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Electrostatic methods for surface cleaning of PV panels

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Abstract

The graduate dissertation titled "Electrostatic methods for surface cleaning of PV panels" investigates the effectiveness of electrostatic cleaning techniques for maintaining solar panels. The arising challenges, such as energy consumption and water scarcity, require the finding of novel techniques for surface cleaning. Electrostatic methods with low power consumption profiles are a good candidate to resolve even a part of the surface cleaning problem. Indeed, without wasting water and without any contact with the cleaned surface, electrostatic methods offer an interesting way to maintain PV panels.

This work is aimed at the examination of electrostatic methods and their potential applications in solar panel cleaning.The dissertation proposes a series of experiments and simulations to evaluate the cleaning efficiency of electrostatic methods, considering parameters such as particles behavior and removal efficiency. Particularly, electrostatic induction and electric curtains were examined. Even though both methods can achieve the required task, electrostatic induction is easier to implement and leads to high cleaning efficiency.

Keywords: electric curtain, electrostatic induction electrode.

Résumé

Le mémoire de fin d'études intitulé "Méthodes électrostatiques pour le nettoyage de surface des panneaux PV" étudie l'efficacité des techniques de nettoyage électrostatique pour l'entretien des panneaux solaires. Les défis qui se posent, tels que la consommation d'énergie et la rareté de l'eau, nécessitent de trouver de nouvelles techniques de nettoyage des surfaces. Les méthodes électrostatiques avec des profils de faible consommation d'énergie sont un bon candidat pour résoudre ne serait-ce qu'une partie du problème de nettoyage de surface. En effet, sans gaspillage d'eau et sans aucun contact avec la surface nettoyée, les méthodes électrostatiques offrent un moyen intéressant d'entretenir les panneaux PV.

Ce travail vise à l'examen des méthodes électrostatiques et de leurs applications potentielles dans le nettoyage des panneaux solaires. La thèse propose une série d'expériences et de simulations pour évaluer l'efficacité de nettoyage des méthodes électrostatiques, en tenant compte de paramètres tels que le comportement des particules et l'efficacité d'élimination. En particulier, l'induction électrostatique et les rideaux électriques ont été examinés. Même si les deux méthodes peuvent accomplir la tâche requise, l'induction électrostatique est plus facile à mettre en œuvre et conduit à une efficacité de nettoyage élevée.

Mots clés : Rideaux électriques, électrode à induction électrostatique.

ملخص

حثت مذكرة الخريجين بعنوان "الطرق الكهروستاتيكية لتنظيف أسطح األلواح الكهروضوئية" في فعالية تقنيات التنظيف الكهروستاتيكي في الحفاظ على الالواح الشمسية. تتطلب التحديات الناشئة ، مثل استهالك الطاقة وندرة المياه .

إيجاد تقنيات جديدة لتنظيف األسطح. تعتبر الطرق الكهروستاتيكية ذات ملفات تعريف استهالك الطاقة المنخفضة مرشً حا

جيدًا لحل حتى جزء من مشكلة تنظيف السطح. في الواقع ، بدون إهدار المياه ودون أي اتصال بالسطح النظيف ، توفر الطرق الكهروستاتيكية طريقة ممتعة للحفاظ على األلواح الكهروضوئي.

يهدف هذا العمل إلى فحص الطرق الكهروستاتيكية وتطبيقاتها المحتملة في تنظيف األلواح الشمسية. تقترح المذكرة سلسلة من التجارب والمحاكاة لتقييم كفاءة التنظيف للطرق الكهروستاتيكية ، مع مراعاة المعلمات مثل سلوك الجسيمات وكفاءة اإلزالة. على وجه الخصوص ، تم فحص الحث الكهروستاتيكي والستائر الكهربائية. على الرغم من أن كلتا الطريقتين يمكن أن تحقق المهمة المطلوبة ، إال أن الحث الكهروستاتيكي أسهل في التنفيذ ويؤدي إلى كفاءة تنظيف عالية.

الكلمات المفتاحية : الستارة الكهربائية,قطب الحث الكهروستاتيكي

List of figures

Summaries

General Introduction

General Introduction

Solar energy refers to the radiant light and heat energy emitted by the sun, which is harnessed and converted into usable electricity or thermal energy. It is a renewable and abundant source of energy that holds immense potential for sustainable power generation. Solar energy is captured through the use of solar panels or photovoltaic cells, which absorb sunlight and convert it into direct current (DC) electricity. This clean and renewable energy source offers numerous advantages, including reduced dependence on fossil fuels, lower greenhouse gas emissions, and the potential for decentralized energy production. Solar energy plays a crucial role in the transition towards a more sustainable and environmentally friendly energy system, contributing to a greener future and mitigating the impacts of climate change.

However, these panels are not immune to challenges, with one significant problem being the accumulation of dust and debris on their surfaces. Dust particles, whether from natural sources or human activities, tend to settle on solar panels over time, forming a layer that obstructs the incoming sunlight. This dust layer acts as a barrier, reducing the amount of light reaching the solar cells and impeding their ability to convert solar energy into electricity efficiently. Consequently, the accumulation of dust negatively impacts the overall performance and energy output of solar panels. It is crucial, therefore, to address this issue and develop effective cleaning methods to maintain optimal functioning and maximize the energy generation potential of solar panels.

In this work, cleaning solar panels was studied in innovative ways without the need to use water.The aim is to highlight the electric curtain and the electrostatic induction pole and their effective role in cleaning and maintaining the quality of solar panels.

For a better understanding of the subject, we have built the dissertation into four chapters:

The first presents the state of the art of the topic, in which we provide general information about renewable energies and the characteristics and advantages of each one As for the second chapter, it included various concepts related to the electric curtain and the electrostatic induction.

The third chapter is devoted to studying the materials and tools used in the experiment, in addition to the installation steps and working methods for each case, which we mentioned earlier.

The results obtained with their interpretations are presented in the last chapter.

Chapter I

Renewable energies

Chapter I: Renewable energies

I.1. Introduction

Renewable energies, often referred to as green or clean energies, encompass a diverse range of natural resources and technologies that harness energy from sustainable and replenishable sources. Solar power, wind energy, hydropower, biomass, geothermal energy, and emerging technologies such as wave and tidal power all fall within the realm of renewable energies. By capitalizing on these abundant and environmentally friendly sources, renewable energy offers a promising solution to mitigate climate change, reduce greenhouse gas emissions, and foster a more sustainable future. Through this chapter, readers will gain a comprehensive understanding of the fundamental principles underlying renewable energy sources and their significance in addressing the pressing energy and environmental challenges of our time.

I.2. Definition of renewable energies

Renewable energy refers to energy that is obtained from renewable sources that are naturally replenished over a relatively short period of time, such as solar, wind, hydropower, geothermal, and biomass. These energy sources are considered renewable because they are continuously replenished, in contrast to non-renewable sources like fossil fuels that are finite and will eventually be depleted. Renewable energy has gained increasing attention in recent years as a means of mitigating climate change, reducing dependence on fossil fuels, and promoting energy independence.

One of the main advantages of renewable energy is that it is generally much cleaner and produces fewer greenhouse gas emissions compared to non-renewable sources. For example, solar and wind power do not produce any emissions during operation, while hydropower and biomass produce relatively low emissions. This makes renewable energy a key component in reducing the overall carbon footprint of a country or region, and in meeting greenhouse gas reduction targets. Another advantage of renewable energy is that it can help reduce dependence on imported fossil fuels. By relying more on domestic sources of energy, countries can improve their energy security and reduce their exposure to volatile international energy markets. In addition, many renewable energy sources, such as solar and wind, can be installed in remote areas, providing energy access to regions that may not have access to conventional power grids.[1].Renewable energy also has the potential to create new jobs and stimulate economic growth. The renewable energy sector is rapidly growing, with many countries investing heavily in research and development, as well as in the deployment of renewable energy technologies. This growth is leading to the creation of new jobs in manufacturing, installation, and maintenance of renewable energy systems. Moreover, as renewable energy technologies become more efficient and cost-competitive, they can also become more attractive to investors, further driving growth and job creation.

However, renewable energy also has some limitations and challenges. One of the main challenges is that renewable energy sources can be intermittent and may not always be available when needed. For example, solar power is only available during daylight hours, and wind power is dependent on wind speeds. This intermittency can be addressed through the use of energy storage systems or through integration with other sources of energy, such as natural gas or nuclear power. However, energy storage can be expensive, and integrating renewable energy sources with conventional sources can present technical and regulatory challenges.

In addition, renewable energy technologies can require significant upfront investments, which may be a barrier for some countries or regions. However, as the cost of renewable energy technologies continues to decline, they are becoming more cost-competitive with conventional sources of energy. Moreover, many countries are implementing policies and incentives to encourage the adoption of renewable energy, such as feed-in tariffs, tax credits, and renewable energy mandates.[2]

In conclusion, renewable energy has the potential to play a key role in reducing greenhouse gas emissions, promoting energy independence, and stimulating economic growth. While there are still challenges and limitations to be addressed, the rapid growth and deployment of renewable energy technologies in recent years is a promising sign of their potential to transform the global energy landscape.

I.3. Types of renewable energy

They are as follows:

- Wind energy.
- Hydro energy.
- Geothermal energy.
- Biomass energy.

- Ocean energy.
- Solar energy.

I.3.1. wind energy

Wind energy refers to the energy generated from the wind. This energy can be harnessed by using wind turbines, which convert the kinetic energy of the wind into mechanical energy that can be used to generate electricity. Wind energy is a renewable energy source, as the wind will always be present, and it does not produce any harmful emissions or pollution.[3].

Wind turbines typically consist of blades, a rotor, a nacelle (which houses the generator), a tower, and other components such as brakes, control systems, and electrical infrastructure. When the wind blows, the blades on the turbine rotate, which in turn rotates the rotor. The rotor is connected to a generator, which produces electricity that can be sent to the electrical grid for distribution.

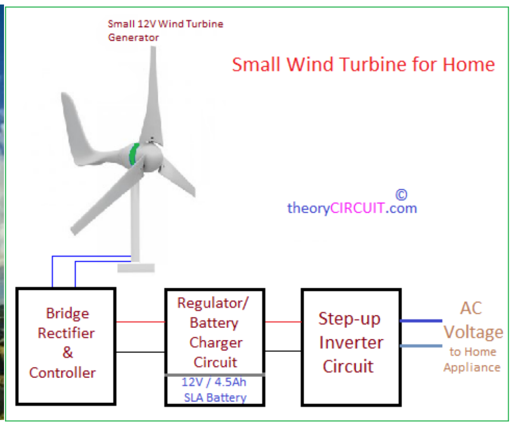

Figure I. 1: wind farm.[4]

Figure I. 2: small wind turbine for home.[5]

Wind energy is becoming an increasingly popular form of renewable energy, as it is abundant and widely available in many areas. It is also cost-competitive with other forms of energy, and the technology has improved over the years to make it more efficient and reliable. However, wind energy does have some limitations, such as its intermittency and variability, which can make it challenging to integrate into the electrical grid. Nevertheless, wind energy is expected to continue to play an important role in the global energy mix, as countries strive to reduce their reliance on fossil fuels and transition to a more sustainable energy future.

I.3.2. Hydro Energy

Hydro energy, also known as hydropower, is a form of renewable energy that harnesses the power of water to generate electricity. This is done by using turbines and generators to convert the kinetic energy of moving water into electrical energy.[6]

There are several types of hydropower plants, including dams, run-of-the-river, and pumped- storage plants.

- Dams are the most common type of hydropower plant and are typically built in areas where there is a large amount of water flowing downhill, such as near rivers or waterfalls. The dam is constructed to create a reservoir of water behind it, which is then released through turbines to generate electricity.
- Run-of-the-river hydropower plants, on the other hand, do not use a dam to create a reservoir of water. Instead, they use the natural flow of the river to turn turbines and generate electricity. These types of plants are typically built in areas where there is a steady flow of water.
- Pumped-storage plants are a bit different in that they do not generate electricity directly from the flow of water. Instead, they use excess electricity from the grid during off-peak hours to pump water from a lower reservoir to a higher reservoir. Then, during peak hours, the water is released to generate electricity.

Hydropower is a reliable and clean source of energy, as it produces no greenhouse gas emissions or air pollution. It also has a relatively low cost of production, as the energy source (water) is free and abundant. However, there are also some drawbacks to hydropower, such as its impact on aquatic ecosystems and the displacement of people living near dams.

Despite its many benefits, there are also concerns about the environmental and social impacts of hydropower. The construction of dams and reservoirs can lead to the displacement of communities and the loss of important habitats and ecosystems. Additionally, the alteration of water flow and temperature can impact aquatic species, such as fish and amphibians.

To address these concerns, there has been a shift towards more sustainable hydropower practices. This includes the use of fish-friendly turbines, the construction of fish ladders to allow fish to migrate around dams, and the release of water at certain times to mimic natural river flows. Additionally, there has been a push towards decommissioning old, outdated dams that are no longer economically or environmentally viable.

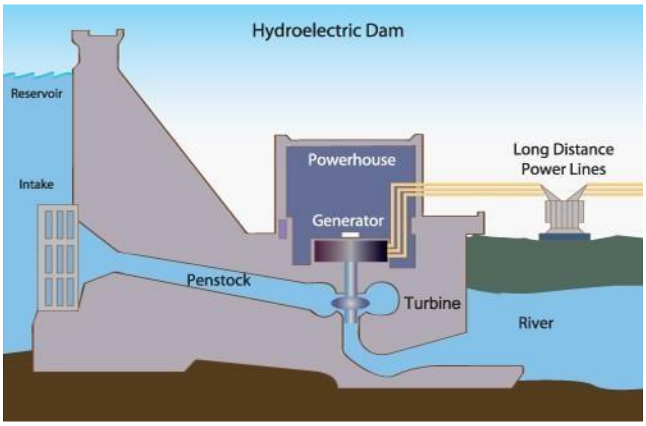

Figure I. 3: water dam for hydro-energy.[7]

Figure I. 4: hydro-energy system.[8]

Overall, hydropower is an important source of renewable energy that has the potential to help mitigate climate change and reduce our dependence on fossil fuels. However, it is important to ensure that it is done in a sustainable and responsible

I.3.3. Geothermal Energy

Geothermal energy is an abundant and renewable source of energy that has the potential to provide a significant portion of the world's energy needs. Unlike fossil fuels, é energy is clean and does not produce harmful emissions, making it a viable option for reducing greenhouse gas emissions and combating climate change. In this essay, we will explore the benefits and challenges of geothermal energy and its potential to be a sustainable source of energy.

Geothermal energy is produced by harnessing the heat that is naturally generated within the Earth's core and mantle. The heat is brought to the surface by the movement of tectonic plates and can be used to generate electricity or for direct heating and cooling. Geothermal energy is a renewable resource because the Earth's heat is continually replenished by radioactive decay and the planet's internal energy. It is a reliable source of energy that is available 24/7 and can provide base load power, making it an attractive alternative to intermittent renewable sources like solar and wind.[9]

One of the major benefits of geothermal energy is its low environmental impact. Unlike fossil fuels, geothermal energy does not produce harmful emissions, including carbon dioxide, sulfur dioxide, and nitrogen oxides. This makes it a cleaner option for generating electricity and heating homes and buildings, reducing greenhouse gas emissions, and combating climate change. Geothermal power plants also use relatively small amounts of land compared to other types of power plants, and the land can often be used for other purposes, such as agriculture or recreation.

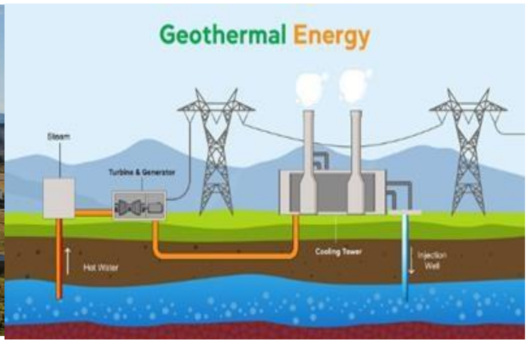

Figure I. 5:geothermal energy.[4]

Figure I. 6:geothermal power management.[10]

Another advantage of geothermal energy is its cost-effectiveness. Although the upfront costs of drilling and installing geothermal power plants can be high, the operating costs are relatively low, and the energy is essentially free once the plant is operational. Geothermal energy is also less vulnerable to price fluctuations than fossil fuels because it is not subject to geopolitical tensions or supply disruptions.

Despite its many benefits, there are also some challenges associated with geothermal energy. One of the main challenges is the limited availability of suitable sites for geothermal power plants. Geothermal resources are generally concentrated in specific areas, and not all regions have the geological conditions necessary for geothermal energy production. Additionally, the drilling and exploration process can be expensive and time-consuming, and there are risks associated with drilling, such as the potential for earthquakes and other geological hazards.

Another challenge of geothermal energy is the potential for environmental impacts. While geothermal power plants are generally cleaner than other types of power plants, they can still have environmental impacts, such as the potential for land subsidence, water depletion, and the release of toxic gases. Proper management and monitoring are necessary to minimize these impacts and ensure that geothermal energy is produced in a sustainable manner.

In conclusion, geothermal energy has the potential to be a significant source of clean and renewable energy. It has many benefits, including its low environmental impact, cost-effectiveness, and reliability. However, there are also challenges associated with geothermal energy, such as limited availability and potential environmental impacts. Despite these challenges, geothermal energy is an important part of the renewable energy mix and has the potential to play a significant role in the transition to a low-carbon future.

I.3.4. Biomass Energy

Biomass energy is a form of renewable energy that is derived from organic matter, such as plant material, agricultural waste, forestry residues, and even municipal and industrial waste. It is considered one of the most promising renewable energy sources due to its abundance, renewability, and availability. Biomass can be converted into energy through various processes, such as combustion, gasification, or anaerobic digestion. In this paper, we will discuss the different types of biomass energy, their advantages and disadvantages, and their potential as a source of renewable energy.[11]

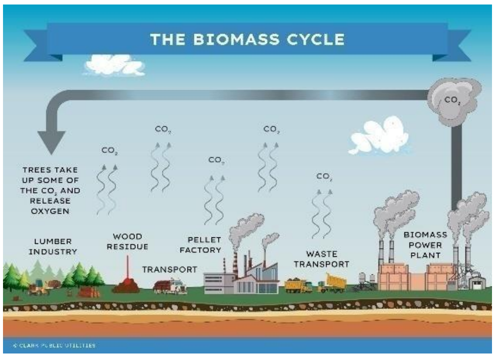

Figure I. 7: the biomass cycle.[11]

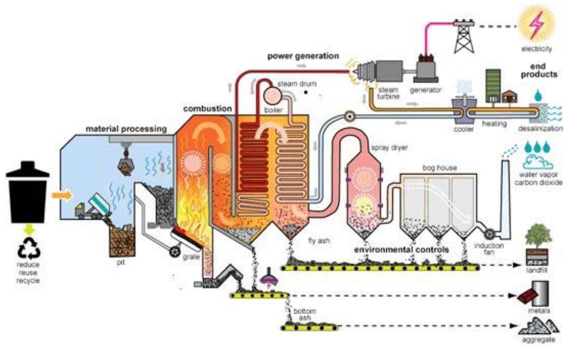

Figure I. 8: A massive combustion waste to energy plant.[12]

I.3.4.1. Types of Biomass Energy

There are several types of biomass energy, including:

- **Woody Biomass**: This type of biomass energy comes from the stems, branches, and trunks of trees. Woody biomass can be harvested from forests, plantations, and other woody resources. It is commonly used for heating and electricity generation.

- **Agricultural Biomass**: This type of biomass energy comes from agricultural waste, such as crop residues, animal manure, and food processing waste. Agricultural biomass can be used for electricity generation, heating, and as a fuel for vehicles.
- **Municipal Solid Waste:** This type of biomass energy comes from municipal waste, such as food waste, yard waste, and paper waste. It can be used to generate electricity and heat.
- **Energy Crops:** This type of biomass energy comes from crops that are grown specifically for energy production. These crops include corn, sugarcane, and switch grass. Energy crops can be used for electricity generation and as a biofuel for vehicles.[13]

Advantages of Biomass Energy:

1. Renewable: Biomass energy is a renewable energy source that can be replenished through natural processes such as photosynthesis. Unlike fossil fuels, which are finite and take millions of years to form, biomass can be grown and harvested on a relatively short time scale.
2. Reduction in Greenhouse Gas Emissions: Biomass energy has the potential to reduce greenhouse gas emissions by replacing fossil fuels. When biomass is burned, it releases carbon dioxide, but this is offset by the carbon dioxide that is absorbed by the plants during growth. Additionally, using biomass energy reduces the need for fossil fuels, which are a major source of greenhouse gas emissions.
3. Economic Benefits: Biomass energy can provide economic benefits by creating jobs in the production and processing of biomass and by providing a source of energy that is often produced locally. This can help to support local economies and reduce dependence on foreign sources of energy.

Disadvantages of Biomass Energy:

1. Land Use Competition: Biomass production can compete with food production, leading to higher food prices and food shortages. Additionally, the cultivation of energy crops can lead to land use change, which can have negative environmental impacts.
2. Transportation Costs: Biomass energy is often produced in rural areas, which can make transportation costs high. Additionally, biomass energy is less energy-dense

than fossil fuels, which means that more fuel is required to generate the same amount of energy.

3. Environmental Impacts: The production of biomass energy can have negative environmental impacts, such as soil erosion, water pollution, and habitat destruction. Additionally, the combustion of biomass can produce air pollutants, such as particulate matter and nitrogen oxides.

I.3.5. Ocean energy

Ocean energy is the renewable source of energy generated from the ocean's natural resources, including waves, tides, currents, and temperature differences. As climate change and global warming threaten our planet, the need for renewable energy sources has become more critical. With the ocean covering over 70% of the earth's surface, it presents a vast potential for producing renewable energy. In this paper, we will explore the various types of ocean energy and their potential to meet the world's energy demands.[14]

Figure I. 9: Ocean power [4]

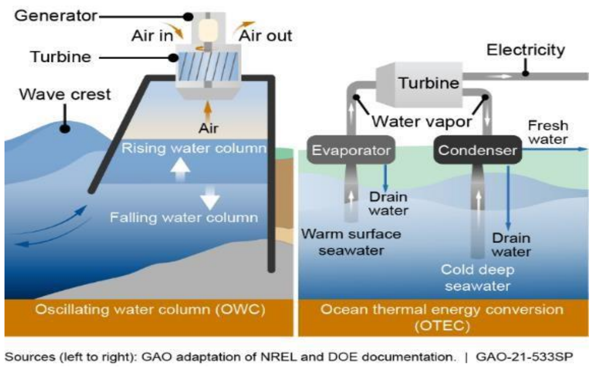

Figure I. 10: How energy power does work [15]

I.3.5.1. Types of Ocean Energy

Wave Energy: Wave energy is generated by the motion of waves on the ocean surface. This energy is captured by devices called wave energy converters (WECs), which convert the wave's motion into electrical energy. WECs come in various designs, such as oscillating water columns, point absorbers, and attenuators. The amount of energy generated from wave energy depends on factors such as wave height, wave speed, and frequency.

- Tidal Energy: Tidal energy is generated by the movement of the tides, which are caused by the gravitational pull of the moon and the sun on the earth's oceans. Tidal energy is captured using tidal turbines, which resemble wind turbines but are designed to work underwater. As the tides flow, they rotate the blades of the turbines, generating electricity. Tidal energy is highly predictable and reliable as tides occur twice a day.

- Ocean Current Energy: Ocean currents are the continuous, directional movements of ocean water. These currents can be used to generate electricity through underwater

- turbines, which work similarly to tidal turbines. The amount of energy generated from ocean currents depends on the current's speed and volume, which varies based on location.
- Ocean Thermal Energy: Ocean thermal energy is generated by the temperature difference between the warm surface water and the cold deep water. This temperature difference is used to power a heat engine, which generates electricity. Ocean thermal energy is abundant in tropical regions where the temperature difference is significant.

I.3.5.2. Advantages of Ocean Energy

- Renewable: Ocean energy is renewable, which means it will not run out, unlike fossil fuels.
- Predictable: Tidal energy and ocean current energy are highly predictable, making it easier to plan and manage energy production.
- Low Carbon Emissions: Ocean energy production does not produce carbon emissions, making it a clean source of energy.
- Potential for Large Scale Production: The ocean's vast potential for producing energy means it can potentially meet a significant portion of the world's energy demands.

I.3.5.3. Challenges of Ocean Energy

High Capital Costs: The initial costs of building and installing ocean energy infrastructure can be expensive, making it challenging to attract investors.

Environmental Impact: The construction of ocean energy infrastructure can have an impact on marine life, such as affecting migration patterns of whales and other marine animals.

Maintenance Costs: Ocean energy infrastructure requires regular maintenance due to the harsh marine environment, which can be costly.

Dependence on Location: The effectiveness of ocean energy varies based on location, and some areas may not be suitable for energy production.

I.3.6. solar energy

Solar energy is the energy that is derived from the sun's radiation. It is a renewable and sustainable source of energy that can be harnessed using various technologies, such as solar panels or concentrated solar power systems.

Solar panels work by capturing the energy from the sun's rays and converting it into electricity. They are made up of photovoltaic (PV) cells, which are typically made from silicon or other materials that exhibit the photovoltaic effect. When sunlight hits the PV cells, it knocks electrons loose from their atoms, creating a flow of electricity.

The use of solar energy has been increasing rapidly in recent years, thanks to advances in technology and a growing recognition of the benefits of renewable energy. Solar power is becoming more cost-effective and efficient, making it a viable alternative to traditional sources of energy such as fossil fuels. In addition to being environmentally friendly, solar energy can also provide energy security and independence, especially for remote or off-grid locations.

There are two main types of solar energy systems: photovoltaic (PV) and concentrated solar power (CSP). PV systems are more common and are used to generate electricity directly from sunlight. CSP systems use mirrors or lenses to concentrate sunlight onto a small area, which heats up a fluid that then drives a turbine to generate electricity.

Overall, solar energy has the potential to revolutionize the way we generate and consume energy. With ongoing advances in technology, it is likely that solar power will become an increasingly important source of energy in the years to come.

Figure I.11: solar energy – solar panels [4]

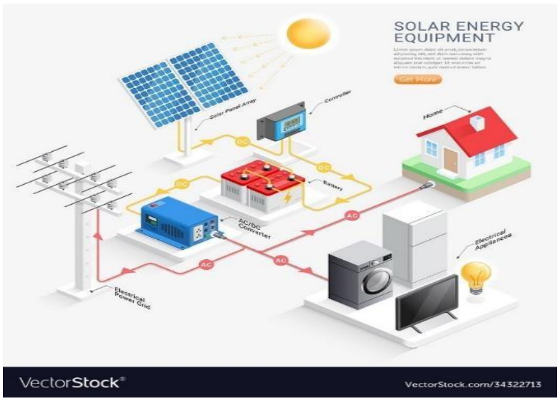

Figure I.12: solar energy equipment [16]

The benefits of solar energy are many. Perhaps most importantly, solar power is a renewable and sustainable source of energy. Unlike fossil fuels, which are finite and will eventually run out, solar energy is constantly replenished by the sun's rays. This means that solar power has the potential to provide a reliable and long-lasting source of energy.

Another major benefit of solar energy is its environmental friendliness. Solar power does not produce any greenhouse gas emissions or other pollutants that can harm the environment. This makes it a much cleaner and safer alternative to traditional sources of energy such as coal, oil, and natural gas.

In addition to being environmentally friendly, solar energy can also help to reduce our dependence on foreign oil and other nonrenewable resources. By harnessing the power of the sun, we can create energy security and independence, especially in remote or off-grid locations where traditional sources of energy may not be available.

Despite these benefits, there are some challenges associated with solar energy. One of the biggest challenges is the cost of installation and maintenance of solar panels and other solar power systems. While the cost of solar power has been declining in recent years, it can still be expensive to install and maintain solar panels, especially for individual homeowners and small businesses.

Another challenge is the intermittent nature of solar power. Solar panels only generate electricity when the sun is shining, which means that they cannot provide a constant and reliable source of energy. This issue can be addressed through the use of energy storage systems, such as batteries, which can store excess energy generated by solar panels for use when the sun is not shining.

Despite these challenges, the future of solar energy looks bright. Many countries around the world are investing heavily in solar power, and technological advancements are making solar energy more efficient and cost-effective. Some experts predict that solar power could become the dominant source of energy in the coming decades, potentially displacing fossil fuels and other nonrenewable sources of energy.

In addition to large-scale solar power projects, there are also many opportunities for individual homeowners and small businesses to benefit from solar energy. Rooftop solar panels are becoming increasingly popular, as they can help to offset electricity bills and reduce reliance on traditional sources.

Solar energy efficiency refers to the amount of energy that is generated by a solar power system relative to the amount of sunlight that falls on the solar panels. Solar energy efficiency is affected by various factors such as the quality and design of the solar panels, the temperature and weather conditions, and the orientation and angle of the solar panels.

I.3.6.1. Efficiently of solar panels

The efficiency of solar panels is typically measured by their conversion efficiency, which is the percentage of sunlight that is converted into usable electricity. The conversion efficiency of solar panels can range from around 15% to over 20%, depending on the quality and design of the panels. However, it's worth noting that the overall efficiency of a solar power system can also be influenced by other factors, such as the efficiency of the inverter used to convert the DC electricity generated by the solar panels into usable AC electricity.

Improvements in solar panel technology and manufacturing processes have led to significant increases in solar energy efficiency in recent years. Additionally, advancements in energy storage technology have made it possible to store excess solar energy for use when the sun isn't shining, which can further improve the overall efficiency and effectiveness of solar power systems.

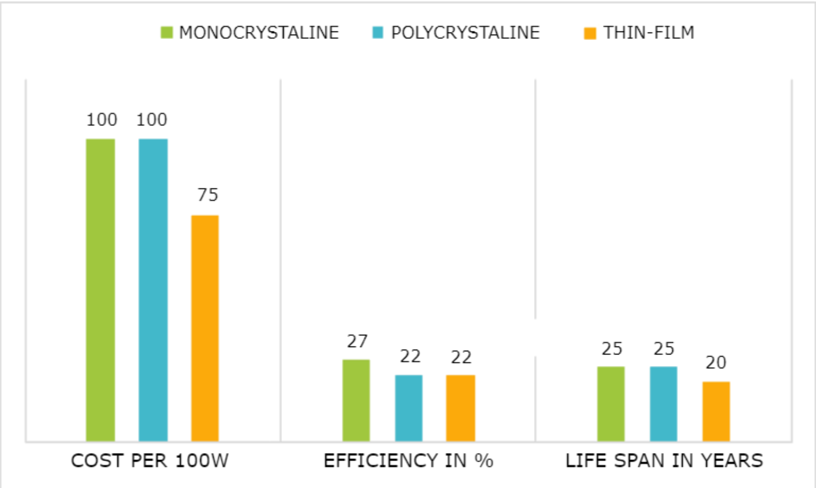

Figure I.13: diagram of efficient solar panels in 2023.[17]

I.3.6.2. Yield

Solar energy yield refers to the amount of energy that a solar power system can produce over a given period of time. The yield of solar energy is affected by a number of factors, including the amount of sunlight the system receives, the efficiency of the solar panels, and the operating conditions of the system.

The amount of sunlight a solar power system receives is affected by factors such as the latitude and climate of the location where the system is installed, as well as any shading that may be present. The efficiency of the solar panels is affected by the quality of the panels, the temperature of the panels, and the angle at which they are installed.

The operating conditions of the system are also important in determining the solar energy yield. Factors such as the cleanliness of the panels, the type and quality of the inverter used to convert the DC power generated by the panels to AC power for use in homes and businesses, and the maintenance of the system all play a role in determining the amount of energy that can be generated.

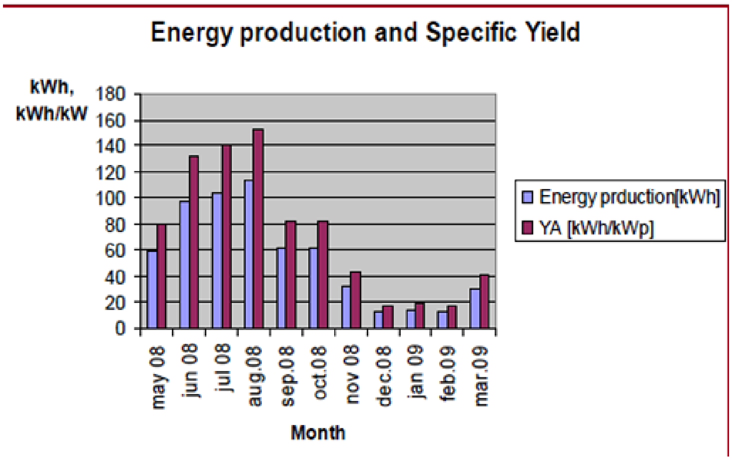

Figure I.14: How the yield of the solar power plant is defined.[18]

Overall, the solar energy yield of a system can vary widely depending on these factors. Awell-designed and maintained system in a location with high levels of sunlight can generate a significant amount of energy, while a poorly designed or maintained system in a location with low levels of sunlight may generate very little energy.

I.3.6.3. Cleaning

Cleaning is the process of removing dirt, dust, stains, and other unwanted substances from surfaces or objects to maintain cleanliness and hygiene. It can involve various methods and techniques depending on the type of surface or object being cleaned, as well as the nature and extent of the dirt or stains.

Cleaning can be performed in various settings, including homes, offices, public places, hospitals, schools, and industrial facilities. Some common cleaning tasks include dusting, vacuuming, sweeping, mopping, wiping, scrubbing, and disinfecting. Effective cleaning not only helps to keep surfaces and objects clean and hygienic but also helps to prevent the spread of germs and infections, reduce allergens and irritants, and improve indoor air quality. Regular cleaning is essential for maintaining a healthy and safe environment.

Figure I.15: workman cleaning.[19]

Figure I.16: solar panels Robotic cleaning.[20]

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I.3.6.4. Advantages of Solar Energy:

1. Renewable: Solar energy is a renewable source of energy. The sun provides an unlimited supply of energy, and it will continue to do so for billions of years.
2. Cost-effective: Once installed, solar panels require very little maintenance and can generate electricity for years. The cost of solar panels has decreased significantly in recent years, making solar energy more affordable for many people.
3. Environmentally friendly: Solar energy is a clean and green source of energy. It does not produce any harmful emissions or pollutants, unlike fossil fuels.
4. Reduces electricity bills: Solar energy can help reduce your electricity bills, especially if you live in a sunny area. You can generate your own electricity and

use it to power your home or business.

5. Increases property value: Installing solar panels on your property can increase its value. Solar energy is an attractive feature for homebuyers and can make your property more attractive to potential buyers.

I.3.6.5.Disadvantages of Solar Energy

1. Weather-dependent: Solar energy production is dependent on the weather. It is most efficient when the sun is shining, which means it may not be a reliable source of energy in areas with cloudy or rainy weather.
2. High upfront costs: The installation cost of solar panels can be high, and it may take several years to recoup your investment. This can be a barrier for some people, especially those on a tight budget.
3. Land use: Solar panels require a lot of space to be installed, which can be a problem in densely populated areas. They can also affect wildlife and ecosystems if installed in sensitive areas.
4. Energy storage: Solar energy can only be generated during the day, which means it cannot be used at night. Energy storage solutions such as batteries can be expensive and may not be practical for some people.
5. Production of solar panels: The production of solar panels requires the use of rare earth metals, which can have environmental impacts. The production process also requires energy, which can produce carbon emissions.

There are several proposed solutions to remove deposits in solar panels, including:

- Regular Cleaning: Regular cleaning of solar panels can prevent the buildup of deposits on the surface of the panels. This can be done using a soft brush or a non-abrasive sponge with a mild detergent and water.
- Coating: Coating the surface of the solar panels with a hydrophobic coating can prevent the accumulation of dirt and other debris on the surface. The coating can also improve the efficiency of the solar panel by increasing the amount of sunlight it can absorb.
- Self-Cleaning Panels: There are some manufacturers who are developing self-cleaning solar panels that use a technology called photovoltaic cleaning (PVC). This technology uses a special coating that reacts with sunlight to break down any organic material on the surface of the panel.
- Anti-Soiling Technology: Anti-soiling technology involves the use of materials that

are resistant to the accumulation of dirt and other debris on the surface of the solar panel. This technology can be applied to the surface of the solar panel to prevent the buildup of deposits.

- Automated Cleaning Systems: Automated cleaning systems can be installed to clean the solar panels periodically. These systems use a combination of brushes, water, and detergents to clean the panels without damaging them.

Among these advanced methods is the idea of cleaning without using water.
And this by electric curtain and electrostatic induction electrode.

Conclusion:

In this chapter, we have discussed everything related to renewable energies, their definition, types, characteristics of each one, in addition to the pros and cons of some of them. Other than that, the efficiency and efficiency of solar energy are both mentioned. Also, the difficulties facing the panels in cleaning.

And trying to find a solution New and different from everything that preceded it, which is represented by cleaning by the electric curtain and electrostatic induction electrode. This is what we will talk about in the next chapter

Chapter II

Electrostatic methods for particles removal

Chapter II: Electrostatic methods for particles removal

II.1. Introduction

In this chapter, two electrostatic potential solutions will be discussed for particle removal. First, the electric curtain as an early developed solution will be presented along with its efficiency. Secondly, electrostatic induction as a simple and more convenient solution to clean surfaces, especially PV panels. The concept and the characteristics of the two solutions are presented and detailed in this chapter.

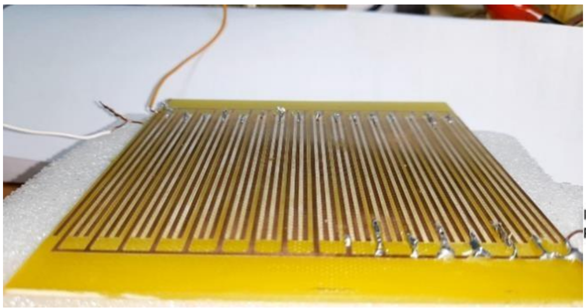
II.2. An overview of static electricity

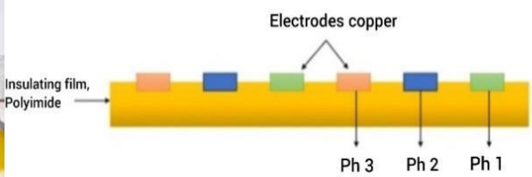
Static electricity is a fascinating phenomenon that involves the accumulation and imbalance of electric charges on the surface of objects. It occurs when there is a transfer of electrons between materials, resulting in a buildup of positive or negative charges. Static electricity can be generated through various means, such as friction, contact, or separation of materials. Besides, dielectric objects can acquire an electric charge if they are exposed to a corona discharge or an electron beam. When objects with opposite charges come into proximity, they can attract each other, while objects with similar charges repel each other. Static electricity can cause objects to stick together, produce sparks, or give individuals an electric shock. It plays a significant role in our daily lives from the shocks we experience after walking on carpets to the way our clothes cling together in the dryer. Understanding static electricity is crucial in industries such as electronics, where it can damage sensitive components, and in safety measures to prevent fire hazards caused by electrostatic discharge.

II.3. Electric curtain

An electrostatic curtain is a remarkable technological innovation that serves as a barrier using the principles of electrostatics. It is designed to create an invisible shield or forcefield, effectively repelling or redirecting airborne particles, dust, pollutants, and even insects. This cutting-edge system harnesses the power of electric charges to create a high-voltage field, which generates an electrostatic force. The curtain consists of a series of electrodes that create an intense electrostatic field. As objects or particles approach the curtain, they experience the repulsive force of the electric charges, effectively preventing them from passing through. The electric curtain technique has been proposed by NASA as an effective active method for dust removal from solar panels in planetary and lunar exploration, and this method also has potential for mitigating dust accumulation on solar panels. The electrostatic method is a technique to move and transport charged particles using an alternating non-uniform electrostatic field (ANEF). This method was initially proposed by Tatom et al [21] for cleaning lunar dust, and later proven by Masuda et al,who designed an electric curtain (EC) consisting of parallel electrodes to confine and transport charged particles. The EC can be single-phase or polyphase type depending on the type of AC voltage applied. Dielectrophoretic and Coulomb forces are the primary forces used to move the particles [22]. This electrostatic method has been successfully tested for simulated Martian and lunar conditions and the lunar low gravity condition. The travelling-wave electrostatic field (TEF) is suggested to be more effective for particle directed transport compared to the standing- wave type, with high voltage amplitude and low frequency being generally preferred [23].

The electrostatic curtain's key characteristics include its transparency, versatility, and non- contact nature. Its transparency allows for unobstructed visibility, making it suitable for various applications, from clean rooms and laboratories to residential and commercial spaces. Furthermore, this technology does not require physical contact with the objects it interacts with, minimizing wear and tear while maintaining a high level of effectiveness.





(a) **(b)**

Figure II. 1: (a) picture of a three-phase electric curtain, and **(b)** schematic representation.

II.3.1. Electric curtains classification

Electrostatic curtains can be classified based on the number of phases they use. The series of electrodes in the curtain can be divided into several configurations:

- Biphasic curtains that use two interleaved combs and are powered by periodic voltages with a phase shift of π.
- Triphasic curtains that have three interleaved electrode series, with each connected to a periodic voltage source with a phase shift of 2π/3.

- 4-phase curtains that use a network of electrodes with four interleaved series (combs) and are powered by voltage sources with a phase shift of π/2.

II.3.2. Multi-phase electric curtain

A multi-phase electric curtain can be energized by more than one phase voltage. The number of phases will define the created electric wave behavior above the surface of the curtain. A double phase system will generate a standing wave or pulsatory wave type. Beyond two phases, a travelling wave in one direction will appear on the surface. So, depending on the number of used phases, an electric curtain is either a standing-wave or a traveling wave type. Figure (II.2) shows an example of a travelling wave electric curtain for particle removal using a four-phases system.

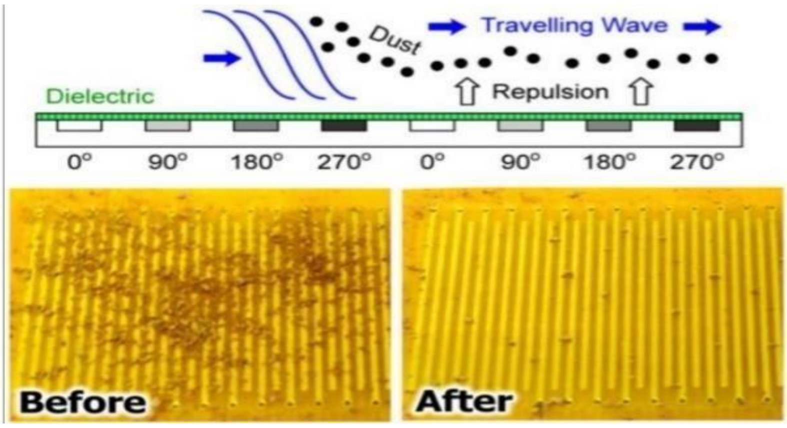


Figure II. 2: (top) Illustration of the electric curtain using four sequentially phase shifted signals at the same frequency applied to successive electrodes in an array. (bottom) Experimental results showing the initial and final dust distribution after the application of a 600 V, 50 Hz signal.[23]

II.3.3. Standing Waves Electric Field

Standing waves are formed when two identical waves propagate in opposite directions and interfere with each other. The result is a wave that appears to be standing still, with nodes and antinodes that remain stationary. In a standing wave electric field, the displacement of the electric field is at a maximum at the antinodes and zero at the nodes. This means that the electric field oscillates back and forth within a fixed space. The standing wave curtain is equivalent to mono-phase electric motor.

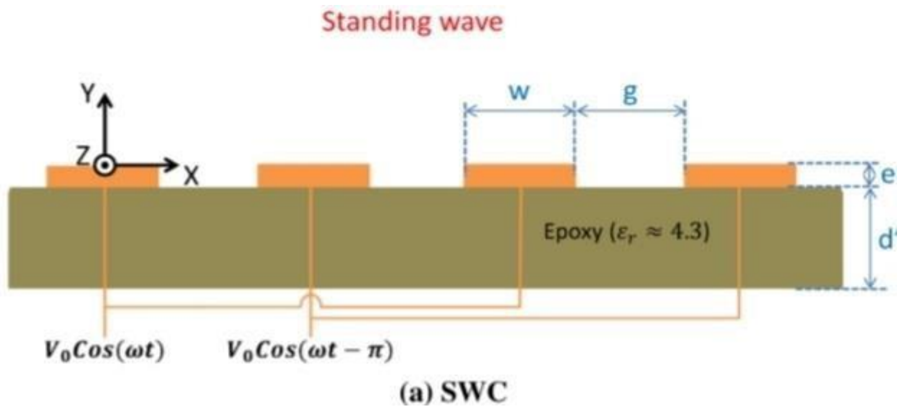


Figure II. 3: Cross section of the electric curtain-standing wave angle. [24]

II.3.4. Traveling Waves Electric Field

In a traveling wave electric field, the displacement of the electric field moving in a specific direction, carrying energy with it. This means that the electric field propagates through space, rather than remaining stationary like a standing wave. The configuration of a traveling wave curtain is exactly the same as a linear three phase electric motor, except that electric field is moving instead of the magnetic field.

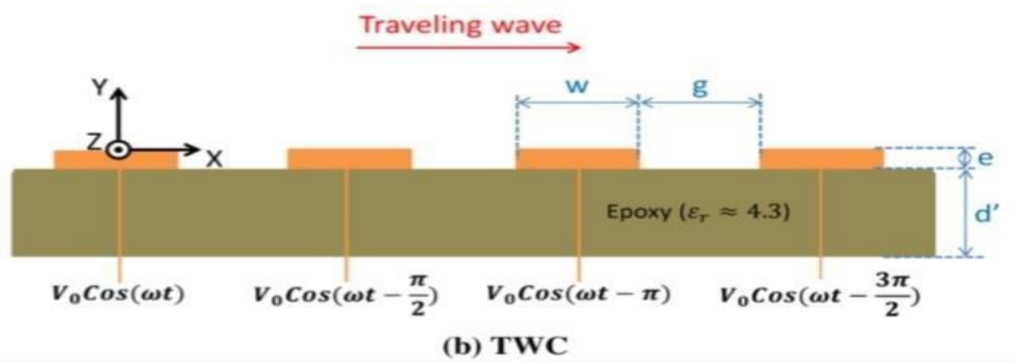


Figure II. 4: Cross section of the electric curtain-traveling wave angle. [24].

II.3.5. The difference between traveling and standing wave electric curtains (directionality and efficiency)

The electric potential's spatial waveform for a traveling wave curtain can be decomposed into two primary sinusoidal waves, with different amplitudes and frequencies, propagating in opposing directions. Conversely, for a standing wave curtain, both waves possess the same amplitude and frequency as the supply voltage. Compared to standing waves, traveling waves have a higher total efficiency figure (II.5). Symmetry of the configuration yields similar displacement efficiencies in both directions for standing waves. In contrast, displacement efficiency tends to be higher in the forward direction for traveling waves, transporting most particles in the direction of wave propagation. However, certain factors such as low voltage, large particles, and a specific frequency range can cause particle transport in the opposite direction. This behavior is likely due to harmonics of the electric potential that can travel in reverse.

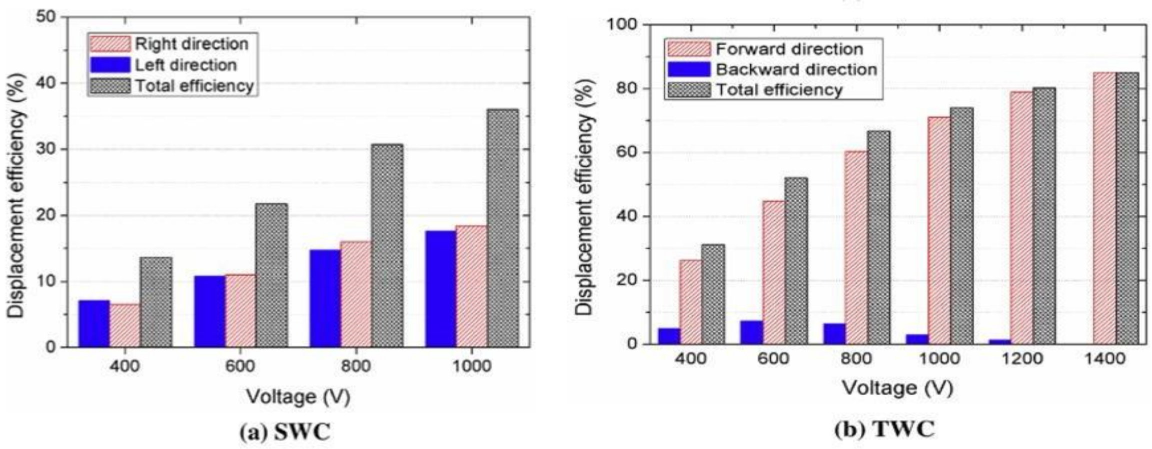


Figure II. 5: Evolution of the particles displacement efficiency as a function of the applied voltage value for (a) SWC and (b) TWC. [24]

II.3.6. The application of three-phase electric curtain on solar panels

Solar panels are an important source of renewable energy, but they require regular maintenance to maintain their efficiency. One solution to this problem is the use of electrostatic curtains three-phase technology. This technology uses electric fields to create a cleaning effect on solar panels, removing dirt, dust, and other debris that can accumulate over time. This device called an electrodynamic screen (EDS).

II.3.7. EDS technology for electric curtains

Electrodynamic screen technology (EDS) uses electrostatic forces to remove dust particles from optical surfaces, which offers a potential solution for reducing the costs and environmental impacts associated with water-based cleaning methods.

EDS consists of parallel electrodes deposited on a substrate and embedded in a thin transparent dielectric film. When a low frequency and high three-phase pulse voltage is applied to the electrodes, the dust particles on the EDS surface are charged and repelled by the electrostatic force, which is predominantly the Coulomb force. However, the distribution of the electric field generated by the EDS is not uniform, which can result in the accumulation of charged or neutral dust particles experiencing dielectrophoretic forces (DEP). Therefore, it is important to understand the influential parameters in the distribution of the electric field, such as the width of the electrodes, the spacing inter-electrodes, the thickness, and the relative permittivity of the dielectric coating.

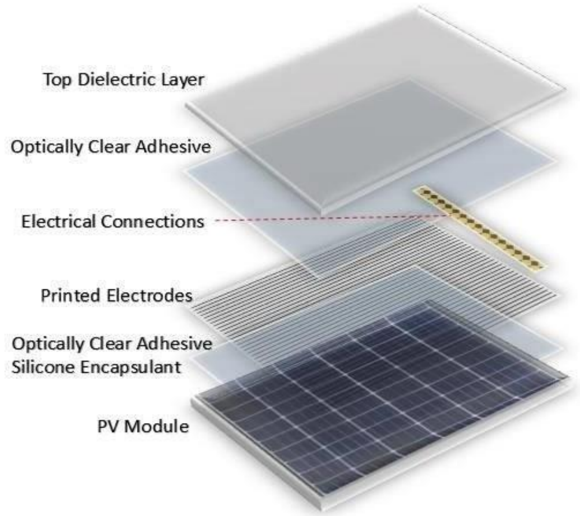


Figure II. 6: EDS film on small a solar panel.[25]

II.3.8. The mechanism of an electrostatic electric curtain

The mechanism of an electrostatic electric curtain is based on the principles of electrostatic charge and repulsion. The curtain comprises a series of electrodes strategically placed to create an intense electrostatic field. Each electrode is charged either positively or negatively, generating a strong electric potential difference. When powered, this potential difference creates an electric field that extends across the curtain's designated area. As airborne particles, dust, or other objects approach the curtain, they come into contact with the electric field. Due to the repulsive nature of like charges, the particles are immediately repelled away from the curtain, unable to pass through. The electrostatic field acts as an invisible barrier, redirecting or preventing the movement of unwanted objects.

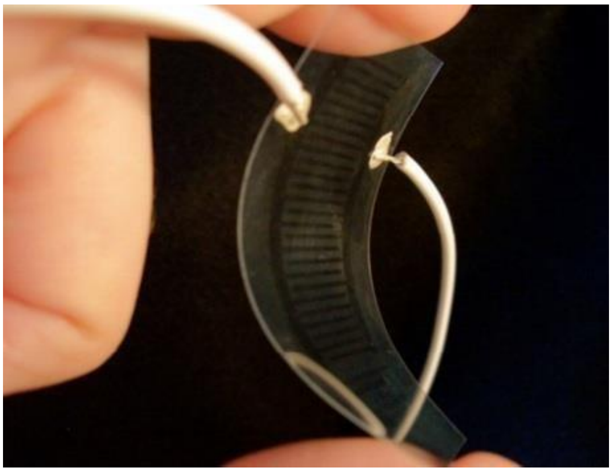


Figure II. 7: Electrodynamic Dust Shield (EDS) with transparent indium tin oxide parallel electrode.[27]

II.3.9. Benefits of using electrostatic electric curtains three-phase for solar panel cleaning

Using electric curtains with three-phase technology for solar panel cleaning offers several benefits. First, it is a highly efficient method of cleaning, as it can remove even the smallest particles from the surface of the panels (Figure II.8). Additionally, this technology is environmentally friendly, as it does not require the use of harsh chemicals or detergents that can harm the environment. Finally, it is a cost-effective solution, as it requires minimal maintenance and can extend the lifespan of solar panels, reducing the need for costly replacements. Using this technology allows for water savings by avoiding the use of water in washing surfaces.

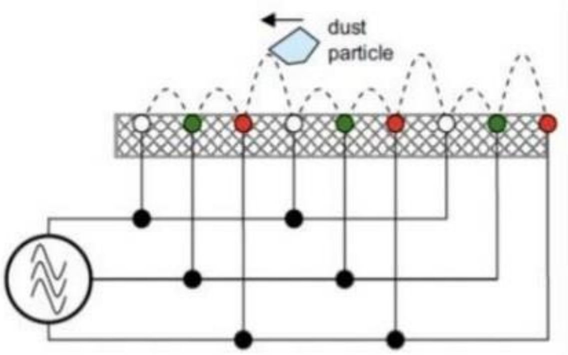


Figure II. 8: Dust particle motion on a three phase EDS[24].

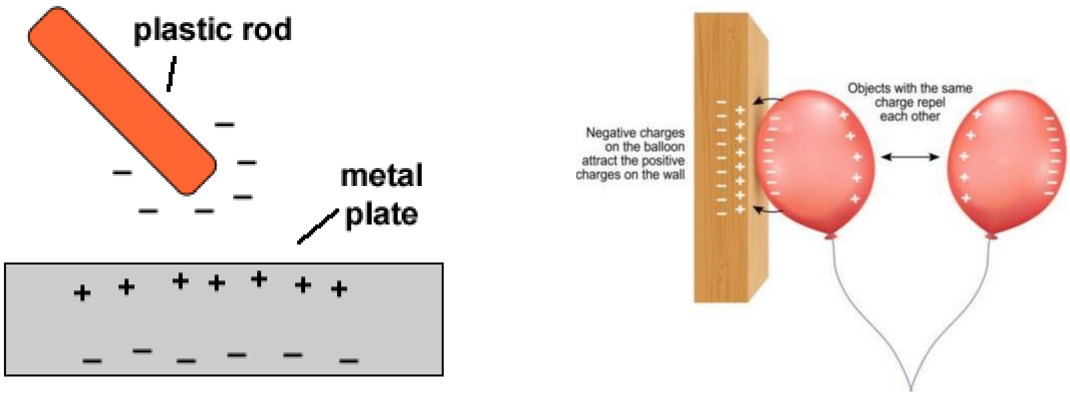
II.4. Electrostatic induction electrode

II.4.1 Mechanism of Electrostatic Induction

The mechanism of operation of electrostatic induction involves the interaction between the charged object and the conductor. When a charged object is brought close to a conductor, the charges in the conductor redistribute themselves to minimize the electric potential energy.

a) **Charging by Contact:** If the charged object comes into direct contact with the conductor, the charges transfer between them until they reach an equilibrium. The conductor acquires the same charge as the charged object through this process.

b) **Charging by Proximity:** When the charged object is brought near, but not in contact with, the conductor, the charges within the conductor redistribute themselves due to the influence of the electric field created by the charged object. This redistribution results in an excess of charges of the opposite sign near the charged object and an equal deficiency of charges of the same sign on the far side of the conductor (Figure II.11).



(a) **(b)**

Figure II. 9: (a) Picture showing how an electrostatic induction electrode gains charge, and **(b)** forces between charged objects.[28]

Electrostatic induction finds numerous applications in various fields. It plays a crucial role in the operation of many electronic devices, such as capacitors and transistors. It is also utilized in technologies like electrostatic painting, where charged particles are attracted to a surface to create a desired coating. Understanding electrostatic induction is essential not only for the practical applications it offers but also for comprehending the fundamental behavior of electric charges and fields. By studying this phenomenon, scientists and engineers gain insights into the nature of electricity and develop innovative solutions to technological challenges.

The induction by proximity is an interesting situation, as it allows particles charging and manipulation without any contact. The amount of induced charge depends on the distance, size and shape of the objects in the proximity. In fact, the charge is the results of capacitance formed by the two objects (Figure II.12). In this case, the induced charge is:

$$Q = C.V$$

Where C is the formed capacitance and V is the potential difference between the objects.

The capacitance C takes into account the geometrical aspects of the two objects.

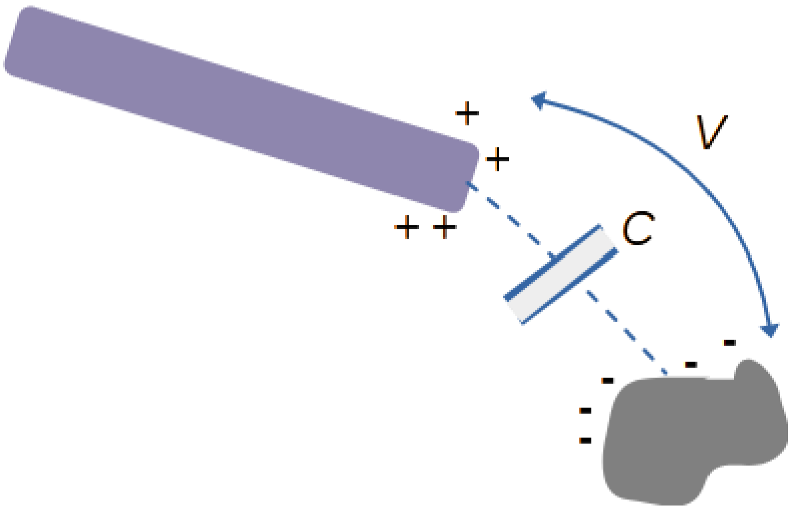


Figure II. 10: Formed capacity between objects defines the induced charge quantity

II.4.2. A description of Electrostatic Induction Electrode

The two electrostatic induction electrodes used during experiments are shown on figure II.13. They consist of a copper rode (cylinder) electrode of 2 cm diameter and a metallic plate of 10 cm x 8cm.

(a) **(b)**

Figure II. 11: Photo of the electric induction electrodes **(a)** copper cylinder and **(b)** metallic plate.

II.4.3. Factors Involved in Electrostatic Induction

Several factors influence the magnitude and direction of the induced charges during electrostatic induction. These factors include the distance between the charged object and the conductor, the magnitude and sign of the charge on the object, and the presence of other nearby conductive or non-conductive objects.

Distance: The closer the charged object is to the conductor, the stronger the electric field and, consequently, the greater the induced charges. As the distance increases, the strength of the induced charges decreases.

Charge magnitude and sign: The magnitude and sign of the charge on the object significantly affect the electrostatic induction. An object with a larger charge will induce a greater charge separation in the conductor, whereas an object with an opposite charge sign induces charges of the opposite sign in the conductor.

Presence of nearby objects: The presence of other conductive or non-conductive objects near the charged object and the conductor can influence the distribution of induced charges. Conductive objects can provide alternative paths for charge redistribution, while non- conductive objects can alter the electric field distribution.

Conclusion

In conclusion, the electrostatic curtain and the electrostatic induction electrode are critical elements in effective solar panel cleaning and maintenance. Their ability to repel and capture dust and debris, combined with a non-invasive cleaning approach, not only increases energy production, but also contributes to a sustainable future. By harnessing the power of these technologies, we can ensure the continued growth and widespread adoption of solar energy. The results of these two electrostatic methods will be presented in the next chapter

Chapter III

Materials and methods

III.1. Introduction

There are many ways to clean solar panels with water, but they are expensive, require huge amounts of water, and do not last for long periods. The aim of this chapter is to show the possibility and preference of cleaning these panels without resorting to the use of water and taking into account the preservation of their quality and quantity of production, depending on the application of high voltage in three different ways. We will list all the hardware and tools we used in each installation with explanation of how it works.

III.2. Cleaning with electric curtain

III.2.1. Appliances and used tools

- Figure III.1: Electric curtain three phase (10cm/10cm,1mm for each copper line)
- Figure III.2: High impact polystyrene pellets (HIPS).
- Figure III.3: Acrylonitrile Butadiene granules (ABS).
- Figure III.4: Three high voltage transformers 50 Hz (220v /~2500V).

Figure III. 1: Electric curtain tree-phase

Figure III. 2: HIPS and ABS

Figure III. 3: Three microwave transformers

Figure III. 4: Voltage source

III.2.2. Types of particles used in this experiment

a) <u>Acrylonitrile Butadiene Styrene (ABS)</u>

Acrylonitrile butadiene styrene (ABS) is an amorphous polymer made by emulsionor bulk polymerization of acrylonitrile and styrene in the presence of polybutadiene. The most important properties of ABS are impact resistance, hardness and a good rigidity. ABS is characterized by its good resistance to thermal deformation and to shocks even at low temperatures. It is hard, abrasion resistant and has good dimensional stability.

ABS resins represent one of the most valuable mixtures of resin and elastomer.Their success is due to the excellent properties resulting from this alliance. Their fundamental properties being toughness, impact resistance and surface hardness, they are mainly used in the manufacture of furniture, elements for industry automotive, TV chassis, panels and others.

(a) (b)

Figure III. 5 (a): Acrylonitrile Butadiene Styrene (ABS), (**b):**High Impact Polystyrene(HIPS)

b) <u>High Impact Polystyrene (HIPS)</u>

HIPS belongs to the family of high-density compacted polystyrene, it is low cost easy to machine, it is often specified for structural applications of low strength when impact resistance, machin ability, and low cost are required. Heis frequently used for machining pre- production prototypes, as it has excellent dimensionally stable and easy to fabricate. It is generally used for devices household, electrical and electronic components.

III.2.3. Particle charging method

Tribo-electricity is used as mechanism to charge particles. For that purpose, several methods can be used among them the fluidized bed apparatus, specifically designed for charging insulating granular mixtures with millimeter-sized particles. A variable speed blower supplies fluidizing air, while an air diffuser, positioned at the bottom of the chamber, ensures uniform fluidization of the particles. To prevent granules from escaping, a filter is installed at the upper end of the chamber. Within the cylindrical polyethylene terephthalate-PET chamber (100 mm in diameter and 450 mm in length), the particles undergo fluidization induced by the air and acquire opposite electrical charges through contact. As the air velocity increases, particle vibration becomes more pronounced. The chamber features transparent walls, facilitating visual observation of the tribo-charging process.

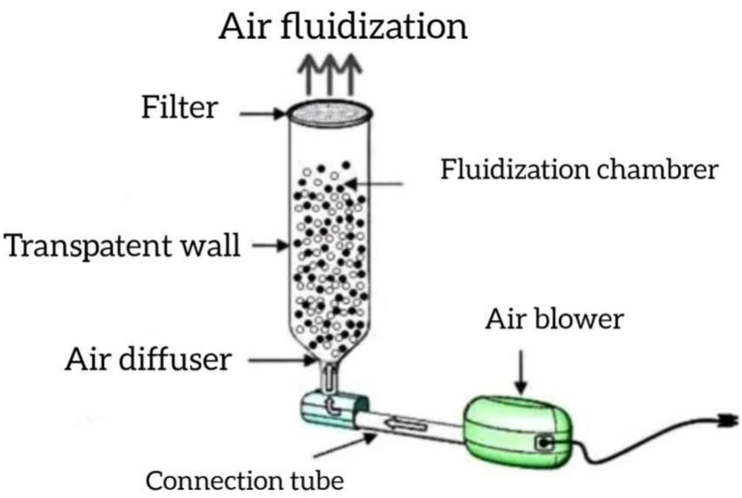


Figure III. 6: Fluidized-bed device for the tribo-charging of plastic granules.

In this work, a vibration method is used instead of the fluidized bed, mainly because it is easily realized (Figure III.5).

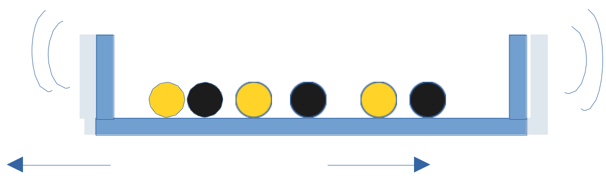
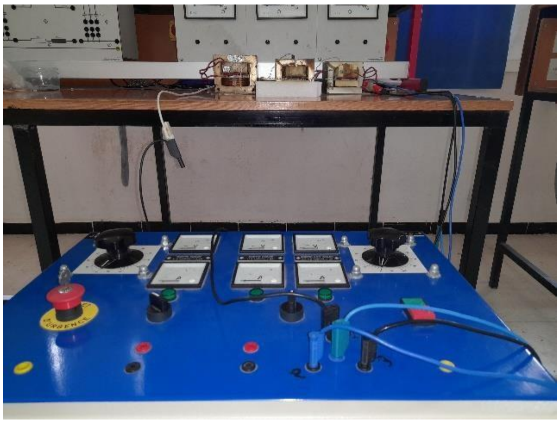


Figure III. 7: Tribo-charging of particles using vibrational device

III.2.4. Connecting and installing devices

In our setup, three high voltage transformers, each with dual inputs and outputs, are used. First, we pair these transformers triangularly at the inputs (we take an input from each transformer), and then we connect the remaining inputs to the voltage source as shown in the Figure(a);(b).

After that, we connect each outlet and its part to the three-phase curtain (we automatically choose one of the outlets). This is for installation and connection.



(a) **(b)**

Figure III. 8 (a);(b): Experimental setup of travelling wave curtain

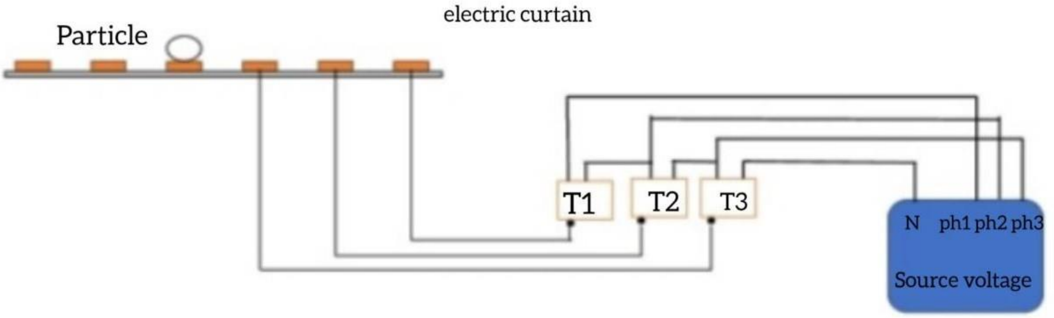


Figure III. 9: Schematic representation of our experiment

After verifying the installation and setting the electrical protection standards, we turn on the voltage source and try to gradually raise the voltage to several values, taking into account the maximum value of the inputs of the transformers. Then we notice whether there is a change in the movement of the particles on the surface of the electric curtain or not.

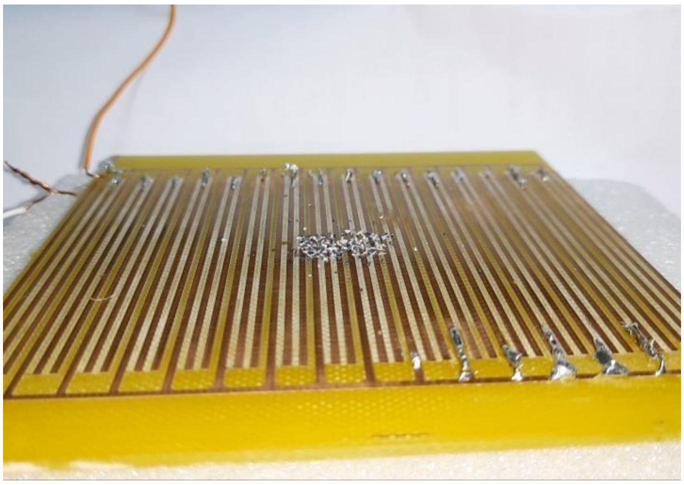


Figure III. 10:an electric curtain with some particles on it

III.2.5. The used Oscilloscope

An oscilloscope is a versatile electronic instrument used in various fields such as electronics, telecommunications, and research to visually display and analyze electrical waveforms. It captures and graphically represents voltage signals over time, allowing engineers, technicians, and scientists to observe and measure characteristics such as amplitude, frequency, phase, and distortion. With its high-speed sampling rate, it can capture fast-changing signals, helping in troubleshooting and debugging electronic circuits, validating signal integrity, and verifying the performance of electronic devices. By providing a visual representation of electrical signals, an oscilloscope aids in waveform analysis, signal characterization, and waveform generation, making it an indispensable tool for a wide range of applications in the electrical and electronic domains.

Figure III. 11:GW-Instek 2204A oscilloscope device.

III.3. Induction type cleaning device

III.3.1. Appliances and tools used

- Metal plate (length=13cm; width=9cm; Height=2mm).
- Copper tube (length=13cm;diameter=2cm)
- Glass plate (length=30cm; width=13cm; Height=2mm).
- Positive High voltage source.
- Amount of desert sand.
- Ground wire.

Figure III. 12: Copper tube

Figure III. 13: Metal plate

Figure III. 14: Positive High voltage source

Figure III. 15: Amount of desert sand.

III.3.2. Experiment details

a. Metal plate electrode

We connected the metal plate to the positive high voltage source, then a quantity of sand is spread on a glass placed over a grounded plate.The grounded plate and the sand polluted glass are displaced under the metal plate so that sand particles are attracted by induction. Consequently, we gradually raise the values of the high voltage at the same time the glass plate moves from left to right. And the changes that occur during this process are presented in the last chapter.

Figure III. 16:photograph of a vertical section metal plate experiment

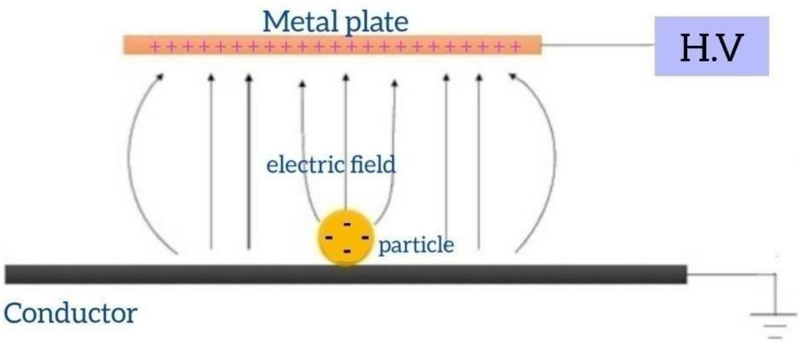


Figure III. 17: Schematic representation of metal plate and induction mechanism

b. Copper tube electrode

The metal plate is replaced by a copper tube of 2 cm diameter (Figure III.17) and carried the same experiments. We repeat the same process again and notice the difference between the plate and tube. The aim is to determine the appropriate shape and metal for this process.

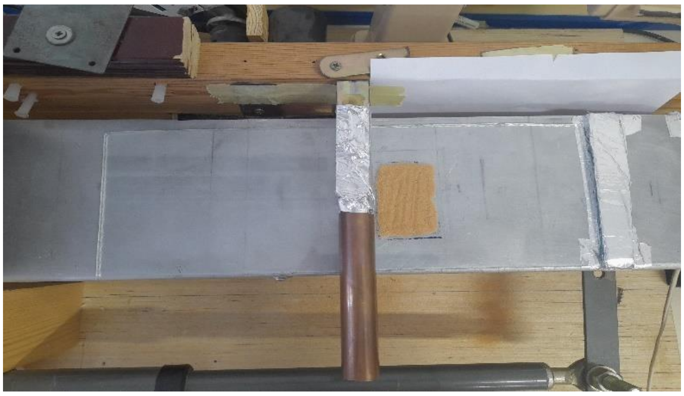


Figure III. 18: An overview image of the copper tube experiment

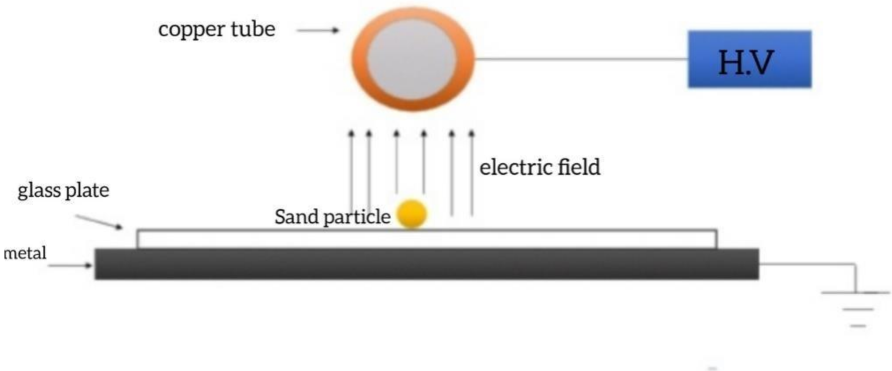


Figure III. 19: Schematic representation of horizontal section of a copper tube experiment.

Conclusion

This chapter is devoted to the description of tools and cleaning methods using electrostatic procedures, namely electric curtain and electric induction. A detailed description is given for each method along with used equipment. Two electric induction electrodes were described in view to choose the most efficient configuration.

Chapter IV

Expremental results and discussion

Chapter IV: Experimental results and discussion

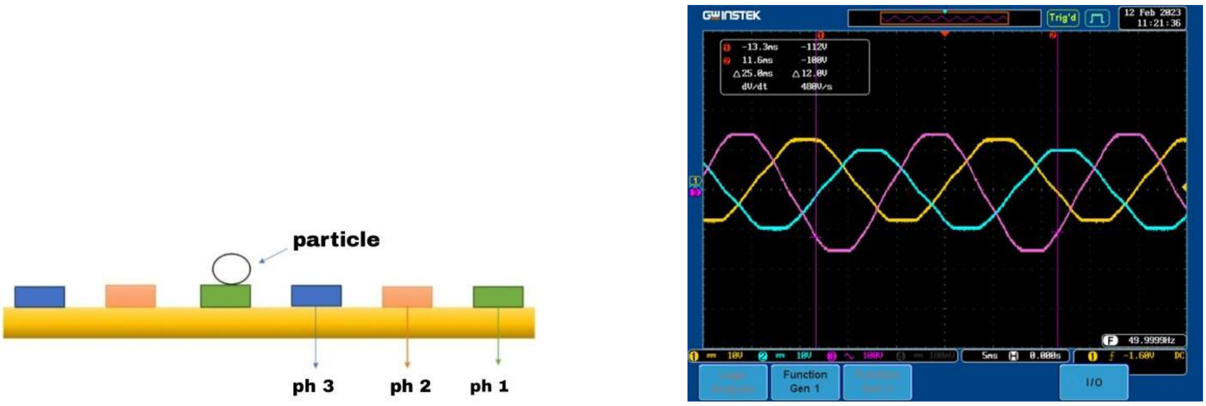
IV.1. Introduction

This chapter includes the experimental results of electro-cleaning system using the described methods in the previous chapter, namely electric curtain and electrostatic induction. The results include particles movement and behavior but also the efficiency of the electrostatic induction in surface cleaning.

Particle removal using an electric curtain

IV.1.1. Setup and voltage description

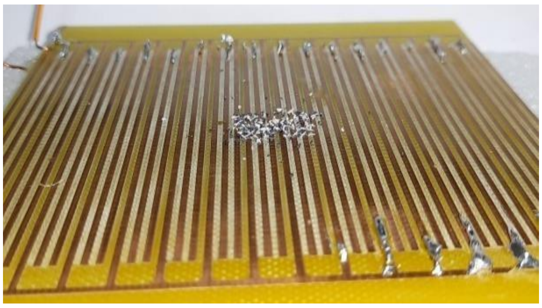
The experiments were realized for three-phase travelling wave electric curtain. The Figure (IV.1)shows a cross-sectional view on the x-y plane of a traveling wave conveyor configuration (three-phase configuration). The conveyors consist of multiple copper electrodes 1 mm wide and 35 µm thick, etched in parallel on a 10 cm × 10 cm dielectric surface. The space between the electrodes is fixed at 1 mm. The dielectric surface is epoxy resin reinforced with fiberglass (**ε_r = 4,3**).We call the geometric period**λ =6.** The applied three phase voltages visualized on the oscilloscope are shown on Figure IV.1.b. The high voltage three phase system is obtained by 50Hz three high voltage transformers of **1: 10** ratios.



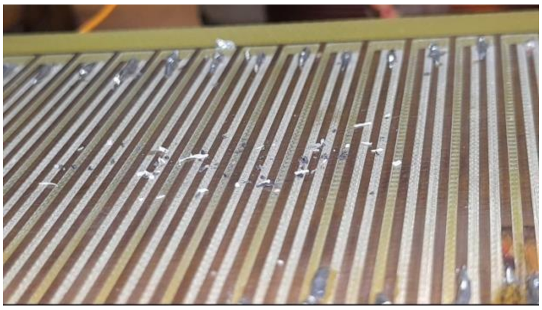
(a) (b)

Figure IV. 1: Traveling wave curtain setup (a) schematic description and (b) applied three-phase voltages.

The studied particles consist of High Impact PolyStyrene (HIPS) and Acrylonitrile ButadièneStyrene (ABS) materials of around 0.5mm to 1mm size. To check functionality of the realized curtain, a first series of experiments were carried out. The figure IV.2 shows the particles positions before and after voltage application. As can be seen, the particles are moved away from their initial positions leading to dispersion of the sample. This can be a sufficient argument for system functionality.



(a): before



(b): After

Figure IV. 2: Photographs of the particles deposited on the three-phase electric curtain before and after voltage application.

IV.1.2. Particle tracking

A particle tracking program is a powerful tool used in various scientific and engineering disciplines to analyze the movement and behavior of particles in a fluid or solid medium. It employs sophisticated algorithms and mathematical models to track the trajectories of individual particles over time, allowing researchers to gain insights into their motion patterns, interactions, and transport properties.

The program works by utilizing data from experimental observations or numerical simulations, extracting particle positions, velocities, and other relevant parameters, and then reconstructing their paths through the application of tracking algorithms. The importance of particle tracking programs lies in their ability to provide crucial information about fundamental processes in fields such as fluid dynamics, materials science, environmental science, and biophysics.

In our experiments, a custom developed python code in LGEG lab (Guelma university) is used (Figure IV.3). The code is based on computer vision algorithms to provide a tracking of a single particle position from a recorded video. The videos from a fixed camera are treated frame by frame to define the particle's position, and then afterward, successive points are connected to form the trajectory (Figure IV.4). The image treatment includes removal of unchanged or unmoving objects, which will be considered as a background, and the sharpening of the image through a filter to increase particle's border detection. The code algorithm is shown on figure IV.5.

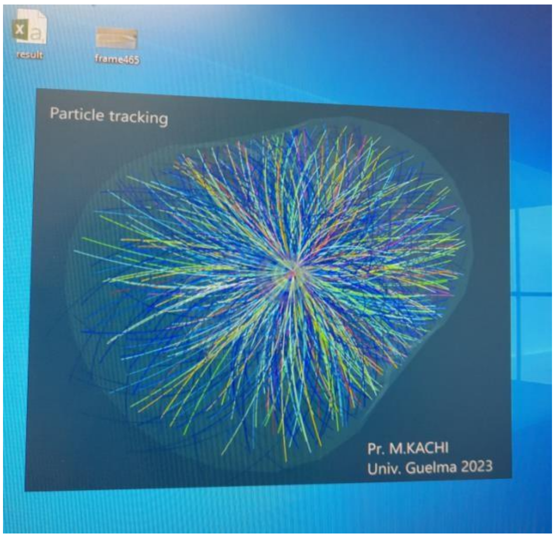
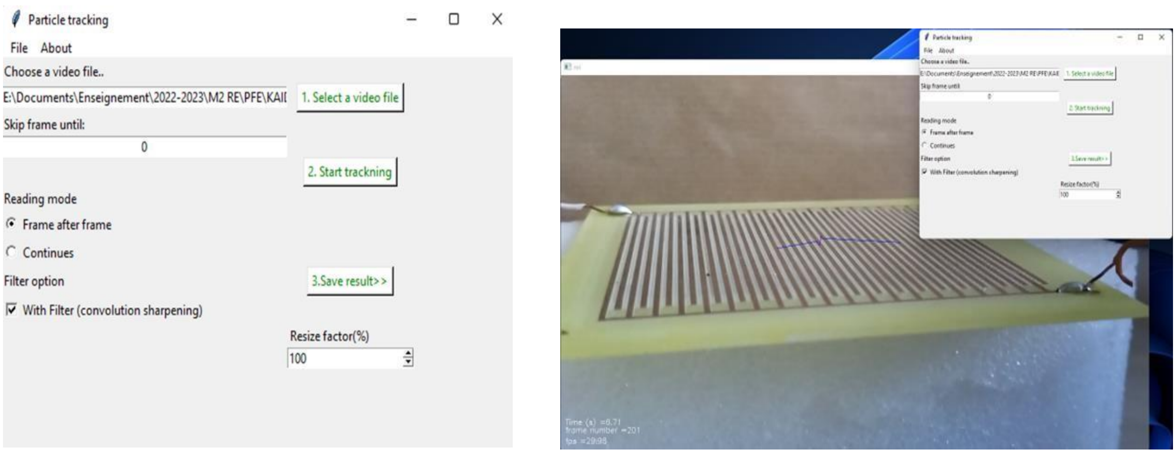


Figure IV. 3: Image showing particle tracking software.



(a) **(b)**

Figure IV. 4: (a) ProgramGui, and (b) pictures showing some of the stages of particle tracking by the software.

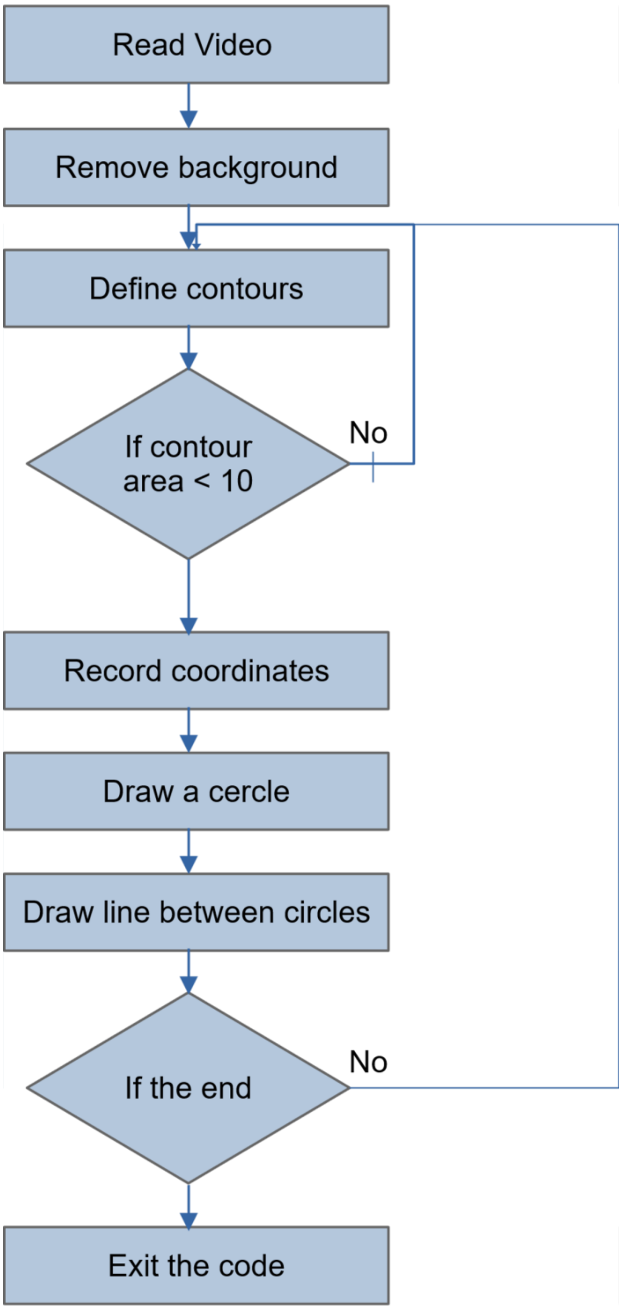
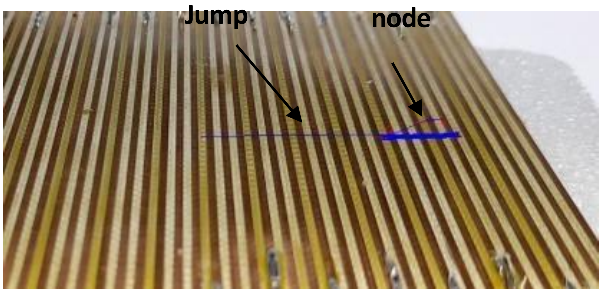
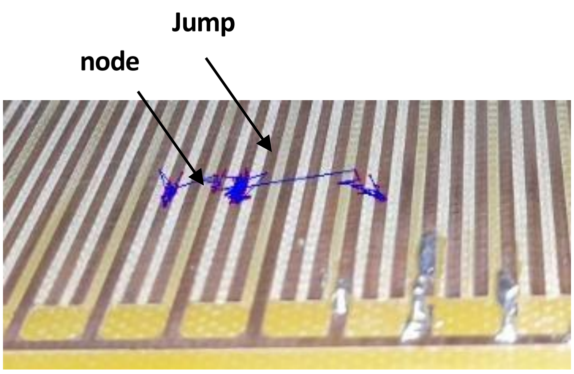


Figure IV. 5: Functional diagram for particle tracking software.

IV.2 Particle trajectory

The figure IV.6 shows the tracking results of a single particle on the surface of a traveling wave curtain starting from two different initial positions. Overall, the trajectory is formed by jumps segments over relatively high distance (in the order of centimeter distances), and nodes that represent vibration of the particle around the same position between two adjacent electrodes or over an electrode. As can be observed, the initial position plays an important role in the particle behavior and trajectory. Indeed, in the first case (Figure IV.6.a), particle jumps over longer distance and then carry a series of rolling and vibration movements. In the second case, the particle carries both jumping and rolling, or vibration. As consequence, the particle's movement is far from being uniform and is rather a quasi-random. The resulting trajectory form would be defined by the sum of the electric and non-electric forces exerted on the particle. Electric forces are mainly Coulomb force and dielectrophoretic force (resulting from field gradient), whereas, non-electric force include adhesion force or van der waals force and gravitational force. The former forces act on lifting and moving particle horizontally. The later forces, i.e non-electric forces, act on maintaining the particle on the surface. However, as the field gradient increases near the electrodes, the vertical component of the dielectrophoretic force also contribute to particle attraction towards the curtain surface. So, whenever forces are stronger, the particle is lifted, moved, or stuck to its position.





(a) (b)

Figure IV. 6: Particle's trajectory for two initial positions **(a)** position 1, and **(b)** position 2. Voltage 1000 V, 50 Hz.

IV.3 Particles removal and surface cleaning using electrostatic induction electrode

In this section, the results of experiments on surface cleaning using an induction type electrode are presented. During these experiments, a piece of glass, representing the PV panel, placed over a grounded metallic surface is passed beneath an energized metallic electrode. First, a particular region of the glass (bleu rectangle in the following figures) is covered by a quantity of sand. After that, the glass is passed under the high voltage (HV) electrode to be cleaned. To estimate cleaning efficiency, luminescence though glass is measured before and after passing the glass under the HV electrode. For comparison purpose, two form of metallic electrodes are studied, namely cylinder or a rode electrode and plate electrode.

IV.3.1. Plate electrode

After a single pass of the sand-containing glass under the high-voltage metal plate; we notice the crowding, overlapping, and collision of sand grains, trying to change their path and get out of the field of the electric field, due to the effect of the Coulomb force and the gravitational force. Figure (IV.7) shows different instants of glass cleaning using metallic HV plate captured from the above.

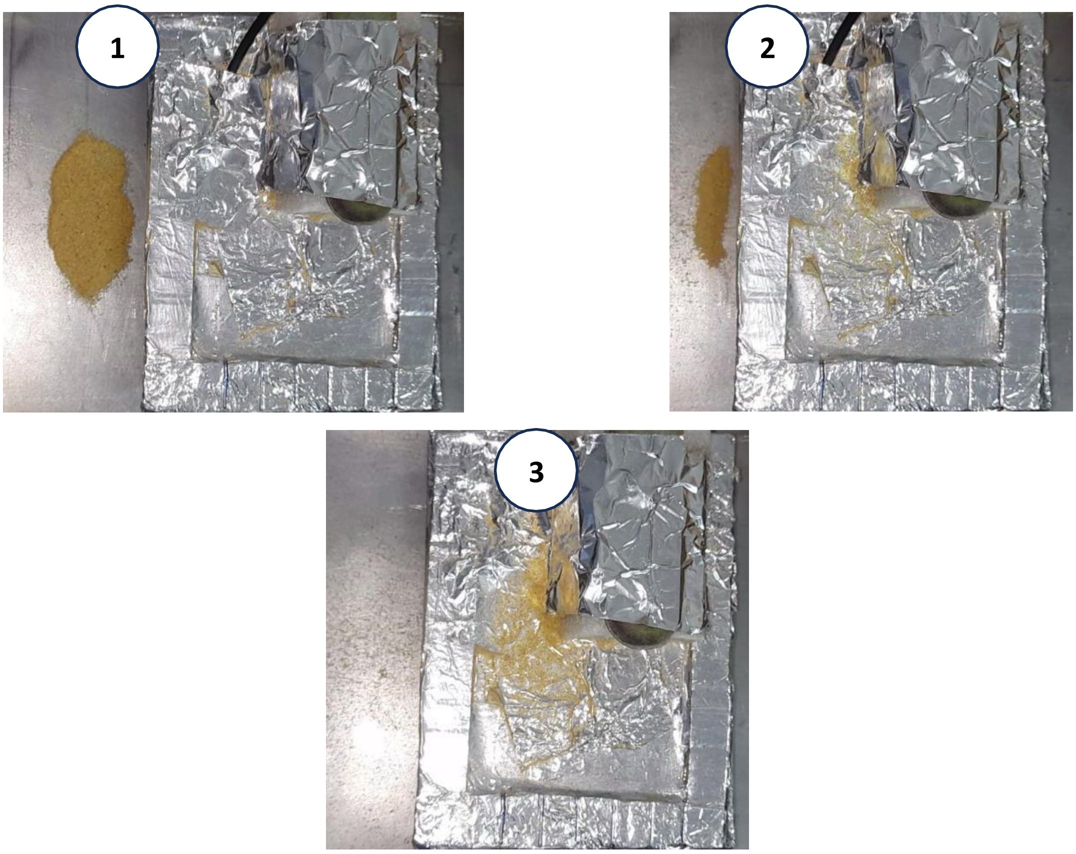
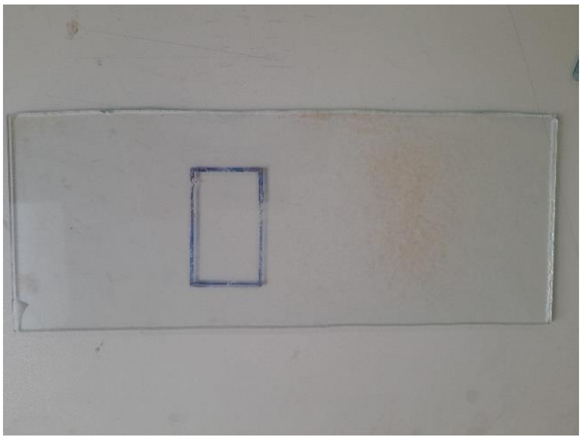


Figure IV. 7: Different instant of glass cleaning using a metallic plate (upper view).

To evaluate the induction method efficiency, the light intensity passing through the glass is measured before and after carrying out the cleaning process. The light is measured in a rectangle area (bleu rectangle) before and after cleaning, as shown in figure IV.8.

(a): Before



(b): After

Figure IV. 8: Deposited sand on the glass (a) before cleaning (b) after cleaning with metallic plate.

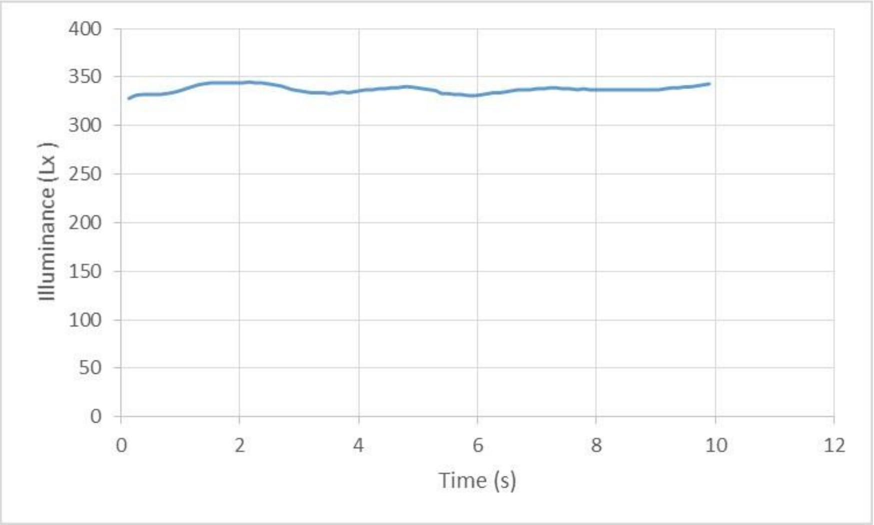
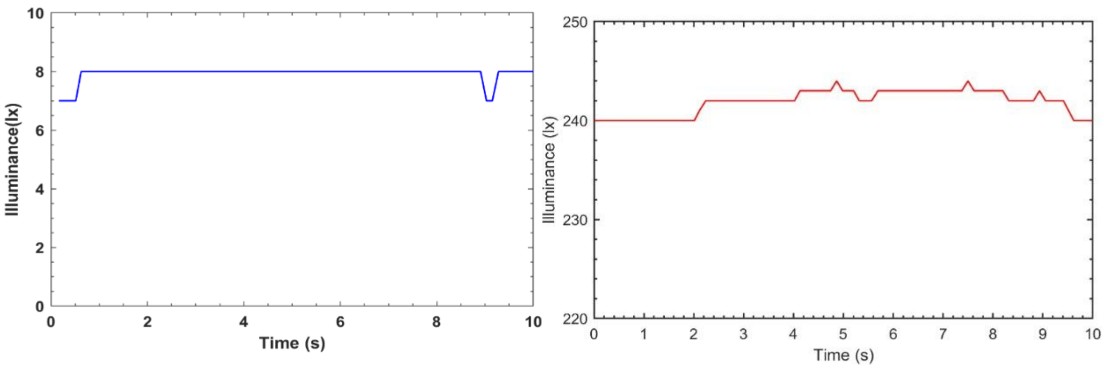


Figure IV. 9: showing the results without sand (reference curve).



(a): Before **(b):** After

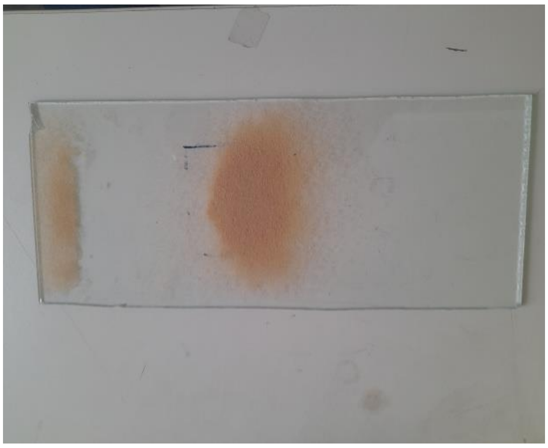
Figure IV. 10: showing results before and after cleaning.

The graphs of figure IV.9 represents the results of light intensity measurements corresponding to the glass before and after cleaning. The results show a net improvement of light passing through the glass after passing under the HV plate electrode. Indeed, before cleaning only 8 lux of light passes through the glass. After cleaning, the recorded light intensity passing through the glass is increased up to 240 lux, which is 30 times the light before cleaning. This is clear evidence of the efficiency of electrostatic induction method.

IV.3.2. Rode electrode

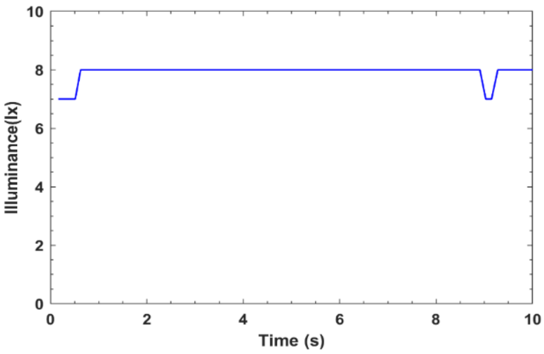
With the rode electrode we carry out the same steps as before .The glass with sand is passed once under the copper tube connected to positive 9kV high voltage supply. The obtained result is shown in Figure IV.10. Since the grains of sand collided with each other and with the tube, only partial cleaning occurred. This glass plate was not devoid of sand, but moved from its place and a few of them left the electric field.

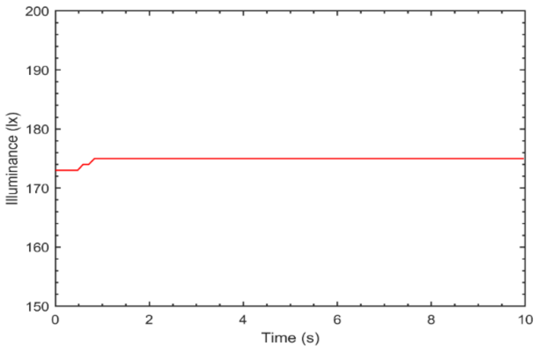
As before, the light intensity measurements (figure IV.11) reveals a net increase of the glass transparency. The measured light increased from 8 lux to around 178 lux. However, the plate electrode seems to be more efficient and cleaning is more regular and cover a wide space of glass surface.



(a): Before **(b):** After

Figure IV. 11: Rode electrode (a) before, and (b) after passing the glass.





(a): Before **(b):** After

Figure IV. 12: Graphs showing the illuminance difference before and after cleaning with copper tube.

Conclusion

Our experiments proved effectiveness of the electrostatic methods to remove and clean surfaces, which can be applied mainly in PV panels maintaining. The electric curtain is quite interesting solution but it has some drawbacks, such as complexity, number of needed high voltage sources and so on. On the other hand, electrostatic induction is more interesting as it does not require a complex structure and needs only one HV source. A simple moving metallic plate can clean with high efficiency the surface of glass covered with sand particles.

General conclusion

General conclusion

In this dissertation we have explored the effectiveness of electrostatic cleaning as a sustainable solution for enhancing the performance and longevity of solar panels. By investigating the principles of electrostatics and its application in the context of solar panel maintenance, we have shed light on the potential benefits and challenges associated with this innovative approach.

Through a series of experiments and data analysis, we have demonstrated that electrostatic cleaning techniques can significantly reduce the accumulation of dust and debris on solar panels. Our findings indicate that electrostatic forces can effectively repel particulate matter from the surface of solar panels, leading to improved energy output and overall efficiency. Moreover, the non-contact nature of electrostatic cleaning minimizes the risk of panel damage, making it a safe and viable alternative to traditional cleaning methods.

Beyond the empirical results, our study has broader implications for the renewable energy industry and environmental sustainability. The ability to maintain optimal cleanliness on solar panels has a direct impact on their energy conversion efficiency, making them more economically viable and contributing to the wider adoption of solar power. Additionally, by reducing the need for water-intensive cleaning methods, electrostatic cleaning offers an eco- friendlier approach, conserving water resources and reducing environmental impacts.

While this dissertation has provided valuable insights into the potential of electrostatic cleaning for solar panels, there are still avenues for further research and development. For instance, investigating the long-term effects of electrostatic cleaning on different types of solar panels and exploring the scalability of this technology to large-scale solar farms could enhance its practicality and applicability.

In addition, influence of ambient conditions like the humidity on electrostatic solutions needs to be pointed out.

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Bibliographies

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