoring and inspections are essential issues to ensure a correct maintenance of the CSP installation. Table II shows a compilation of the most important non-destructive detection techniques that can be employed for identifying anomalies or abnormal behaviours of certain components, explained in detail in reference [130]. The main characteristics, capacities and limitations of each technique are indicated qualitatively in Table II.

Several studies justify the necessity of this inspections and monitoring techniques. For example, Mahoney [131] calculated a failure rate of 30%-40% in solar absorbers. According to this work, an extra annual cost of €500,000 is estimated for an average CSP plant, considering that the price of replacing each absorber tube is around €1000.

Table II. Inspection methods characteristics [130].

Inspection Characteristics	Detection Method											
	Visual /Automatic inspection	Liquid penetrant Inspection	Magnetic Particle Inspection	Magnetic Flux Leakage	Eddy Current	Alternating Current Field Measurement	Radiographic inspection	Ultrasonic testing	Long Range Ultrasonic Testing	EMATs	Infrared thermography	Acoustic emission
Detection capability	Limited	High	Average	High	High	High	High	High	Average	High	Limited	Average
Detection resolution	Average	High	Average	Average	High	High	High	High	Low	Average	Low	High
Depth estimation	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Probability/Access	High	High	High	Average	High	High	Low	High	Low	Average	High	Low
Couplant required/surface treatment/surface access	No	Yes	Yes	No	Surface preparation required	No	No	Yes	Yes	No	No	Yes
Simplicity	High	High	High	Average	Average	High	Low	High	Average	Average	Average	Low
Inspection Speed	Average	Average	Low	High	High	High	Low	Average	Low	High	High	Static
appropriate for use in Pigging	No	No	No	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Appropriate for use in robotic crawlers (internal or external)	Yes	No	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No
Level of training required	Low	High	Low	Average	High	Low	High	High	High	High	Low	High
Cost	Low	Low	Low	Average	Low	Low	High	Average	High	Average	High	High

The extra cost caused by the failure rates of the absorber tubes is not the only reason for carrying out a complete maintenance strategy. In this paper, several degradation mechanisms are demonstrated to be the triggering factors of catastrophic accidents such as leaks and fires that can lead to severe

infrastructure damage. It has been shown that there is a necessity to improve the reliability of CSP plants in order to reduce the aforementioned risks and the maintenance costs [130].

3.2. Fault prevention and improvement techniques

Coatings, surface modifications and materials to avoid corrosion and erosion are common techniques, applied to mirrors and ATs.

Regarding mirror coatings, Hunter et al. [132] proposed a hydrophobic coating based on nano-silica and polymer materials. These materials allow durability to be increased up to 2 years in a working environment, but they cause a reduction in reflectivity. Sueto et al. [133] studied the effectivity of multi-layer coating on Fresnel lenses. In each experiment, 1g of sand was discharged. Then, the electrostatic voltage and deposited sand in the samples were measured. A significant difference between both samples was obtained, see Figure 6. The stability of this coating was also tested under high humidity, thermal cycling and freezing conditions without observing any additional degradation.

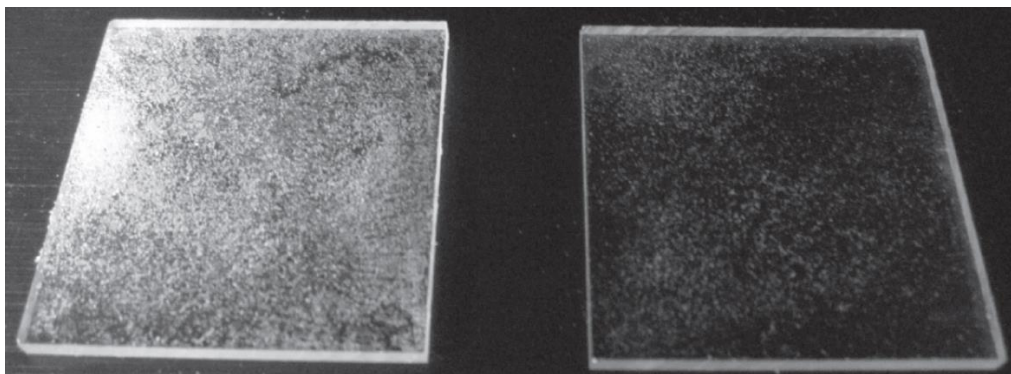


Figure 6. Samples without (Left) and with (Right) coating after experiments [133].

A study of coatings on polymer reflectors was carried out by Jorgensen et al. [134]. The objective was to obtain a suitable coating that can withstand the abrasion of harsh conditions and contact cleaning. For this purpose, they compared several coatings according to the reflectance variations after irradiation, condensation and abrasion cycles and accelerated weathering tests. They demonstrated the features where each coating stands out, highlighting a formulation from Red Spot Paint & Varnish Company Inc. as one of the best coatings.

An intermediate step between automated cleaning and surface coating is proposed by Mazumder et al. [135]. They employed transparent electrodes to create a cover named Electrodynamic Screen, capable of repelling particles from the surface by applying an electrical current. Finally, they studied

the effects of inter-electrode separation and different materials on the performance of this Electrodynamic Screen.

The thermal performance can be improved by changing the material of internal pipes. The selective coating is a useful option that consists of a coverage of the AT, where the absorption capacity depends on the light wavelength being optimum for sunlight. Ambrosini and Ho [136] classified these coatings according to preparation requirements (thermal spray and solution-based) and their features (absorptance and emittance). They also briefly studied the effects of roughness and heat treatment for the pipeline.

An economic viability analysis of anti-soiling coatings and surfaces was carried out by Lorenz et al. [137]. The authors simulated cost balance of the coating for dry and rainy years with and without manual cleaning. The simulations showed a positive economic effect of the coatings, with an average gain in performance around 3.3% in the dry, rainy and reference year scenarios.

Barriga et al. [138] proposed an improvement of the AT system through several modifications, the coating development being one of the most significant. On the other hand, Raccurt et al. [139] observed the stability of a selective coating under different high temperatures.

Heat transfer improvement can be also made using some techniques such as the addition of pins in the inner surface [140] of the pipe, or other irregularities such as dimples, protrusions or helical fins (see Figure 7) [141], or the use of a corrugated tube [142]. These methods use FEM and fluid dynamics equations to model the turbulence and heat transfer capacity of these irregularities.

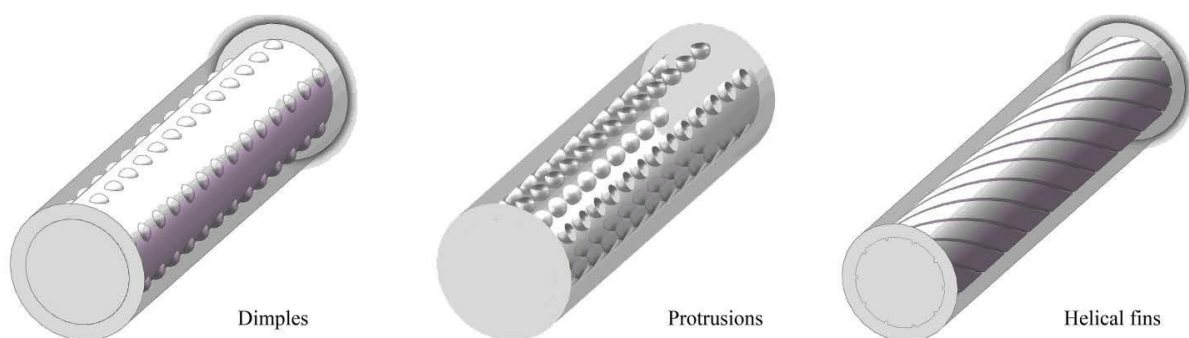


Figure 7. Proposed irregularities in the inner surface of the pipe [141].

Coating the surface is a common solution to corrosion. Gomez-Vidal et al. [143] compared corrosion resistance of different coatings in the laboratory in high temperature and concentration ambient. Gomez-Vidal et al. [144] measured alumina-forming alloys to create a protective layer. Hata et al. investigated the benefits of preventive coatings in turbines in corrosive environments [145], and Ahmad and MacDiarmmid [124] analysed the steel corrosion inhibition with different polymers.

Corrosion prevention can be achieved by correctly selecting both the material of the tank walls and the molten salts of the HTF. Gil et al. [146] compiled the main properties and requirements for TES systems, such as the structure of the tank, fusion point or corrosion resistance, among others. Regarding the HTF, Fernández and Pérez [147] studied the corrosive effects of different molten salts on steels. They achieved a corrosive capacity reduction on new salts compared to the previous ones.

Cheng et al. [148] studied the corrosion of Cr-Mo steel at 550 °C for up to 1000h, Wang et al. [149] focused on low carbon steel and steel alloy with aluminium coatings at 900°C, and Chatha et al [150] analysed the corrosion of nickel alloys at 750 °C.

Prevention is considered in this paper as the active avoidance of faults and failures of CPS technology. The common prevention techniques focus on the surface of the components and can be divided into coatings and surface modifications. Coatings are considered as the addition of different materials to the surfaces in order to prevent faults, such as soiling or corrosion. Surface modifications change the contact face of the component to avoid faults without changing its materials. On the other hand, material selection can also be considered as a failure prevention technique, since a correct decision can improve the life cycle of the component. This is critical for corrosion, since it is an irreversible process that affects the ATs and the TES tanks. The degradation mechanisms that will affect a CSP plant can be predicted through simulation models. These models study the behaviour and the feasibility of CSP plants under the specific characteristics of its environment [151].

3.3. Mitigation techniques

These techniques are used to mitigate faults and degradation mechanisms and are applied once the fault has occurred, and irreversible mechanisms cannot be mitigated but prevented.

There are several methods that can be used to attenuate the consequences of soiling. Sayyah et al [152] differentiated between three techniques: natural cleaning, manual cleaning (Figure 8) and surface coating. However Sarvver et al. [153] considered two methods: restoration (washing and using mechanical methods) and prevention (surface modifications and active prevention).

Regarding restoration, Truong Ba et al. [154] modelled the reflectivity losses caused by soiling and created a procedure to decide the periodicity of cleaning in a CSP plant. They used Monte Carlo simulation to vary cleaning periods depending on the season and the conditions. They worked in an Australian CSP plant to validate the model, setting the probability of self-cleaning, percentage of savings and cleaning costs.



Figure 8. Manual cleaning of CSP mirrors using high-pressure spray [152].

Fernández-García et al. used an experimental installation to compare 3 cleaning methods: High-pressure water, high-pressure water with detergent, and water with a horse-hair brush. They made comparisons every 3 months over 2 years, depending on rainfall [155]. They concluded that the most effective cleaning procedure is demineralized water with a brush and is the only effective one for dry periods. The usage of detergent turned out to be unnecessary when a brush is used. Ashley et al. [25] achieved an increase of around 5% in the total energy by applying an heuristic approach for scheduling the Heliostat field cleaning.

The installation of wind barriers close to the heliostat field is used to prevent wind loads and subsequent soiling and abrasion. Moghimi and Ahmadi [156] optimised a wind barrier to minimize the number of particles affecting the mirrors. They used fluid mechanics and FEM to study the effects of variables such as distance to the mirror, height or incidence angle. Bendjebbas et al. [157] studied the effects of openings on barriers surrounding the heliostat fields. They modelled the wind profile and turbulence. They defined equations to compare the effects of the barrier openings with different mirror orientations in the field.

Therefore, mitigation is, unlike prevention, passive elimination or mitigation in the event of faults. Mitigation techniques cannot be applied to all faults, since most of them are irreversible. It can be concluded that only soiling is reversible and easily mitigated. Mitigation of this phenomenon involves cleaning the mirrors and applying protective coverings to them in order to prevent dust deposition.

4. ANALYSIS AND DISCUSSION

4.1. Degradation mechanisms analysis

The components must be controlled to ensure their correct performance and reliability of the system.

The three main components in PTC are mirrors, ATs and storage system.

Table III shows the main characteristics of the explained degradation mechanism, together with the main causes, effects and detection, prevention and mitigation techniques. This table shows some quantitative values that allows the importance of some degradation mechanisms to be determined. It must be considered that these quantitative data correspond to specific study conditions since there are numerous variables that affect the main performance indicators. In this paper, an analysis of the main degradation causes is carried out. An exhaustive FMEA of CSP components can be found in Reference [158].

Table III. Causes, effects and detection of main degradation mechanisms.

COMPONENT	DEGRADATION MECHANISM	CAUSES	EFFECTS	DETECTION	IMPROVEMENTS PREVENTION OR MITIGATION
ABSORBER TUBES	Deformation	Heterogeneities in the heat flux distribution of the heat collection element. Heat transfer fluid weight and pressure.	Drop of the optical efficiency (dependent on vertical displacement). Drop of average energy efficiency. Reduction of exergy efficiency.	EMAT Ultrasounds. Visual inspection. FEM	Material engineering. Structure improvement
	Cracks	Aging of tubes. Corrosive atmospheres. Unproper working conditions relative to HTF temperature or pressure.	Depending on the crack size, crack location, level of pressure of the plant, etc... Significant leaks that causes loss of pressure and temperature in the HTF. Fires due to combustion of the HTF. Energy efficiency and exergy efficiency drop.	Thermography. Visual inspection. EMAT Signal processing. Frequency analysis. Crack modelling. Thermal fatigue analysis.	Material engineering. Structure design.
TANKS AND TUBES	Thermal losses	Temperature of HTF. Temperature gradient. Lack of insulation. Vacuum loss.	Energy losses. Loss of performance.	Thermography. FEM.	Tube and tank design. Material design.
	Thermal stress	Cyclical temperatures. Fatigue loads.	Storage tank fatigue. Component deterioration.	Vacuum evaluation. Sample measurement. Modelling. Thermocouples. Thermography. Optical measurement Thermal fatigue analysis.	Material selection.

	Corrosion	Molten nitrate salts in contact with these metallic components. High temperature.	Premature replacement of corroded components. Loss of efficiency. Overdesign for higher corrosion resistance. Decreasing of heat exchange rate. Effects related with cracks and breakages.	Electrochemical spectroscopy. Gravimetric analysis. ANNs. Data mining.	Material design. Molten salt design. Coatings. Surface modifications.
MIRRORS	Soiling	Dirt, dust or other substances accumulation over the mirrors. Fallout of environmental contaminants. Lack of cleanness.	Changes in the optical properties. Reduction of the effective mean specular reflectivity of the mirrors. Directly proportional to the LCOE. Reflectance drop. Reflectivity drop. Espesial affection in desert environments.	Dust characterization. Reflectance measurements. Soiling modelling. Time pattern dynamic modelling.	Material selection. Coatings. Surface modifications. Condition-based cleaning.
	Erosion	Surface damaged by direct impact of particles (sand). Mechanical contact cleaning.	Reduction of optical performance of solar mirrors. Depending on climatic parameters (wind speed, humidity, etc), particles parameters, geological parameters and surface parameters. Specular reflectance proportional to the injected sand mass	Parameter effect determination. Laboratory testing. Data mining. Visual Inspection	Material selection. Coatings.
	Degradation/Corrosion	Highly concentrated solar flux Irradiance cycles	The thermal diffusivity, and the conductivity of the coating are affected. Reduction of thermal contact resistance with the mean irradiance. Lamination and laceration of reflector materials.	Spectroscopy. Thermography. Visual inspection.	Material selection. Mirror edge insulation.
	Atmosphere/ambient effects	Aerosols. Water vapor content	Losses caused by absorption and scatter processes in the atmosphere Loss of radiation between the heliostat field and the receiver in CSP tower plants Accelerated ageing.	Aerosol concentration.	Tubes and tanks sealing. Plant location decisions.
	Weight/deformation	Deviation from ideal shape due to gravity load	Strong dependence on constructional design and stiffness of support structure. Loss of performance due to focus deviation	Visual inspection.	Structure design.

The main problems related to mirrors are soiling, erosion and mirror degradation, which cause a reduced reflectance and a loss of efficiency. Soiling involves the deposition of dirt, dust and sand on the mirror surface. CSP plants are usually located in desert environments where these particles are present.

ATs transport the HTF at temperatures higher than 300°C. It generates corrosion because of the chemical composition of the HTF, and heat losses due to the design of this component. Corrosion is difficult to detect because it appears inside a multi-layer tube. There are not enough research studies about it. Heat losses cannot be totally avoided because a temperature gradient between the tube and the ambient is inherent to the system. However, heat transmission to the HTF can be improved by modifications of the inner surface of the tube (mentioned in Section 3).

The thermal storage system failures are like the failures of ATs. Literature shows that there is no difference between the failures in ATs and in thermal storage systems.

Table IV presents a compilation of the main studies about degradation and failure mechanisms of CSP systems, together with their causes, effects and affected components. It also shows additional characteristics of the main studies related to these mechanisms and the location and duration of these studies, where possible.

Table IV. Degradation mechanisms in CSP technology.

COMPONENT	DEGRADATION MECHANISM	TYPE OF STUDY	STUDIES RELATED	DURATION	LOCATION	TOPICS/ KEYWORDS
ABSORBER TUBES	Deformation	Causes and effects	[33, 34]	-	USA/China	Property definition, absorber materials, stainless steel.
			[35]	-	Iran	FEM, thermal influence, temperature distribution.
			[36]	-	India	FEM, material influence, thermal influence.
			[37, 38]	-	China	FEM, thermal influence, applications.
	Cracks	Causes and effects	[39]	-	Spain	EMAT, AT, signal processing.
			[40, 41]	-	India/Italy	Crack modelling, fluid-filled pipelines, frequency analysis.
		Detection	[115]		United Kingdom	EMAT, ultrasounds, crack identification.
TANKS AND TUBES	Thermal losses	Causes and effects	[55]	-	Mexico	Heat transfer modelling, different models, literature review, ATs.
			[56]	-	Spain	Vacuum evaluation, sample measurement, ATs.
			[57]	-	Germany	PTC, several installations, optical measurement, ATs.
			[58]	Several hours	USA	PTC, modelling, thermocouple, ATs.
			[59]	1 year	Germany	LFS, Solarmundo, several stations, ATs.
			[60]	-	India	FEM, modelling, non-vacuum conditions, ATs.
			[61]	-	Saudi Arabia	FEM, different conditions, half-insulated pipeline, ATs.
			[62]	-	USA	Thermal modelling, field losses modelling, ATs.

			[63]	-	Spain	Vacuum evolution, HITECO project, thermal losses, ATs.	
			[65]	-	China	Thermal fatigue, receiver, FEM.	
			[66]	Up to 100 h	Spain	Pilot plant, thermography, solution proposals, TES.	
			[67]	140 h	Spain	Pilot plant, temperature distribution, several installations. TES.	
			[68]	-	Spain, USA	Thermal modelling, FEM, different locations, TES.	
			[69]	4 h	Spain	Thermal modelling, modular, FEM, transient, TES.	
			[70]	Several hours	Spain	Thermal modelling, FEM, mechanical calculations, transient state, TES.	
			[71]	1 h	Spain	HTF, transient state, FEM, TES.	
			[72]	Several days	Spain	Transient state, FEM, TES.	
			Prevention	[136]	-	USA	Classification, commercial coatings.
				[138]	-	Spain	HITECO, cermet, energy cost reduction.
				[139]	-	France, Italy	Selective coating, project MATS, high temperature.
				[140, 141]	-	China	FEM, different models, different velocities.
				[142]	-	China	Structure reinforcement, different velocities, FEM.
	Thermal stress	Causes and effects	[64]	-	Iran	Thermal stress, FEM, deformation, ATs.	
	Corrosion	Causes and effects	[47]	Up to 10 months	China	Marine ambient, steel, eddy currents, corrosion.	
			[48]	Up to 2015	Australia	Literature review, high temperature storage, hot corrosion, TES	
			[49]	200 minutes	China	Aluminium, impedance spectroscopy, TES	
			[50]	>1500 h	Spain	Different materials, hot corrosion, spectroscopy, TES	
			[51]	Up to 2000 h	Spain	Gravimetric analysis, impedance spectroscopy, TES	
[52]			100 h	China	Hot corrosion, stainless steel, gravimetric analysis, TES		
[53]			2000 h	Spain, Chile	Stainless steel, gravimetric analysis, microscopy, TES		
[54]			4000 h	USA	Nickel alloys, TES, properties evolution, gravimetric analysis,		
Detection		[121]	-	USA	Hot corrosion, sensor, in situ monitoring.		
		[122]	-	Algeria, France	Spectroscopy, galvanised steel.		
		[123]	-	USA, Israel	High temperature, gas turbine.		
		[124]	-	USA	Polymeric coating, corrosion mitigation.		

MIRRORS	Prevention	[143]	-	USA	Coating, high temperature, several compounds.	
		[144]	-	USA, Chile	High temperature, CSP, several compounds	
		[145]	-	Japan	Corrosion fatigue, turbine blade, coating.	
		[146]	-	Spain	State of the art, TES, system modelling	
		[147]	-	Spain, Chile	Hot corrosion, molten salts, TES, steel alloys.	
		[148]	-	Taiwan	Hot corrosion, steel alloy, TES	
		[149]	-	Taiwan	Hot corrosion, steel, alloy, coating, TES.	
		[150]	-	India	Hot corrosion, nickel, coatings, TES.	
	Soiling	Causes and effects	[74]	12 months	Australia	Dust measurement and characterization.
			[75]	-	Morocco	Parameter characterization, particle characterization.
			[18]	Up to 2016	Worldwide	Literature review, PV and CSP.
			[19]	Up to 2017	Worldwide	Literature review, dust modelling, particle characterization.
			[76]	3 months	Morocco	Different materials, dust characterization, reflectivity measurements.
			[77]	-	Germany, Israel	Reflectance measurement, angle influence, modelling.
			[78, 79]	6 months	Morocco	Soiling modelling, time pattern dynamic modelling.
[80]			Up to 1 month	Germany	Pyrheliometer, measurement correction.	
[81]			Several months	Morocco	Site characterization, different locations, reflectance measurement.	
[82]			3 months	Morocco	Reflectivity measurements, sensor comparison, aerosol concentration.	
Detection		[116]	-	Spain, North Africa	New sensor creation, live measurements.	
		[117]	-	Spain	Real time inspection, CENER.	
		[120]	-	Spain	Light filtering, EuroTrough, thermography.	
Prevention		[132]	-	USA	Coating, polymers.	
		[133]	-	Japan	Fresnel lens, degradation testing.	
		[135]	-	USA	Electrodynamic cleaning, several materials.	
		[137]	-	Germany	Feasibility analysis, several scenarios, several materials.	
Mitigation	[25]	-	-	Heuristic shedding		
	[152]	-	USA	Several methods, mitigation, review.		
	[153]	-	USA	Literature review, dust classification.		

			[154]	-	Australia	Modelling, several scenarios.		
			[155]	-	Spain	Several methods, manual cleaning.		
			[156]	-	South Africa, USA	Wind barriers, FEM, fluid mechanics, optimization.		
			[157]	-	Algeria	Wind barrier, FEM, barrier holes.		
	Erosion	Causes and effects	[83]	-	Netherlands	Method development and classification.		
			[84]	22 months	Morocco	Desert and oceanic ambient, laboratory testing.		
			[85]	-	Spain	Laboratory testing, fault characterization.		
			[86]	-	Libya	Dust characterization, reflectance measurements.		
			[87]	-	Morocco	Laboratory testing, glass mirrors, parameter effect determination.		
			[88]	24 months	Spain, Morocco	Outdoor and laboratory comparison, dust modelling.		
			[89]	Several months	Morocco, Qatar	Prototype development, particle blower.		
	Degradation / corrosion	Causes and effects	[90, 91]	Up to 5700 h	France	Accelerated ageing, modelling, protective paint degradation.		
				Up to 1 h	France	Concentrated solar flux, accelerated ageing, modelling.		
			[94]	Several years of service	Spain	Accelerated ageing, different materials.		
			[95]	5h cycles/ 9 months	Sweden	Accelerated ageing, outdoor exposure, result comparison, different materials.		
			[96]	21 months	Morocco	Different materials and locations, outdoor exposure.		
			Atmosphere / ambient effects	Causes and effects	[97]	-	Spain	Atmospheric transmission losses, ambient influence.
					[98]	20 hours	USA	Aerosol impact, atmospheric losses.
	[99]	Up to 2016			Spain	Atmospheric extinction, literature review.		
	[100]	40 cycles of 24 hours.			Spain	Acid atmosphere, different materials, reflectance measurement.		
Weight / deformation	Causes and effects	[101]	-	Germany	Influence on focusing, FEM, different cases, mirrors.			

This paper analyses the state-of-art for the main degradation mechanisms and the main advances made to prevent them. The paper is limited to faults or degradation mechanisms found in the literature and affect certain locations or configurations. The effect of the degradation mechanisms on performance indicators such as the produced energy, the exergy, or the LCOE is not quantified in

general, since every single CSP plant has its own response, depending on numerous endogen and exogen variables. For this reason, literature contains energy, exergy and economic calculations of specific CSP plants and components , such as small plants [159], linear Fresnel reflections [160] or parabolic trough [161].

4.2. Discussion of detection, prevention and mitigation techniques

Prevention and mitigation techniques are employed to improve the availability and reliability of CSP installations and the efficiency of the conversion process. NDTs play an essential role in detecting faults and inspecting CSP plants [162] [163]. Infrared thermography is employed since it allows heat losses to be measured in the ATs and, indirectly, reflectance variations caused by soiling, and faults associated with mirrors can be identified. Nowadays, the combination of thermography and UAVs has become a useful inspection technique. The detection and monitoring of faults, such as cracks and corrosion, are more complicated.

Advanced data processing software is also employed, since it facilitates the early identification of faults. Failures can be predicted, for example, by using machine learning and pattern recognition algorithms, such as ANNs [164] [165]. Surface modifications or coatings can be used to reduce soiling effects, and irregularities can be developed in the inner surface of the tubes to improve heat transfer.

Most degradation mechanisms are irreversible, such as corrosion, erosion or degradation, or cannot be totally eliminated, such as heat losses. Many studies about mitigation of failures are focused on soiling, e.g. active cleaning with and without using water.

4.3. Future trends and challenges

A quantitative analysis of the state of art employing “Google Scholar” has been carried out. Figure 9 shows the publications related to the faults of CSP technology over the last ten years. The results present a positive trend, with ten times more publications in 2017 with respect to 2008. Corrosion and heat loss can be highlighted as the most studied phenomena, with more than 500 publications in each one in 2017. Erosion and deformation are studied more than ageing or soiling. Publications about erosion have remained almost constant over the last six years. Finally, ageing and soiling are the least studied faults, showing a slow growth over the last four years, and even a decrease in 2017 with respect to 2016.

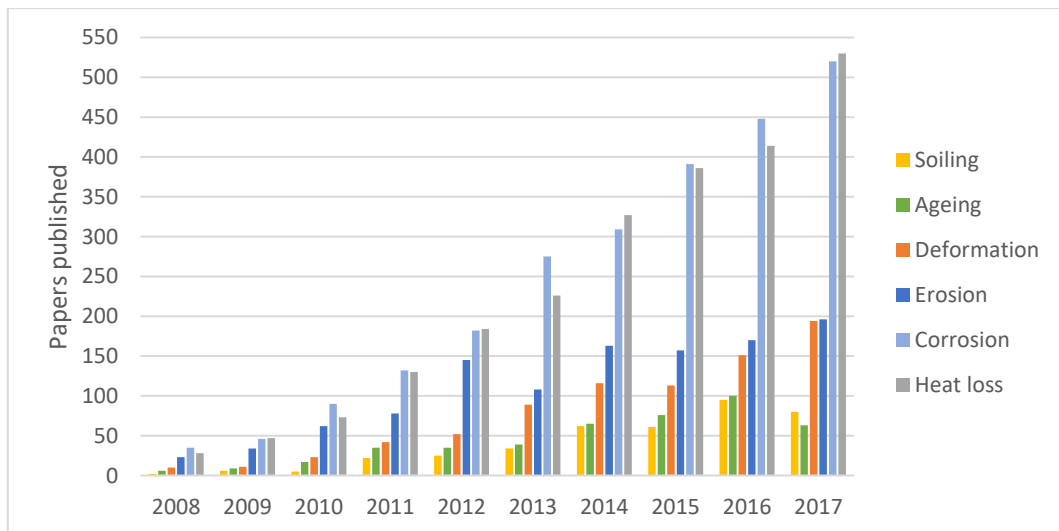


Figure 9. Evolution of the papers about faults published in the last ten years.

Figure 10 shows the proportion of papers about each fault. There has been no significant variation in the last ten years. Corrosion and heat loss account for more than 60% of publications every year, and erosion has suffered a decrease of more than 20% to less than 15%.

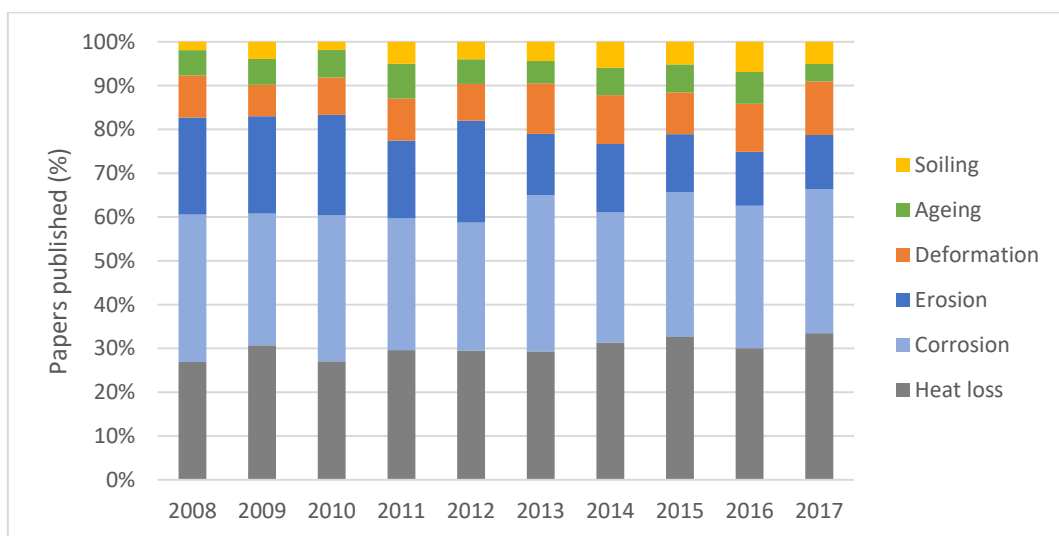


Figure 10. Percentage evolution of the papers published in the last ten years.

The following limitations of this research and future challenges can be concluded from this paper:

- There are not many publications related to soiling and ageing (less than 15%); therefore, they should be considered in future research.
- Most publications are related to PTC or SPT technologies. LFR and PDS faults should be the focus of more studies. It could be useful to investigate faults related to these technologies since they are growing.

- Due to the irreversibility of most degradation mechanisms, there are few publications related to their mitigation, most of them focus on soiling. It would be useful to investigate if any possible activities can be carried out on components after the appearance of these faults, e.g. polishing techniques on mirrors affected by erosion, the reparation of ATs after being affected by corrosion, etc.

5. CONCLUSIONS

A survey of the main faults and degradation mechanisms in concentrated solar power technology has been presented in this paper. These phenomena mainly affect mirrors, absorber tubes and storage tanks. This paper also outlines the main techniques for their detection, prevention and mitigation. These faults have been classified as follows:

- Absorber tube deformation and cracks: deformation is an unavoidable fault caused by the weight of the pipeline and is heavily dependent on thermal energy storage. This fault causes focusing decreases as absorber tubes move away from the focus of the mirrors. It is studied by using finite element modelling and takes into account the influence of key parameters such as temperature, mass flow or absorber tube size. Cracks are not sufficiently studied since they do not usually appear in absorber tubes. Deformation is a studied fault in concentrated solar power, accounting for 10% of the publications of the faults studied, while for cracks there has been little research so far.
- Corrosion in absorber tubes and thermal energy storage tanks: this fault is irreversible. It is important in thermal energy storage tanks, because the heat transfer fluid works at higher temperatures than in absorber tubes. There are many studies on this fault since it is one of the most important and severe degradation mechanisms in concentrated solar power technology. It is studied in more than 30% of publications related to fault detection in concentrated solar power faults. The number of studies focused on corrosion have increased by 1400 % in the last ten years.
- Thermal issues in absorber tubes and thermal energy storage tanks: it is not possible to remove heat losses and they are mainly caused by vacuum losses. Most research studies aim to model and improve the thermal behaviour of thermal energy storage tanks. Other faults are thermal stress and fatigue, both in the absorber tubes and the thermal energy storage tanks. They are, together with corrosion, the most studied faults in concentrated solar power technology, with more than 33% of publications in 2017.
- Mirror soiling and erosion: Both faults can be easily simulated in the laboratory. Unlike soiling, erosion is not a reversible fault. Most publications on these faults are from countries with large desert areas and contain experimental setups that accurately simulate the effects of sandstorms on components. The proportion of studies related to soiling has decreased in the last ten years from

25% to 17%. The number of publications regarding erosion remained almost constant from 2014 to 2017.

- Mirror ageing and degradation: the main cause of these faults is the long-term exposition to harsh environments. They depend on ambient conditions, maritime zones being the most adverse locations. Permanent losses of reflectivity can be caused in the mirrors. These faults are usually modelled in the laboratory through accelerated ageing techniques, considering different materials and conditions. There are not many publications on these faults as their most relevant effects are for the long term, making it difficult to evaluate them. The number of publications has decreased by 8% in the last ten years.

Regarding detection, prevention and mitigation techniques, new technologies have been employed to evaluate the condition of power plants and attenuate the severity of the faults. It is necessary to include inspection tools, as unmanned aerial vehicles, to minimize and automatize the inspection of plants, or artificial neural networks to process information and learn to detect faults early. The lack of research about mitigation techniques also poses an interesting challenge for future years.

The results of this paper can be used by researchers to find opportunities for new research lines by detecting those fields where improvements are required. Some of them are suggested in the set of future challenges.

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