Water Saving Comparison Study between Innovative and Conventional Cleaning Systems for CSP Technologies
Abstract

The study was conducted to compare two different cleaning technologies for CSP plants at PSA (Plataforma Solar de Almería): namely innovative and conventional cleaning method. The CSP applications are installed in dry and dusty locations. Whereas the water is the main concern to clean the CSP plants. The large amount of water is consumed by the conventional cleaning method (pressurized water jet) than innovative one (ultrasonic cleaning).

The literature review helped to understand about different cleaning techniques, and methodology to clean the mirrors in terms of achieving better performance of the plants. All the research work was done based on real situations, which were able to recover around 99 % of original reflectance of the mirror by cleaning different technics and methodologies, as mentioned in the literature.

The study about ultrasonic cleaning device (USD) was scheduled to analyses the cleaning performance of the device. In term of water consumption, electricity consumption, cleanliness level, and the processing time, was used by US device in comparison with pressurized water jet. All the tests were performed in similar environmental conditions every week during the study period. Moreover, the study also illustrated the breakdowns faced during set up the device, to achieve operational frequency.

It was found that the US cleaning device required furthered development to work with real environmental conditions. As it was able to recover maximum 95.7 % of its original reflectance by consuming less water, power, and higher processing time. The US device consumed, on average, 63 % less water than pressurized water jet. On the other hand, almost 7 times less power compare to pressurized water jet.

It was realized that the Energy use of US device was higher than the pressurized water jet (PWJ) in first two tests which was not initially expected, and in third test it was lower (it would be fair to say that it requires more experiments to compare energy use by using both devices). Although there are many factors contributing to this, the main observations drawn from this were that more testing needs to be done to determine the optimum speed for operating the US device. The higher energy use may be attributed to the sub-optimal swiping speed used during this experimental study. Furthermore, the flow pump used was oversized and a smaller pump may be used which would further reduce the energy use.

Due to having time limitation, it was not possible to perform the tests as planned and the detail error analyses. Nevertheless, achieved measurements were enough to compare both the technologies, according to the aim of the study.
Acknowledgment

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## Abbreviations

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<tr>
<td>CF</td>
<td>Cleaning factor</td>
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<tr>
<td>CSB</td>
<td>Conditional based cleaning</td>
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<td>CSP</td>
<td>Concentrating solar power</td>
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<td>DNI</td>
<td>Direct normal irradiation</td>
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<tr>
<td>ES</td>
<td>Electro-deionized water from piping system</td>
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<td>ET</td>
<td>Electro-deionized</td>
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<tr>
<td>LCOE</td>
<td>Levelized cost of electricity</td>
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<td>OT</td>
<td>Osmosis plant tank</td>
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<tr>
<td>PPM</td>
<td>Parts per million</td>
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<td>PSA</td>
<td>Plataforma Solar de Almería</td>
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<td>PT</td>
<td>Parabolic-trough collectors</td>
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<td>PWJ</td>
<td>Pressurized water jet</td>
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<td>USD</td>
<td>Ultrasonic cleaning device</td>
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<tr>
<td>W</td>
<td>Water from well</td>
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<tr>
<td>Nm</td>
<td>Newton meter</td>
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## Nomenclature

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\lambda$</td>
<td>wavelength</td>
<td>Nm</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Average monochromatic specular reflectance</td>
<td></td>
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<tr>
<td>$\rho_{\text{initial}}$</td>
<td>Initial reflectance</td>
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1 Introduction

Concentrating solar power (CSP) technologies is one of the most reliable technologies within the field of the renewable energies and is very well positioned to become one of the principal actors in the energy mix market together with the rest of renewable technologies available. However, it is quite common to install CSP plants in sunny and dry lands where the scarce of water is high. It might possible that these dry areas have lots of aerosols and aggressive environmental conditions, due to sand storms dust particles are present, these reach the surface of the mirrors, which affects their performance and therefore the overall performance of the CSP plants. To ensure a high performance of CSP plants, regular cleaning is needed. According to a survey of plant operations, the average water consumption is around 400000-500000 m$^3$ for a 50 MW CSP plant, in which 10 to 20 % of the water is used for cleaning the mirrors[1].

1.1 Different cleaning methods

The most common method to clean the mirrors is by using pressurized water jet (called conventional cleaning method) or by using brushes. On the one hand, the pressurized water jet cleaning recovered around 97.84 % of relative reflectance without any physical contact with the surface, but it consumes a very high amount of water [2]. On the other hand, the brush method provided a good cleaning while consuming less water than the pressurized water jet method. However, due to the physical contact with the surface to be cleaned, the brush method can reduce the reflectance permanently [2]. Thereby, water saving is a big issue to implement CSP plants all around the world successfully, to ensure its financial deployment and therefore diminishing its LCOE (Levelized cost of electricity). A new cleaning system was developed to achieve this goal under the framework of the European Project WASCOP (H2020 program)[1]. This method is based on the application of an innovative ultrasonic cleaning system specially designed for reflectors in CSP plants which implies a much lower use of water compared to conventional cleaning. The technology for ultrasonic cleaning that will be tested in this thesis was developed by the company IK-4 Tekniker.[2]

There are few methods for cleaning the mirrors, known as wet, dry and hybrid cleaning. The wet cleaning system involves using water in order to clean the mirror surface, whereas the dry-cleaning system does not use water (brushes are used to clean the mirror). The hybrid cleaning uses both water and brushes together, which save water when compared to wet cleaning system. The wet cleaning system can maintain the plant efficiency, but it consumes up to 90 % more water than a hybrid and a dry system.[1]

There are several systems practiced under the wet, dry and hybrid methods. The dry cleaning system, for example, is powered by electricity and does not consume any water.[1]. Other systems include:

- The natural clean up by rainwater systems,
- the truck or hosing systems,
- fixed nozzle systems, (pressurized water jet)
- robotic cleaning systems,

All these cleaning systems have cleaning schedules. For instance: the conditionally based cleaning (CBC) is a strategy that is mainly developed for reflectance degradations due to seasonal changes; cleaning decisions are made by comparing the reflectance according to the seasonal variation in different weather conditions such as DNI and rain. Another is called fixed time strategy, which is performed as per the time management. For example monthly, fortnightly, weekly and daily. The CBC strategy has found that it can save 5 to 30 % of the cleaning cost in comparison with the fixed time strategy.[3] [1]
Two different technologies are shown in Figure 1. The left image shows cleaning with pressurized water nozzles. In the pressurized water jet method, water is supplied to the mirror surface by a rotating rig at high pressure. In these systems, the pump has the ability to supply 170 liters/minute at a pressure of 241 bar, which consumes 0.72 l/m² of reflector surface [1]. The image on the right shows the water and brush cleaning method being used to clean the mirrors. In this method, water is pressurized at the mirror surface with a certain amount of flow rate, and brushes apply on the mirror surface. Water consumed by the technology is around 0.3 l/m², which is lower compared to using the pressurized water nozzle method [1].

![Figure 1: Cleaning of mirrors by using pressurized water jet(left) and water and brush cleaning (right)](image)

**1.2 Ultrasonic cleaning (US) principle**

The ultrasonic cleaning device has been used during the last decades for cleaning mirrors. With the device tested in this work the principle of ultrasonic technology is going to be used for CSP applications. The working principle of the ultrasonic device is based on the cavitation of liquid (water) when it is exposed to high pressure waves (sound). During this process, millions of microbubbles implode releasing heat and strong shock waves. When the bubble comes surrounding the boundary (solid wall, free surface, or another bubble), the disturbance (sound) creates a jet of liquid, which it’s passing into and through the bubble. The velocity of the jet is depending on the distance between boundary and bubble. The velocity can reach up to 100 m/s. When it gets into contact with the solid surface, it removes soil particles attached to it. In comparison with other technologies such as pressurized water or brushing, this technology has the advantage of going into the deep imperfections of the material (cracks and pores) and as a result, provides better cleaning performance in comparison with the traditional one [2]. The picture below shows the bubbles attack the surface in the process of cavitation, where thousands of shock waves generates and help to clean the surface. The red arrows are showing the process of liquid jet passing bubbles and strike to the mirror surface.

![Figure 2: Bubbles implosion evolution when applying high ultrasonic waves](image)

The US device (see below in Figure 7) consist of an ultrasonic piezoelectric transducer attached to the bottom. At the time of performing a cleaning operation, the transducer starts to emit ultrasounds, where water is supplied over the band and makes a water film over the band and generates cavitation of bubbles, where the bubble diameter is not more than 15 µm. In comparison to the pressurized water method, the water consumption is much lower by using an ultrasonic device. This is because, in the case of ultrasonic device,
water flows over the band at very low velocity by making a small water layer, while a larger flow of water is used in a pressurised water jet which uses a high velocity stream and thus more water. Therefore, this device is potentially more useful for desert areas where there is a lack of water. As per the principle, it is possible to remove micrometric particles like dessert dust. [2]

1.3 Aims
The main targets of the work proposed are to investigate the water consumption, electric power, process time, cleanness level (reflectance) and cleanness durability. These data will be analyzed with the data obtained from the outdoor test campaign for cleaning the mirrors at the CSP heliostat field with the new ultrasonic technique and compared to traditional pressurized water jet technique at the facilities of CIEMAT-PSA (Plataforma Solar de Almería) research center in Almeria Spain.

1.4 Methodology
Comparison of ultrasonic cleaning method with the conventional one in real outdoor conditions for a period of three months will be performed. It will be evaluated at facets of the mirrors in the CESA heliostat field.

With aim of testing the worst soiling conditions, the lower mirror facet of one of the heliostats was studied. The ultrasonic cleaning device is fed by two different systems.

- Water supply. Demineralized water was pumped from a tank which mass flow was kept constant during the trials.
- Power supply. The device was fed by a frequency generator, which power consumption was measured by a LabVIEW application. The system was powered by the 220 V power supply.

Additionally, the heliostat close to the one installed with the new device was selected to be used for validating and compare the innovative ultrasonic cleaning system with a conventional cleaning system (water pressurize jet).

The testing campaign consisted of measuring the monochromatic specular reflectance with a portable specular reflectometer before and after the cleaning to assess the efficiency of the two cleaning methods. The efficiency of the cleaning was calculated as the cleaning factor (CF), which is the measured reflectance divided by the maximum reflectance\(^1\) of the tested mirrors. A mask was designed to place the reflectometer in five different spots selected inside the working area covered by the cleaning system. By this, the reflectance was always measured in the same position of the mirror during the tests.

Following variables were registered during each test:

- Water consumption. The plan was to set up a flow meter to be able to monitor the water consumption during the test (due to unavoidable logistical circumstances relating to its installation, the flow meter was not installed). Then a 100 mL of graduated cylinder was used to measure water flow/consumption rate. Before each experiment run, the water flow rate was determined by measuring the time elapsed in filling a 100 mL volume. The flow rate could be varied with the help of a flow control valve. This flow rate can be extrapolated to calculate the overall water consumption over the experiment/cleaning time interval.
- Electricity consumption is measured for each cleaning test.
- Processing time, the processing time to clean by using the conventional method and same as when using the ultrasonic method. It was measured manually by using

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\(^1\) This refers to the initial reflectance of the mirror, when the mirror is properly cleaned; in this case, the mirror is cleaned according to PSA methodology at the beginning of the campaign. [5]
stop watch and simultaneously measuring the area cleaned during the measured time interval

- Cleanliness level $^2$, monochromatic specular reflectance values were measured with a reflectometer.

1.5 Previous work

There are some previous studies that have been done for different cleaning methods to clean the mirrors using different technologies. These studies will help to understand different techniques, methods and measurements intervals (how often it requires cleaning for the mirrors).

The research was based on non-immersion ultrasonic cleaning for Heliostats by Jon Ander Sarasua, Alejandro Sanda, et al. $^2$. The described technology using ultrasonic principle would not be feasible for cleaning heliostat mirrors, the main aim of the research is to, focus on the development of US device that does not need high amount of water to clean the mirror and how the ultrasonic technology can be used to clean the mirrors without contacting the surface of the mirror. The system uses ultrasonic vibrations to generate a liquid interface between mirror and band to clean the mirror. There are some experiments performed at the laboratory with real mirror probes, different gaps between cleaning device and mirror surface and various sweeping speed of the device over the mirror surface (m/min). The monochromatic reflectance values before and after the cleaning by using ultrasonic technology were measure and compared with the reflectance values obtained with the conventional method (pressurized jet). Finally, the results had obtained up to 99% of relative reflectance by using US device, in comparison with the pressurized water jet, which obtained 98.65% and 97.85% when using different distances between the water nozzles and the mirror (namely, at 0.5 and 1.5 meters). However, water consumed by US device was 0.033 l/m², where the pressurized water jet consumed 1.25 l per probe equal to 2.75 l/m². Moreover, the US cleaning device was tested in three different directions of the mirror - horizontal, vertical and inclined- and better performance was achieved by using the device on horizontally placed mirrors. Because in the horizontal position it is possible to maintain thicker water layer to cover the mirror surface compare to vertical and inclined. In the position of inclined and vertical, water does not stay over the mirror surface which means that larger flow is required to keep proper water flow for the process of cavitation of liquid. $^2$

Figure 3 shows the relative reflectance after cleaning by an ultrasonic device. The figure shows the relative reflectance in the left from 50 to 100%, and in the right, the reflectance has taken before cleaning the mirror (mentioned as dirty). At the upper-right corner, it shows the gap between mirror surface and ultrasonic device while performing the task. At the bottom line (horizontally), it indicates the sweeping speed (m/min). In Figure 3, it is clearly seen that there is a dependence on the sweeping speed and gap between mirror and ultrasonic device. When the gap between the US device and mirror is 3 mm reflectance decreases while increasing sweeping speed. So, this is important to find out the optimum parameters while using the device to ensure the right cleaning performance. $^2$

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$^2$ The cleanliness level is established by researchers at PSA. In order to clean the mirror the reflectance should below than 94% then the mirror required cleaning. If it is more than 94%, it considers clean and not required cleaning.
Another research work was done under the name of optimization of the cleaning method for concentrating solar power plants at Plataforma Solar de Almería, Spain by Maria Elena Cantos Soto [6]. This paper demonstrates an overview of pressurized water cleaning technology, which is useful to study related to the thesis topic since the ultrasonic technology will be compared with the pressurized water jet method.

A few tests have been done to verify the lower washing water qualities than the one commonly used (less than 5 ppm of hardness (CaCO₃)) which could provide good mirror reflectance. The research was completed on four different water qualities selected from PSA. For instance, water from the electro-deionized water tank (ET), water from the electro-deionized water tank after being passed through a piping system (ES), water from the reverse osmosis plant tank (OT), and water from the well (W). In the end, the result achieved by using 12.21 ppm hardness of water (reverse osmosis water) with a mixture of medium washing water temperature and medium washing water pressure (around 125 bars at 50 °C). The reflectance obtained is quite similar when using hardness below 5 ppm (i.e. de-ionized water) (with the maximum difference in reflectance found being 0.5 %) [5]. The result shows that it is possible to use lower water qualities to maintain suitable mirror reflectance. Washing with osmotic water³ had given similar results in comparison to washing with electro-deionized water. While using it with high temperature at more than 65 °C, gave lower reflectance values. Thereby, to achieve the best reflectance values, it requires medium washing water temperature along with medium washing water pressure.

[6] This study will help to perform and understand the pressurized water jet water cleaning method, which is going to be compared with the US cleaning method.

Another research paper considered for this master thesis has been done by Dr. C L Sansom and Dr. Kumar Patchigolla at the Cranfield University[1]. This research describes the water use in CSP plants, different cleaning technologies and the method to use clean the mirrors such as “The traditional high-pressure rig-low-water-volume”. This technology uses the rig to move down one row and returned to clean the adjust row. Figure 4 shows the water delivered at the pressure of 207 bars. The high-pressure low volume method uses 0.72 liters/m² of demineralized water of the reflector surface.

³ Osmotic water is outcome of treated by chlorine through a reverse osmosis membrane.
Figure 4: The traditional high-pressure rig/low-water-volume [1]. Printed with permission from the author.

Figure 5. shows a cleaning operation performed by using pressurized demineralized water and brush cleaning (hybrid cleaning), which consumes less water than the traditional one (pressurized jet). While performing the task they move up to 5 km/h of speed to clean the mirrors, which has a cleaning chassis 50 % lighter than conventional technology. After cleaning the mirrors, they have achieved 99.6 % of its original reflectance using between 0.25 and 0.3 l/m² of water consumption[1]. The paper explains reflectance achieved by wet and hybrid cleaning technics, which will help to compare the reflectance values with US cleaning technic, that how effective is the US technology in comparison with traditional one.

Travis Sarver and Ali Al Qaraghuli et al. at National Renewable Energy Laboratory [8] show the different cleaning techniques, which are: mechanically removing soiling by washing and wiping, vortex nozzle, converging nozzle, and the ultrasonic transducer with nozzle.

The basic cleaning process of mechanically removing soiling includes deterrence, washing and wiping, and surface modification. Following are the steps to mechanically remove soiling:

1. In the deterrence stage, dirt is kept on the surface and reflectance is measured.
2. Secondly, the washing and wiping stage takes place. For washing, it is possible to use water and a low surface energy detergent-based solution to remove the soiling. To wipe the mirror, cloth or another medium can be used.

3. Lastly, the surface modification process is applied by modifying the surface with treatments, coating, and films (by using chemicals) so that strong bonds of dust particles could not develop (this kind of coating prevents dust particles from settling down on the reflective surface).

This strategy was found to be labor intensive. It required lots of time and manpower to clean the mirror frequently while repeating the technique for the entire field. The cleaning and wiping process could be done by vehicles and robots (mechanically integrated mechanisms) as well; however, these techniques could possibly damage the surface while cleaning. To remove dust easily without any coating removal or damage, where high pressure at 687 bar sprays of the tap water recovered at least 95 % of original reflectance for each case.

Another strategy was accomplished by using air flow. Air was forced directly on or across the mirror surface. This technique used several air nozzles along with a vortex nozzle (which combined rotational and translation motion to convey “rubbing” capabilities to the air flow) and a stream line nozzle that directed flow normally to the surface (with and without water) and achieved the same results as when using water.

In addition, the converging nozzle technique was done by air with water mist injection, along with the transducer which passed ultrasonic energy through the air to the surface and recovered 99 % of original mirror reflectance.

Finally, the ultrasonic technique studied in conjunction with the nozzle -by using air with ultrasonic energy assist- found a between 1 or 2 % improvement in the results in comparison with the vortex and converging nozzles.

The whole process showed the vortex, converging and ultrasonic (with and without water and ultrasonic energy assists) methods successfully restored the lost reflectance of the mirrors. Now a number of these technics are able to minimize the effects of the different environmental situations. [8]

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4 Water-based solutions which are “more environmentally safe to apply on applications in the field” and which remove soiling by wiping them manually over the surface.
2 Reflectometer

The reflectometer is a measurement device which is normally used to measure the specular reflectance of the mirror at CSP plants [6]. For this thesis study, the 15R-USB portable specular reflectometer will be used. It has a LED source of $\lambda=[635-685]$ nm, with a peak at 660 nm. The measured intensity is automatically transformed into a reflectance reading by correlating the measured flux intensities of the reference standard and the sample.[9]

The device has a silicon cell detector. The eyepiece on the top of the reflectometer helps to see the position and shape of the reflected light. By adjusting thumbwheels (located on the side of the instrument) reflected beam can be viewed. For planar surfaces, the maximum value of the reflectance considered when the reflected beam is in the center of the aperture (see Figure 6, right). [10] [9]

The device used in the experiments has following facilities like:

- It is a portable device
- Short measuring time
- Easy to handle as per its size and weigh
- Capable of beam adjustment and positioning
- Capable to measure curved and/or second-surface mirrors
- It has a capacity to store data
- Able to measure reflectance with variable environmental situations, such as bad weather conditions.
- Operating temperature 0 to 50 °C [10].
- Ability to measure reflectance on curved mirror surfaces

![Figure 6: Left Picture of the portable specular reflectometer 15R-USB by D & S. Right: Principle sketch of the optical alignment of the 15R-USB by D & S [10]](image-url)
3 Description of the US cleaning device and system

The device has single MPI transducer, a band is made of aluminum, which is 1007 mm long, 15 mm wide and 2 mm thick (the band size was measured at PSA). It is a tool that creates ultrasonic vibrations and use this vibrational energy for the process of cavitation. The transducer is connected to the generator. This generator creates high-frequency ultrasonic acoustic vibrations, which apply to the band connect with transducer. The generator is used to control the frequency manually.

Figure 7 show the device installed on the heliostat at PSA facet no 1015. The most important parts of the devise are indicated in the figure.

- Fastening point (1): - where the US cleaning device is screwed to the metallic frame (which holds the device) in the upper and the lower part.
- Nozzle (2): - water outlet in which the water layer flows along the band.
- US Band (3): - It works with ultrasounds produced by the transducer (explained earlier in ultrasonic principle).
- Control valves (4): - which controls the water flow manually with help of screw driver.
- Water inlet (5): - connection to the water source.
- Transducer (6): - which generates ultrasonic sounds (details information is given on page 10),
- Handle (7): - to move the device manually along the mirror surface.

Figure 7: Ultrasonic cleaning device and its components
3.1 Generator

The generator used in this task is called MPI WG400 with LCD display. This controls the transducer frequency which can vary from 20 kHz to 100 kHz (Appendix (1)). This device has a facility to connect to the computer with the software MPI welding generators software, and easily control the frequency, as well as possible to see the power consumption consumed by the transducer, see Figure 8 [12]. The generator shows the power as per the frequency level, high frequency means more power consumption.

![Figure 8: Ultrasonic transducer (right) connected with a generator (left) [13]. To the right is the layout of the software used to control the frequency and see the power consumption (red arrow)](image)

3.2 Transducer

The transducer used in the test is called “BJW-151500F-50S PZT8” ultrasonic welding transducer. It is 171 mm long, with input power of 1500 W. As performing the task, it is found that the right frequency for our case are between 21 kHz and 23 kHz (advice from the company IK4-TEKNIKER). In Figure 8 the ultrasonic transducer relates to a booster (where booster converts piezoelectric effect into vibrations), which transfer the ultrasounds to the band attached to the device (marked 3 in figure 7).[13]. Detailed information is given in Appendix (2).

3.3 Digital Water Flow Meter

A digital flow meter is used to measure the flow rate passing through the pipe to the cleaning device. For the purpose of the ultrasonic device, the model “PF2D504” was used and the output was given in volumetric and mass units. This flow sensor is used in specific flow range between 0.4 and 4.0 l/min with load current 0.08 A, and pressure could vary according to the fluid temperature [14]. Details information is given in Appendix (3).

The picture below shows the design of flow sensor. Installing the device horizontally will keep water flow steadily. While connecting to the inlet pipe of the cleaning device the pipe from the flow sensor should be straight and more than 8 times longer than the pipe diameter.

![Figure 9: Flow Sensor[14].](image)
Flow Monitor: - For this thesis study is going to use “PF2D300-A Series “Flow Monitor” from CSM. This device indicates the flow rate values on the LED display. In the picture below, it is shown the working principle of flow monitor. The output status indicates by showing green light (LED out 1 in Figure 10), or if any error occurs LED light starts blinking. Detail instructions available in [14].

![Flow Monitor](image)

**Figure 10: Flow monitor[14]**

3.4 Reflectance measurement mask

The reflectance will be measured with help of acetone mask designed for this particular purpose, size 100 X 70 cm. This will be placed over the selected heliostat (facet) mirror. It has five different measurement sports (holes) marked in red (see Figure 11), the interval between holes is 25 cm, and the holes made of 3.5 cm diameter, according to the lens size of the reflectometer so that lens can easily fit in the hole). Drawing of the measurement mask is given in Appendix (4).

![Reflectance measurement mask](image)

**Figure 11: Reflectance measurement sheet placed over the testing mirror (left), holes where the refractometer placed and measured reflectance (right).**

3.5 Water Pump and Tank

The ultrasonic device would be connected to a 500 L demineralized water tank with help of water pump, see Figure 12, picture (1)) for water tank and picture (3) for water pump, the power consumed by pump was 450 W (Appendix (5). The set of pump and water tank are compiled in the small trolley picture (4), which is carried to the field at the time of performing the task and connect the water supply to the cleaning devises that should be studied [5].
4 Conventional Cleaning Method (Pressurized jet)

The pressurized water jet technology (model HDS 10/20 -4 M Kärcher) will be applied with help of a cleaning machine seen in Figure 12, picture (2), which consists of a hand nozzle with a facility to apply tempered pressurized water. It has a pressure between 30 and 200 bars with a maximum temperature of 80 °C. (see Appendix (6). This system will also be carried in the same trolley with water pump and tank shown in Figure 12, picture (4). [15]

While performing the pressurized water jet cleaning, it needs to be maintained the distance between mirror and jet, which will vary with various experiments, to see the effect of cleaning from various distances. A mirror area of 0.7 m² was chosen for performing the cleaning experiments with the PWJ device.

Figure 12: Water tank (1), pressurized cleaning machine (2), water pump (3), trolley with all cleaning kit.
5 Process Flow Diagram

The system is divided into three parts namely water source (unit 1), flow meter (unit 2), and ultrasonic device (unit 3). Unit 1 consists of a water tank, water pump, and a control valve, in unit 2: flow sensor and flow monitor are connected in series, and finally, unit 3: the ultrasonic device which is operated using a generator. To connect with the flow meter the length between flow meter and water pump should be at least 8 times than the pipe diameter.

![Flow Diagram](image)

Figure 13: Water supply system for the US cleaning device

5.1 Installation of the flow meter

Figure 14 shows the installation of the flow meter. The flow meter would be installed on a piece of wood with help of screws, which was fixed at certain height from the ground (prevent from things use in the field and stepping out by a person). To make sure the flow should be studied, water pipe should not bend. The sensor is connected to the flow monitor which show the water being used for cleaning the mirror. With the flow monitor is connected to a data logger and electricity source. The connection of the flow monitor is shown in Appendix (7). After the flow sensor the water supply is connected to the ultrasonic device.

![Flow Diagram](image)

Figure 14: Connection diagram of the flow meter
6 Experiment layout

The campaign started in the end of January, with setting up the US cleaning device in the field on a facet of the heliostat (see Figure 15 left). Heliostats at PSA are made up of 2 columns with 6 facets on each column. With the aim of testing the worst soiling conditions all tests were performed on the lower facet of heliostat (no. CESA 1015) and for pressurized water jet a different heliostat was chosen (no. CESA 1013). This facet is adjacent to facet 1015 that was used for cleaning with the ultrasonic device to keep constant the same environmental conditions at which they are exposed. In Figure 15 Figure 15(right), the US device is shown installed. At the time of performing cleaning, the device was installed over the forefront (or boundary of the facet). Before setting up the device permanently, the gap must be adjusted properly so that the band does not touch the mirror. This means the gap between the mirror and the band should measure between 1 and 3 mm [2].

Firstly, the heliostat field used in the experiment was originally designed with sun tracking system. During the experiment, the heliostat was kept fixed and the angle of the heliostat was selected at 30° to perform the cleaning tasks to achieve better cleaning performance⁵. Here it was not possible to put the heliostat in a horizontal position, but by putting a higher angle a good level of cleanliness could be achieved. If the angle tilt is higher than 30°, it is not possible to move the US device manually due to physical limitations⁶. The cleaning area was fixed around a 0.8 m * 0.5 m = 0.4 m². It was fixed by PSA and the company. Although it was initially desired to use the same cleaning area for the US and PWJ devices, this had to be altered as the US device used in this study operated with only a single transducer (on the bottom end of the band) as against the original design with a transducer at each end of the band. This mean that the nozzles at the top end would not operate as effectively and hence were not used. This effectively meant that the operating length of the band, and hence the US device, was set at 0.5 m and for a cleaning length (distance) of 0.8 m led to a cleaning area of 0.4 m².

All the test was performed to evaluate the cleanliness level, water consumption, electricity consumption, the gap between the mirror and the band, and the variable processing time (i.e. the time it takes to clean the mirror manually, as it is difficult to maintain the same speed while manually moving the device over the surface for each experiments).

Figure 15: Faced 1015 of the heliostat field at PSA (Left), Installed US device on the same faced (Right).

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⁵ As mentioned in the previous research (Previous work on page 4), the US cleaning device performs better by setting the mirror of the heliostat.
⁶ The Figure 15 show the device during mounting, not as it looks like during experiments.
The tests were performed by changing some parameters to obtain the frequency in order to clean the mirror. The frequency was operated manually from lower to higher between 19 to 30 kHz. The suggested frequency was from 22 to 24 kHz to operate the device.

- Firstly, the test was performed with a minimum gap between the mirror and the band (almost 1 mm) along with placing the heliostat in a less than 30° position. The right frequency was sought by testing a frequency within a 19 to 26 kHz range (It was possible to adjust the gap between the mirror and the band manually).
- Secondly, while maintaining the same position of the heliostat at same frequency level as before, the gap in the bottom part was increased to 3 mm.
- Thirdly, the gap along the band and the mirror was increased to 3 mm (from top to bottom), while retaining at the same heliostat position and frequency.
- In the next test, the gap along the band and mirror was increased. The heliostat angle was fixed at 30° (maintain above page 14) because the device works better in a horizontal position, so try to give as much possible tilt, and tried in the frequency range between 19 and 28 kHz.
- The final attempt was done at 30° of the heliostat angle, by reducing the gap in the bottom part (around 2 mm) with the same frequency range as before (19 to 28 kHz).
- During the tests, water flow has been manually maintained by increasing and decreasing flow as required, in order to see if the band works properly. If the water is very low the frequency might not achieve. The water should be enough to make a proper water film over the band. The minimum volume of the water layer necessary to cover the mirror is 0.002 l [2] in the horizontal position of the heliostat. However, in the case of this study, the heliostat will be fixed at 30° therefore it requires higher water flow to make enough water layer over the mirror surface, because the water does not stay over the mirror in tilt angle.
- While performing these tests with varying tilt and distance of the gap between band and mirror, different frequencies was found to be optimal and it was not possible to find a single frequency that was optimal for all tests. However, the largest problem during the tests was other issues, that is described in the next chapter.

6.1 Experimental challenges

Throughout the period of the thesis work, different tasks had been performed. In each task, various issues have been seen such as some technical issues with the US device, bad weather conditions and so on.

1. The test started by installing the device over the mirror. In the beginning, it was trying to set the right frequency to clean the mirror. After trying around 20 minutes, the screws holding the band to the equipment started to loosen due to the ultrasonic vibrations. Therefore, it was not possible to achieve the right frequencies, where the ultrasonic vibrations generate a liquid interface between band and mirror surface to clean the mirror. It was concluded that the applied torque between the transducer and tightening the band by screws was not enough.

2. After providing enough torque to the screws, another issue has been seen, either it cracks or bend the aluminum band while performing with ultrasounds (see in Figure 16 left marked in a red circle). It was found that it happened because of setting up the right frequent from lower to higher, where higher frequency gives strong ultrasonic effect. This cause to crack the band when the frequency got between 25
and 30 kHz. This, together with providing higher torque to the screws, causes to bend the band (Figure 16 right).

Figure 16: A creak in a band under red circle (left), bended band under red circle (right)

3. Although, it realized later that the torque required to screw the band should be 25 newton meters (this information provided by IK4-TEKNIKER). To provide proper torque dynamometer has been used. To continue the tests, it required a new band to perform the task again, and it took at least more than one week to receive new band from the company.

4. At the beginning of the tests, a band made of aluminum with inclined angle almost 45° at both the corner was used, see . This band was delivered by the company and had a new design, compared to the design usually used by the company which has 90° angle. It was a part of investigation to see that if a new band could perform better. While performing several times it was found that this dimension (a band with 45°) was not fit for the US device to clean the mirror. The reason behind that, because of having curved angle the energy delivered by the transducer was not applied to the band (as it works with old configuration), and not possible to achieve working frequency. After several attempts it was decided to use the old configuration of the band, which has 90° at both corners (which is used in the laboratory by the company) and was able to clean the mirror.

Figure 17: Band used in the beginning with different dimension

5. Next step was taken after receiving the band, which had a slightly convex curve (Figure 18) and small bumps over the surface, due to that, the band was touching the mirror. Thereby, it required support to continue the task which is explained in a next point.
6. While performing with a new band (Figure 18), it was possible to get right frequency at some point (the band with 90° angle at both corners), with proper torque on the screws (25 Nm) and larger gap (around 3 mm) between the band and the mirror. Followed by, the task was performed by putting support to the band (Figure 19 in red circle). Larger gap was given by putting the support (around 3 mm), by tight enough the band towards the US device (the motive of putting a higher gap, to see that does the device work properly or not). And somehow it worked at some points, but due to fluctuating the frequency (frequency was operated manually), it was not possible to take measurements.

7. Followed by the same task (point 6) to obtain right frequency, it was found another breakage in the band (Figure 20 in red circle). While performing few hours to achieve operational frequency. It was totally broken in the corner of the band, which could be due to operating frequency from lower to higher between 19 kHz to 30 kHz. At the higher frequency, it creates high ultrasounds/vibrations which could be cause to a broken band.
8. Moving further to achieve operational frequency, another challenge was seen that breaking up the connecting screw (which connects transducer and booster) in the system (Figure 21). The transducer has high frequency ultrasonic acoustic vibrations which generally applied to workpieces being held together with the transducer. In the case of US device, this transducer is connected to the band with help of a screw (to give vibrations to the band). Due to having high vibrations it loses the connection between transducer and the band, thereby the torque is applied to stiff the looseness, but the provided torque was higher than required. Therefore, it broke the screw which connects transducer and band. (Figure 20).

9. At the end when it was not possible to achieve any success, it was decided to uninstall the device and try if the device could deliver ultrasonic waves in a horizontal position, by putting water over the band to achieve working frequency (see Figure 22).
10. Finally, it ends with breaking five different bands during the period of study (see Figure 23).

11. The whole process explained above was trying to set up the device and achieving operational frequency, to clean the mirror. Meanwhile, there were some points where it was possible to get right frequency to clean the mirror. It was found that it was possible to clean the mirror (see in Figure 24 red circle), but the level of cleanliness was not enough to take measurements. Due to that, no measurements planned from the beginning was performed during the first part of the work.
Figure 24: Cleaned mirror by using ultrasonic cleaning technology
7 Results

After several failures with the measurement device, the set point was achieved at the frequency of 22.7 kHz. Using a new band provided by the company, a few experiments could be performed to test the device and get values so it was possible to do a preliminary comparison of the cleaning with the US device and traditional pressurized water jet cleaning.

From the initial monochromatic specular reflectance campaign, the starting point of reflectance for both facets with an average reflectance of 97 %, was established. This reflectance will be used as an initial reflectance of the mirror which will help in obtaining the cleaning factor of the facets being studied. Cleaning factor shows a level of cleanliness of any object by comparing the actual cleanliness of an object by its maximal possible value.

For this study, the cleaning factor is the ratio of the average reflectance of the mirror (five different spots measured) and the average initial reflectance of the mirror (totally clean mirror).

\[ C = \frac{\rho}{\rho_{\text{Initial}}} \]  
Equ. 1

7.1 Test performed by ultrasonic cleaning

Four tests were performed with cleaning of the mirror with the US device. The first three test was performed with one week between the test, so the mirror got dirty in between the test. The fourth test (called task 3-2) was the done at the same day as task 3-1, on same part of the mirror facet to see if any increment in the reflectance value.

Performing test, initial conditions:
- With gap around 2 mm between the mirror and the band
- The frequency set at 22.7 kHz.
- Mirror tilt at 30˚.

- **Test 1.** This test was performed in a perfectly clear weather along with average wind speed of 1.47 m/s. Appendix (8)). The reflectance measurements were done before and after cleaning the mirror on five different spots and the average was calculated. In Table 1 is shown the average reflectance value before and after cleaning.

- **Test 2.** The same procedure was followed in the second campaign, but it was a windy day with an average wind speed of 8.9 m/s. To avoid the wind effect, the heliostat was turned to face away from the wind, which helped maintain some of the water flowing steadily over the band surface, and performed cleaning.

- **Test 3.** Another test was performed a week later, with average wind speed of 7.8 m/s (see Appendix (8)). Due to the high wind, it was decided to perform two tasks: one was turned away the heliostat from wind 8, and another task was performed with the mirrors to the wind direction (shown in a Table 1 test 3-2). The Test 3-2 was performed to examine the effect of wind in cleaning process.

7 These facets were cleaned at PSA according to their cleaning methodology [5].
8 To avoid the wind effect, the heliostat was turned to face away from the wind, which helped maintain some of the water flowing steadily over the band surface.
The Table 1 below shows the average reflectance of the mirror in both condition (Test 3, with and without wind effect).

7.2 Test performed with pressurized water jet

The facet is cleaned by pressurized water jet technology. It was performed the same days when the ultrasonic device was performed.

The average reflectance measurements were taken before and after cleaning of the mirror with pressurized water jet technique (see Table 1). The distance between the mirror and the jet were fixed at 0.5 meters in each test.

All the tests were carried out at similar conditions, such as ambient water temperature with pressure at 100 bars. Moreover, the heliostat was always set at an angle of 30˚, as performed with ultrasonic device.

The idea was to use pressurized water jet in the same environmental conditions as with the US device. Thus, all the test runs were performed with the same wind velocities as with the US device. However, in the third task with the pressurized water jet, the experiment was only performed at a wind speed of 7.8 m/s (with the mirror towards the wind direction).

Task 3-2 was only performed to test the wind dependence of the US device and the same was not carried out with the pressurized water jet device.

Table 1  Average monochromatic specular reflectance by using ultrasonic device and pressurised water jet.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Ultrasonic device</th>
<th>Pressurized water jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Processing time</td>
<td>Average reflectance</td>
</tr>
<tr>
<td></td>
<td>[m/min]</td>
<td>before cleaning [%]</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.5</td>
<td>93.2</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.68</td>
<td>93.7</td>
</tr>
<tr>
<td>Test 3-1</td>
<td>0.96</td>
<td>93.6</td>
</tr>
<tr>
<td>Test 3-2</td>
<td>0.96</td>
<td>95.3</td>
</tr>
</tbody>
</table>

Figure 25 shows the results cleaning with the US device where the blue bars shows the average reflectance before cleaning, and red bars shows the average reflectance after cleaning. The reflectance increased more than 0.5 % after cleaning test one. At the time of test 2, 3-1, and 3-2 the average increase in reflectance was indicated almost same, although around 2 % increment was perceived after cleaning. The x-axis shows the test performed on weekly bases (except test 3-1 and 3-2 done on the same day and initial measured average reflectance is shown to the left. The tests were performed from 9th of May to 23rd of May. The processing time calculated between 0.5 and 0.96 m/min (see Table 1)
Figure 25: Average reflectance of the mirror (facet) before and after cleaning with the US device.

Figure 26 shows the average reflectance measured before and after cleaning by pressurized water jet. In Figure 25 and 26 time interval of one week was kept between cleaning operations/experiments as US device, and furthermore, cleaning was done on the same day (and virtually same time) for both cleaning methods. The blue bar represents average reflectance before cleaning, and red represents the same after cleaning. Where increment in average reflectance was between 1 and 3 % in the tests campaign. The processing time calculated between 3 and 5 m/min (see Table 1).
7.3 Cleaning Factor

It is shown in Table 2 that the CF (as per values are shown in result section average reflectance before and after cleaning) slightly increased after cleaning by US device between 1 and 2% for all the cases. As well as it is also illustrated in Figure 27 CF of pressurized water jet before and after cleaning can also be seen in the table along with swiping speed in both cases.

Table 2 Cleaning factor of the mirror (facet) using US device and pressurized water jet water.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Ultrasonic Device</th>
<th>Pressurized water Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Processing time [m/min]</td>
<td>CF before cleaning</td>
</tr>
<tr>
<td>1. Test 1</td>
<td>0.5</td>
<td>0.96</td>
</tr>
<tr>
<td>2. Test 2</td>
<td>0.68</td>
<td>0.97</td>
</tr>
<tr>
<td>3. Test 3-1</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>4. Test 3-2</td>
<td>0.96</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Figure 27 shows the CF of four tasks performed during the campaign, cleaning by US device. Where task test 3-1 or test 3-2 were tested same day, with wind and opposite to wind direction (see chapter 7 test 3). The result achieved was same for both the tests. Although, the test 2 indicates a higher CF after cleaning than another test performed. This test was also made leeward from the wind to reduce wind effect.
Figure 27 shows the CF before and after cleaning tested by pressurized water jet. The highest value of CF was obtained during test 3 after cleaning, lowest before cleaning at the same test. Moreover, the CF was similar during test 1 or 2 after cleaning.

Figure 27: Cleaning factor using pressurized water jet
7.4 Power, water and energy use

7.4.1. Power
Power consumption of the US device is a sum of the transducer power and the pump power. The power consumed by the transducer was taken from the MPI welding generator software and the pump power was given from its technical data (Appendix (5)). For the first two tasks, the transducer power was recorded at 114 W (Appendix (9)) and for the third task it rose slightly to 139 W. The pump power, for all three tasks, was determined to be 450 W.

The pressurised jet had one power consuming component, namely the Kärcher equipment which had a connecting load of 7800 W at 200 bars. The Kärcher was operated at 100 bar during the all cleaning runs of the mirror and its power consumption (3900 W) is calculated assuming that it varies linearly with the operating pressure. The energy calculated during the cleaning process is shown in Table 3 below.

7.4.2. Water
The procedure for determining the overall water consumption during an experiment run was explained in Chapter 1.4 and shall be briefly revised here. The flow rate (in l/s) was calculated using the measured time taken to fill up a graduated cylinder to 100 ml. The time taken for Task 1 was 21 s and Tasks 2 and 3 each had 16 s. and 25 s. The flow rate when multiplied by experiment/cleaning time gives the water consumption in liters. This was then compared with the area cleaned during the period to get the water consumption in l/m². A similar process was used in the case of the PWJ device, where the time taken was 1070 ml. in 10 s, and the results of both can be found in Table 3. The flow meter discussed earlier in Chapter 3.3, could not be installed and utilized in this experimental study due to unavoidable logistical circumstances relating to its installation and calibration.

7.4.3. Energy
The swiping speed was determined by dividing the mirror distance travelled by the measured time interval over which cleaning was carried out. This time interval when multiplied by the power gives the average Energy use for the entire cleaning process. The cleaning area was fixed (see Chapter 6) at 0.4 m² for the US device and 0.7 m² for the PWJ device (see Chapter 4). The Energy use tabulated in Table 3 is area specific and it is so calculated as it allows for direct and easy comparison between different cleaning technologies and devices as is the case with the current study.

Table 3: Energy, power, and water consumption along with processing time

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ultrasonic device (US)</th>
<th>Pressurized water jet (PWJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power Use US (W)</td>
<td>Water consumption (l/m²)</td>
</tr>
<tr>
<td>Test 1.</td>
<td>564</td>
<td>1.43</td>
</tr>
<tr>
<td>Test 2.</td>
<td>564</td>
<td>1.109</td>
</tr>
<tr>
<td>Test 3.</td>
<td>589</td>
<td>0.480</td>
</tr>
</tbody>
</table>
8 Discussion and conclusions

The main focus of the thesis was to evaluate and compare innovative and conventional cleaning technologies. Scarcity of water is often a significant concern in those sites where the CSP plants are deployed.

Experiments on the US device was carried out successfully despite abundant challenges and different issues with the US device. The most challenging of these related to achieving the desired operational frequency. The difficulties faced during device operation and experimentation make it fair to conclude that the US cleaning system can be further improved, especially for outdoor conditions.

Nevertheless, after several attempts, it was possible to set the right frequency and perform a few tests. While the experiments did not perform as per plan, owing to some issues with the device, the experimental field results can be used to make preliminary comparisons between ultrasonic and pressurized water jet cleaning systems.

The errors encountered during the study could be due to human error and some technical issues with the technology. This was not delved on in more depth because unknowns with regards to the device that can only be determined after a more thorough investigation. Unknowns here refer to the unknown causes of failure and error of certain components during operation (see Chapter 6.1) which act as indeterminable sources of error. Since the experimental campaign was unavoidably delayed and ultimately started almost two months after schedule, it was not possible to analyze these uncertainties more deeply.

Between the first two experiments/tasks, it was observed that there was no marked change in the cleanliness level i.e the cleanliness level at the end of the first task was the initial level at the beginning of the second despite the passage of one week. This can be observed in Table 1 in the case the US device, but the PWJ device sees a more noticeable decrease in cleanliness level. Between the second and third tasks, a decline was observed in the cleaning factor with a decrease of 0.03 in the case of the mirror used with the US device and 0.02 with the mirror for the PWJ device. This higher degradation was attributed to bad weather conditions during the week\(^9\) (between test 2 and test 3).

The swiping speed used while cleaning the mirror was also a parameter of interest especially in relation to the associated energy and water consumption. Comparing the Energy uses between the US and PWJ devices, it was observed that US system consumed 28 % and 30 % more than the PWJ system in task 1 and 2 respectively. During task 3, a decrease of 26 % was recorded between the US device and the PWJ device.

The Energy use, as mentioned earlier, is the product of the power consumption and the cleaning time. The power consumption of the PWJ device is significantly higher than the US device (see Table 3) however it doesn’t require as much operating time to achieve the same cleanliness. Hence the Energy uses of both devices are fairly similar that is to say they are in the same order of magnitude. More cleaning tests need to be carried out to determine how much faster the US device can be operated to lower its Energy use while simultaneously achieving the same cleaning.

Additionally, the rate of water consumed by US device was approximately 63 % (average of all 3 tests) less than the pressurized water jet (see Table 3). The pressurized water jet operates with high flow compare to US device and this is inherent to the cleaning technology itself. Comparing the previous study on the US device to the current work, the previous work operated the US device on a flat/horizontal mirror surface whereas the

\(^9\) It might be rain and high amount of wind. When the mirror is dirty due to rain water, the dust particles stuck over the surface and make mirror dirtier. which causes to lose the mirror reflectance.
current work used a mirror at a 30° tilt. This may be one of the reasons why it was found that, for the same device, there was more water consumption in the current study than in the previous study.

Compared to wet cleaning, hybrid cleaning is similar in terms of cleaning but more efficient in saving water (which was mentioned earlier). Against wet cleaning, hybrid systems provide a better cleaning performance and consume slightly less water. However, the technology works by contacting the surface of the device (for instance: the device works by contacting the mirror), which in turn affects the performance of the mirror (by scratching the mirror and damaging the surface). The US device operates differently from other hybrids, and works without contacting the surface, it is able to perform better in terms of lower water and electricity consumption. Both technologies were able to recover between 96 and 97 % of the original reflectance.

Another topic which is important to be mentioned is the wind speed while using the device. The device is unable to operate at higher wind speeds, because as per the principle of the device, water should flow over the band continuously and steadily with very low velocity. This, as mentioned earlier, is to maintain the waveforms generated by the ultrasonic transducer so that the mirror surface is struck by water in the form of water bubbles. In windy conditions it was not possible to maintain continuous water flow over the band with a low water velocity. When the wind essentially blows the water besides instead of over the band and the flow is disrupted. In these unsteady circumstances, it was not possible to generate the cavitation effect and the formation of water bubbles. This problem has been observed several times while performing the task on site.

By the above logic, if the disruptive influence of the wind is obviated, it should be possible to achieve the theorized water layer over the band and hence have better cleaning. This was attempted, in windy conditions, by rotating the tested mirror 180° such that it opposed the incoming wind. Although in Task 3-2 (see Table 1 Task 3-2), it was not found to make any change in the reflectance, this result was more to do with the physical cleaning limitations of the device than the influence of the wind. In other words, since the experiment run was started with a reflectance of 95.3 %, the increase in the final cleaning factor was limited to begin with (its maximum value being 97 %) and its lack of cleaning has more to do with the device’s limitations than the negated influence of the wind. The improvement in the relative cleaning factors in Tasks 1 and 2 can be attributed to the effects of the wind on the cleaning process. In Task 2 the mirror was turned away from the oncoming wind whereas in Task 1 it was facing the wind, and this may explain why an improvement in cleaning of 1 % in was observed in Task 2 over Task 1. However, further experimentation and testing needs to be carried out to conclusively determine the influence of the wind speed on the cleaning of the ultrasonic device.

Furthermore, in a commercial plant, the ability to rotate every mirror surface by 180° is simply not feasible and hence for practical applications some improvement must be made to allow the US device to operate more smoothly in windy ambient conditions.

Before the ultrasonic device was tested at the PSA, it had only been tested by the company in a laboratory (indoor conditions) where wind effects were not considered. It was realized later when it was tested at the PSA and in windy conditions that the wind affects the results. While performing the task, the wind speed recorded was around 40 km/h for some of the tests (measured with the help of portable anemometer).

Another thing to be improved is the type of transducer used for outdoor applications. The transducer needs to work long hours. At the time of operation, the transducer always overheats, because it worked continually with energy (electricity). When the temperature of the transducer is high, it does not create the right frequency needed to clean the mirror. At this point, it is absolutely necessary to reduce and maintain the temperature of the
transducer. This, in turn, leads to an increase in the processing time to clean the mirrors. If one considers the practical implications, the cleaning process of an entire field would take excessively long as the device would require some waiting time until the temperature of the transducer subsides.

After facing this heating issue with the device, it would be fair to say that by using a better-quality transducer, or a suitable active cooler, to overcome the heating issue. This might add an additional cost to the device, but it would save the amount of time required in the cleaning process.

### 9 Future work

The main motive of using ultrasonic cleaning technology is to clean the parabolic-trough collectors and not for heliostat, as per the company instruction. The idea is to use a truck with water tank as well as two robotic arms along with installed US devices, 3 in the back and 3 in a front, which works in parallel while cleaning the PT collectors. In the future, large scale test of US devices should be performed on parabolic trough collectors, but first it must be shown that the technology is reliable and not break as it has done in several cases in this study. Since one of the main advantage with ultrasonic cleaning is the reduced water consumption compared to pressurized water jet technology, and optimum between cleaning time, water consumption and cleaning frequency need to be investigated further.

Another future work could be done by microscopic test for both the technologies, the samples from the cleaning surface (cleaned by both technologies) will be taken. It will be analyzed that which technology performed better to clean fine dust particle.
References, appendices


## Appendix A

### 9.1 Appendix (1)

WG Generators - Details

<table>
<thead>
<tr>
<th>Item</th>
<th>Data base system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WG-400W</td>
</tr>
<tr>
<td></td>
<td>WG-1000W</td>
</tr>
<tr>
<td></td>
<td>WG-2000W</td>
</tr>
<tr>
<td>Power</td>
<td>max. 400 W</td>
</tr>
<tr>
<td></td>
<td>max. 1000 W</td>
</tr>
<tr>
<td></td>
<td>max. 2000 W</td>
</tr>
<tr>
<td>Frequency</td>
<td>20 kHz - 100kHz</td>
</tr>
<tr>
<td>Amplitude</td>
<td>constant and load-independent amplitude at the transducer possible with analog voltage, RS 485 interface</td>
</tr>
<tr>
<td>Interfaces</td>
<td>status LEDs</td>
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<tr>
<td></td>
<td>PLC-interfaces</td>
</tr>
<tr>
<td></td>
<td>Remote support via RS485</td>
</tr>
<tr>
<td>Protected against</td>
<td>overloaded</td>
</tr>
<tr>
<td></td>
<td>short circuit</td>
</tr>
<tr>
<td></td>
<td>over-temperature</td>
</tr>
<tr>
<td>Connectors on the rear of the generator</td>
<td>lino-connector</td>
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<tr>
<td></td>
<td>RF-connector (HV-BNC)</td>
</tr>
<tr>
<td></td>
<td>interface-connector Canon 15</td>
</tr>
<tr>
<td></td>
<td>RS485</td>
</tr>
<tr>
<td>Mains</td>
<td>216-240VAC 50-60Hz</td>
</tr>
<tr>
<td>Current consumption</td>
<td>dependant on the module max 7A</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>260 x 210 x 80</td>
</tr>
<tr>
<td></td>
<td>270 x 250 x 135</td>
</tr>
<tr>
<td></td>
<td>435 x 380 x 100</td>
</tr>
<tr>
<td>Weight</td>
<td>4.4 kg</td>
</tr>
<tr>
<td>Standards</td>
<td>CE-conformity</td>
</tr>
<tr>
<td>Applications</td>
<td>welding, bonding</td>
</tr>
</tbody>
</table>
## 9.2 Appendix (2)

Ultrasonic welding equipment consists of a machine press, Ultrasonic Welding Generator, Ultrasonic Welding Transducer, Ultrasonic Horn, and component support tooling and booster.

### SPECIFICATION OF ULTRASONIC WELDING TRANSDUCER

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacity (μF)</th>
<th>Resonance Impedance (Ω)</th>
<th>Full-length (mm)</th>
<th>Joint Bolt (mm)</th>
<th>Frequency (kHz)</th>
<th>Input Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJW-152000F-705 PT8B</td>
<td>13000</td>
<td>15</td>
<td>153</td>
<td>M20×1.5</td>
<td>15</td>
<td>2500</td>
</tr>
<tr>
<td>BJW-152000F-605 PT8B</td>
<td>9000</td>
<td>10</td>
<td>167</td>
<td>M20×1.5</td>
<td>15</td>
<td>2000</td>
</tr>
<tr>
<td>BJW-151000F-505 PT8B</td>
<td>12500</td>
<td>12</td>
<td>171</td>
<td>M18×1.5</td>
<td>15</td>
<td>1500</td>
</tr>
<tr>
<td>BJW-209000F-605 PT4</td>
<td>15000</td>
<td>15</td>
<td>178</td>
<td>M20×1.5</td>
<td>20</td>
<td>1800</td>
</tr>
<tr>
<td>BJW-202000F-305 PT8B</td>
<td>10000</td>
<td>10</td>
<td>128</td>
<td>M18×1.5</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>BJW-207000F-505 PT8B</td>
<td>10000</td>
<td>12</td>
<td>124</td>
<td>M18×1.5</td>
<td>20</td>
<td>1500</td>
</tr>
<tr>
<td>BJW-207000F-205 PT8B</td>
<td>9000</td>
<td>15</td>
<td>112</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>700</td>
</tr>
<tr>
<td>BJW-209000F-205 PT8B</td>
<td>10000</td>
<td>15</td>
<td>133</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>900</td>
</tr>
<tr>
<td>BJW-209000F-505 PT8B</td>
<td>6000</td>
<td>15</td>
<td>121</td>
<td>M18×1.5</td>
<td>20</td>
<td>600</td>
</tr>
<tr>
<td>BJW-305000F-305 PT8B</td>
<td>5500</td>
<td>5</td>
<td>77</td>
<td>M10×1.5</td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td>BJW-263000F-305 PT4</td>
<td>3000</td>
<td>20</td>
<td>92.1</td>
<td>M10×1.5</td>
<td>28</td>
<td>200</td>
</tr>
<tr>
<td>BJW-288000F-255 PT8B</td>
<td>2200</td>
<td>25</td>
<td>91</td>
<td>M8×1.5</td>
<td>28</td>
<td>100</td>
</tr>
<tr>
<td>BJW-285000F-365 PT8B</td>
<td>4000</td>
<td>20</td>
<td>94</td>
<td>1/2-20 UNF</td>
<td>28</td>
<td>250</td>
</tr>
<tr>
<td>BJW-205000F-505 PT8B</td>
<td>20000</td>
<td>10</td>
<td>128</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>BJW-201500F-405 PT8B</td>
<td>16000</td>
<td>10</td>
<td>124</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>1500</td>
</tr>
<tr>
<td>BJW-201500F-505 PT8B</td>
<td>12500</td>
<td>10</td>
<td>128</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>1300</td>
</tr>
<tr>
<td>BJW-207600F-605 PT8B</td>
<td>11000</td>
<td>10</td>
<td>112</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>1800</td>
</tr>
<tr>
<td>BJW-207800F-805 PT8B</td>
<td>5500</td>
<td>10</td>
<td>123</td>
<td>1/2-20 UNF</td>
<td>20</td>
<td>900</td>
</tr>
</tbody>
</table>
9.3 Appendix (3)

<table>
<thead>
<tr>
<th>Model</th>
<th>PF2D50A</th>
<th>PF2D520</th>
<th>PF2D640</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicable sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instantaneous flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated flow range</td>
<td>0.4 to 4.0 L/min</td>
<td>1.8 to 20.0 L/min</td>
<td>4 to 40 L/min</td>
</tr>
<tr>
<td>Setting/display flow range</td>
<td>0.25 to 4.50 L/min</td>
<td>1.3 to 21.0 L/min</td>
<td>2.5 to 45.0 L/min</td>
</tr>
<tr>
<td>Min. setting/display unit</td>
<td>0.05 L/min</td>
<td>0.1 L/min</td>
<td>0.5 L/min</td>
</tr>
<tr>
<td>Accumulated Flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setting/display flow range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 9999.99 L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. setting/display unit</td>
<td>1 L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Switch output

<table>
<thead>
<tr>
<th>Output mode</th>
<th>NPN open collector output, PNP open collector output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch operation</td>
<td>Non-Reversed output, Reversed output</td>
</tr>
<tr>
<td>Max. load current</td>
<td>80 mA</td>
</tr>
<tr>
<td>Max. applied voltage</td>
<td>30 VDC (NPN output)</td>
</tr>
<tr>
<td>Internal voltage drop</td>
<td>NPN output: 1 V or less (at 80 mA), PNP output: 1.5 V or less (at 80 mA)</td>
</tr>
<tr>
<td>Response time</td>
<td>1 s or less</td>
</tr>
<tr>
<td>Repeatability</td>
<td>±0.5% F.S. max</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±0.5% F.S. max</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Hysteresis mode: Variable, Window comparator mode: Fixed (3 digits)</td>
</tr>
<tr>
<td>Output protection</td>
<td>Short circuit protection</td>
</tr>
</tbody>
</table>

Pulse width

| Conversion of accumulated pulse | 0.05 L/pulse | 0.1 L/pulse | 0.5 L/pulse |

Supply voltage | 12 to 24 VDC ±10% |

Power consumption (No load) | 60 mA or less |

Temperature characteristics | ±1% F.S. max. (15 to 35 °C, 25 °C reference), ±2% F.S. max. (0 to 50 °C, 25 °C reference) |

*1: If the flow rate is smaller than the minimum flow of the display range, "0 L/min" is displayed.
*2: Selectable by setting.
*3: Total accuracy when used with applicable sensor.
9.4 Appendix (4)
9.5 Appendix (5)
### Technical Data and Equipment

**HDS 10/20-4 M**

#### Technical data

<table>
<thead>
<tr>
<th>Order no.</th>
<th>1.071-9030</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAN code</td>
<td>4054278134925</td>
</tr>
<tr>
<td>Current type</td>
<td>Ph / V / Hz 3 / 400 / 50</td>
</tr>
<tr>
<td>Flow rate</td>
<td>l/h 500-1000</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar / MPa 30-200 / 3-20</td>
</tr>
<tr>
<td>Max. temperature</td>
<td>°C 80 / 155</td>
</tr>
<tr>
<td>Connection load</td>
<td>kW 7.8</td>
</tr>
<tr>
<td>Heating oil or gas consumption, full load</td>
<td>kg/h 6.4</td>
</tr>
<tr>
<td>Fuel tank</td>
<td>l 25</td>
</tr>
<tr>
<td>Weight</td>
<td>kg 168</td>
</tr>
<tr>
<td>Dimensions (L x W x H)</td>
<td>mm 1330 x 750 x 1060</td>
</tr>
</tbody>
</table>

#### Equipment

- **Spray gun**: EASHForce Advanced
- **High-pressure hose**: m 10 / Long-life
- **Spray lance**: mm 1050
- **Power nozzle**: ■
- **Servo Control**: ■
- **ANTITTwist**: ■
- **Tanks for cleaning agent, calibration protection and fuel can be filled from the outside**: ■
- **Control panel with display light**: ■
- **Pressure cut-off**: ■
- **Pole reverse plug (3-phase)**: ■
- **Service electronics with LED display**: ■
- **Two detergent tanks**: ■
- **Dry-running protection**: ■
- **Included in delivery**: ■
9.7 Appendix (7)

Internal circuit and wiring example
Use sensor PF2350 series for accurate measurement.

**NPN (2 outputs) type**
PF2350-A

Max. 30 V, 80 mA
Internal voltage drop: 1 V or less

**PNP (2 outputs) type**
PF2351-A

Max. 80 mA
Internal voltage drop: 1.5 V or less
Internal circuit and wiring example
Use sensor PF23□□ series for accurate measurement.

**NPN (2 outputs) type**
PF23□□0-A□

Max. 30 V, 80 mA
Internal voltage drop: 1 V or less

**PNP (2 outputs) type**
PF23□□1-A□

Max. 80 mA
Internal voltage drop: 1.5 V or less
9.8 Appendix (8)

Test 1

Test 2

Test 3
9.9 Appendix (9)