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Experimental investigation of a new solar panels cleaning system using ionic wind produced by corona discharge

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ABSTRACT

This paper aims to study a new solar panels cleaning device based on the ionic wind produced by corona discharge plasma. The device comprises a high-voltage electrode composed of a series of parallel sharp needles and a grounded frame electrode. The system is moved using two driven wheels fixed at its extremities, and is placed at a few millimetres above the solar panel surface at. The cleaning operation is done by moving the dust particles from the surface using the ionic wind coming out through a 5 mm-width opening located at the bottom of the device. The study was carried out by measuring the wind velocity and the cleaning efficiency as a function of the device movement speed and the applied voltage level. The results obtained using Algerian Sahara sand dust allowed to obtain an ionic wind velocity of about 2 m/s and a cleaning efficiency that reaches 95% with a consumed power of about 20 W.

1. Introduction

Solar energy is considered nowadays as one of the cleanest energy resources that does not affect the global warming and is often called "alternative energy" to fossil fuel energy sources such as oil and coal [1–4]. Availability of solar energy with minimum ecological hazards associated with its production is one of the important factors for desired improvement in the quality of life of the people. Despite its huge potential, the contribution of solar energy to the global energy supply is still not significant [5,6]. It's well known that solar energy has the potential to fulfil the energy demands of the entire world if technologies for its harvesting and supplying were readily available. Several problems related to fossil fuels has raised global interest in the harnessing of solar energy [7,8]. Solar power is a type of energy with great future potential-even though at present it covers merely a little portion of global energy demands [9–12].

Dust accumulation decreases the photovoltaic (PV) performance and also hampers the life span of the module. It hinders the sunlight from penetrating through the PV module glass and obstructs it to reach the solar cells. Consequently, the resultant effect creates a drastic drop in PV performance [13–15]. Manual cleaning methods of PV panels present several disadvantages due mainly to the workers' accidents and damage to the system. Therefore, automatic cleaning devices of solar panels were developed to face the challenges that arise from traditional manual cleaning. However, most of these cleaning systems are complex to operate.

Therefore, many research works are devoted to recuperate the rated performance by developing effective techniques for cleaning the PV panel glass surface [16–23]. In several regions of the world where PV panels are frequently covered by sand wind, as in north African and middle eastern countries, solar panel should be cleaned frequently which requests hard and time-consuming work especially for the large solar panel arrays.

There are currently three cleaning methods that are used for PV panels: mechanical, coating, and electrostatic techniques. Four different mechanical techniques are generally investigated to clean the PV panels surface: air-blowing, robotic, water-blowing and ultrasonic vibration methods. These methods are heavy to implement and has moving parts which consumes a substantial amount of power. Cleaning with water is efficient, but in addition to the energy consumed, this technique has the

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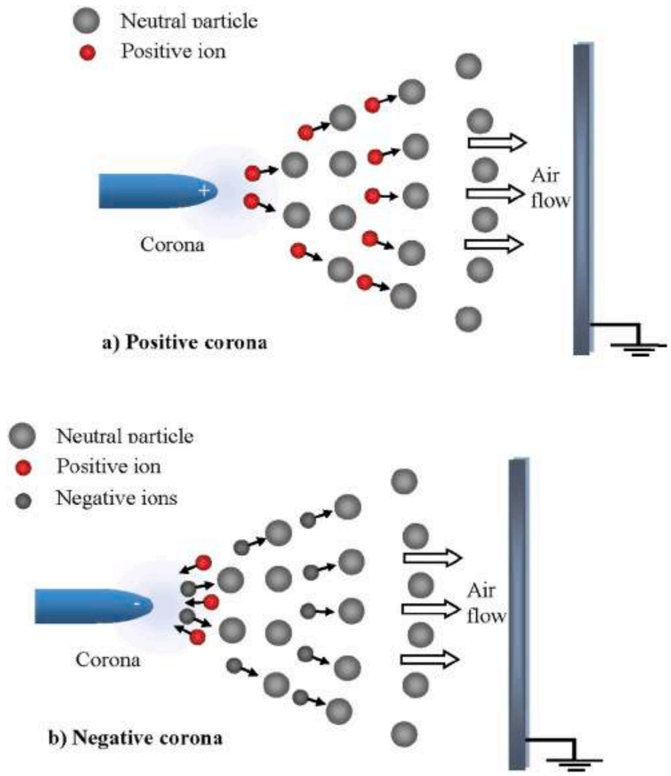

Fig. 1. Ionic wind generation in DC corona discharge under different polarities.

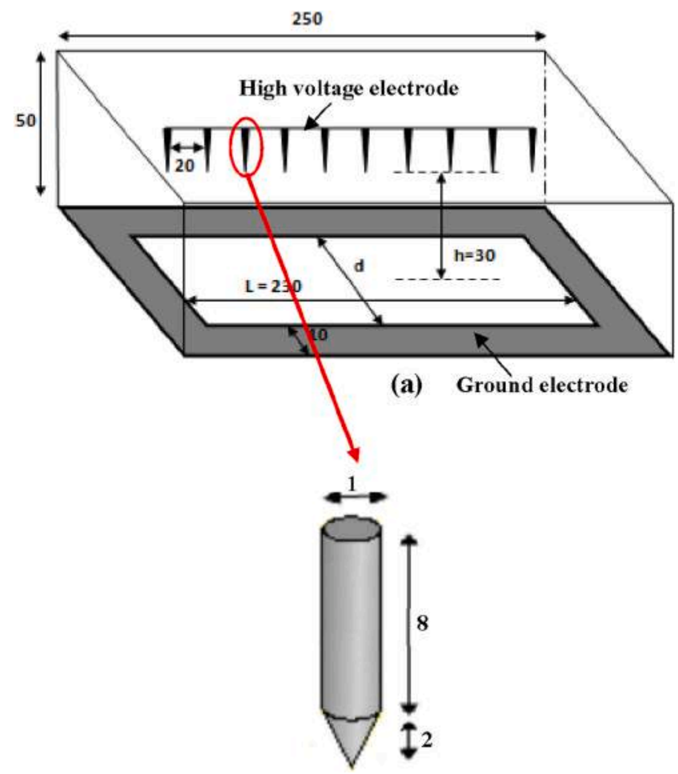

Fig. 2. The actuator with dimensions in mm **a)** Descriptive diagram **b)** Dimensions of the needle tip.

disadvantage of using significant quantities of water, which is a significant drawback especially in arid regions [24–27].

Coating method is based on nanotechnology development and research to obtain super hydrophilic and hydrophobic thin film on the solar panel surface. Super hydrophilic coating reduces the dirt through photo-catalytic reaction while super hydrophobic coating allows rolling the water droplet to carry away the dirt from the surfaces. The effectiveness of this technique is not yet significant, nevertheless it could be combined with the previous techniques to ensure a more effective mixed technique [28–37].

In addition to the method described here, there are two other techniques used for cleaning solar panels that can be classified under the category of electrostatic methods. The first one is based on the induction electrostatic charge acquired by the particles [38,39]. When a Direct Current (DC) high voltage is applied to parallel electrodes, the dust particles acquire an induction charge of the same polarity as the contacting electrode causing their repulsion. This behaviour is akin to conductive metal particles where particle lift-off takes place when the voltage reaches a critical point, enabling the particles to overcome the forces retaining them to the surface. One drawback of this method is that it requires the use of two high voltage power supplies with opposite polarities - one to charge the particles and the other to generate an attractive force to lift them. This process involves a back-and-forth movement to both charge and lift the particles, which can be difficult in practice.

The second electrostatic method is commonly known as EDS (Electrodynamic Screen) cleaning technique [40–51]. The dust is expelled outside from the panel surface using electric curtain boards by the so-called EDS. The EDS consists of parallel wire electrodes that are embedded on a dielectric layer and then deposited on the panel glass [40–51]. The inconvenient of such solution is the use of a transparent electrodes and a transparent dielectric layer. Additionally, the effectiveness of this technique depends on the electrical characteristics of the sand particles, as some types of particles may not be sensitive to the electrostatic force applied [52,53].

Electric wind can be generated in positive and negative corona discharges, but the mechanisms differ slightly for each (Fig. 1) [54–56]. In positive polarity, the electric wind is mainly generated by the movement of positive ions. Indeed, the intense electric field at a sharp electrode ionizes the air molecules, creating positive ions that are accelerated towards the negatively charged electrode. Collisions with neutral air molecules transfer momentum, creating the electric wind. In negative corona discharge, the electric wind is primarily generated by the movement of negative ions. Electrons near the sharp electrode are accelerated, causing ionization and the formation of negative ions by attachment. These ions are repelled by the negatively charged electrode and accelerated towards the positively charged electrode. Collisions with air molecules transfer momentum and generate the electric wind.

Among the different configurations to generate the ionic wind, the "tips-plane" and "wire-plane" configurations, are the most used because of the wind velocity which is higher than other configurations. The objective of the present work is to present and investigate the efficiency of a new patent-pending device that produces a corona electro-hydrodynamic wind, as a new technique for the cleaning of dusty surfaces such as solar panels. The wind is generated by a specific actuator constituted by a high-voltage electrode composed of a series of sharp tips and a grounded frame electrode. The study is presented in three sections: material and methods section where the experimental setup and protocols are presented, results and discussion section, and a conclusion.

The device is driven in a linear motion along the length of the panel. Thanks to the "ionic wind" generated on the surface of the panel, the moving device carries the dust along the longitudinal direction of the inclined panel. This motion of the device, like a broom, enables contactless cleaning of the panel's surface. Upon reaching the end of the panel, the device is driven upward again to return to its initial position, and it can then be activated to perform a second pass and remove the remaining dust. Two "front" wheels, each driven by a stepper motor, are attached to the ends of the device, while two "rear" wheels, free to move, are used to maintain balance. The linear motion of the device is ensured

Fig. 3. The actuator mounted on the PV panel 1) HV electrode; 2) Ground electrode; 3) Exit of the ionic wind; 4) Dust; 5) Driven wheel; 6) Guide rail.

by the use of two rails located at the ends of the solar panel, housing the four wheels.

Moreover, in the process of corona discharge, the electric charges generated are directed towards the ground electrode, following the electric field lines. As a result, these charges do not reach the sand particles, and thus the particles remain uncharged during this process.

2. Material and methods

The studied cleaning device is presented schematically in Fig. 2.

It is an electrostatic actuator that is used to create an "ionic wind" produced by corona discharge generated by a system of electrodes constituted by a series of sharp tips and a rectangular frame both made of aluminium. The grounded electrode of inner length 23 cm has a variable inner width "*d*" and is made of an aluminium strip of 1 cm width. On the other hand, the high voltage electrode is represented by a series of 11 sharp needles situated at a distance of 3 cm above the grounded electrode. The actuator is powered by a high voltage Direct Current source (XP Glassman, 40 kV, 10 mA).

The generated ionic wind passes through the metal frame and then exits the actuator through a small opening of a 5 mm made at the bottom of the "front" wall. This opening through which the wind passes is an empty space between the lower part of the actuator and the surface of the solar panel (Fig. 3).

The parallelepiped shape actuator is made of polyvinyl chloride plastic (PVC) and has two open walls which are the upper one to allow the air to be sucked in and the lower wall to allow the wind exit through it. Three different actuators have been build-up corresponding to 3 different values of the opening width "*d*" of the frame electrode ($d = 1$ cm, $d = 3$ cm, $d = 5$ cm).

In addition, four wheels were fixed to the lateral ends of the actuator of which the two "front" were driven by "stepper" type electric micro-motors. The linear movement of the actuator was ensured by using two rails in which the four wheels were housed. The actuator is then driven in a rectilinear motion along the length of the panel to move the dust and clean the panel surface.

The dust was deposited manually by dispersing it randomly on the panel surface using a sieve of mesh size 500 μm. The surface area on which the dust was deposited had dimensions of 30 cm × 16 cm and was delimited by a rectangular frame of the same dimensions. For each cleaning experiment, a sample of 3 g of sand dust was deposited on the surface, which corresponded to a dust density of 6.25 mg/cm^2. The deposition values chosen for the study were determined through preliminary tests to ensure adequate coverage of the panel surface. The aim was to select values that align with similar studies conducted in the field. This approach ensures that the findings can be effectively compared and contextualized within the broader body of research on similar topics [57–59]. After each experiment, the surface of the panel was thoroughly cleaned with a brush before starting the next experiment. Throughout all of the experiments described in this paper, the panel was maintained in a horizontal position with a tilt angle of zero.

The sand dust used in this study was sourced from Ouargla, a city

Fig. 4. Aspect of the sand particles.

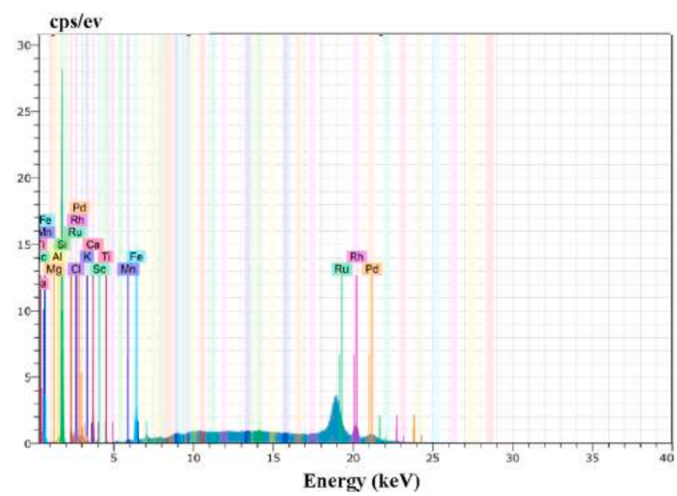

Fig. 5. Elemental composition of dust.

located in the Algerian Sahara. The particle size of the dust was analyzed using a laser granulometer (Fritsch, Analyzer 22) and was found to have an average value of 484.1 μm, as shown in Fig. 4.

The chemical composition of the particles was analyzed using an X-ray spectrometer (M4 Tornado), and it was found that the predominant substance was silica, accounting for over 87% of the total composition (Fig. 5). The procedure for using an X-ray spectrometer involves directing X-rays onto the sample and detecting the resulting characteristic signals to analyze the elemental composition and electronic structure of the sample.

Three types of experiments were conducted:

a) *Current-voltage characteristic of the corona discharge:* The current generated by the discharge was measured in both positive and negative polarities with a microammeter by varying the voltage up to the breakdown value, for 3 values of the opening width ($d = 1$ cm, $d = 3$ cm, $d = 5$ cm).
b) *Wind velocity measurement:* The wind velocity was measured with a hot wire anemometer (Testo 405i) by placing the sensor in the middle part of the actuator at the opening of the "front" wall through which the electric wind escapes. The wind was measured in both polarities for the 3 values of the opening width *d*.
c) *Cleaning experiments*: The cleaning experiments were carried out using the sand dust having an average particle size is 100 μm. For

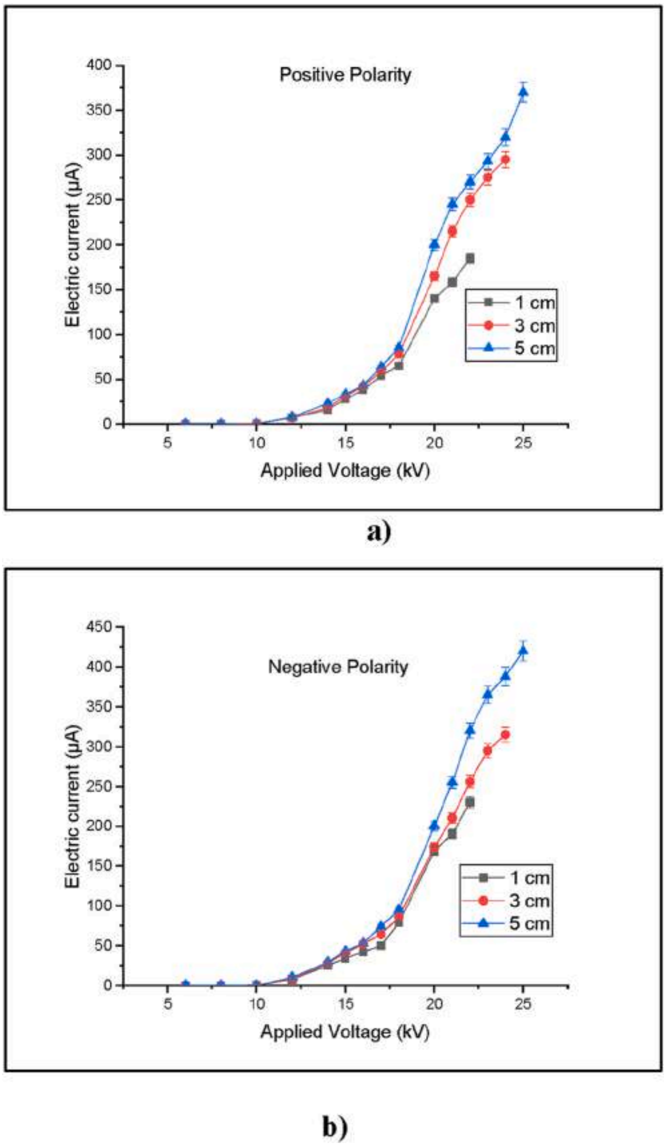

Fig. 6. Current-voltage characteristics of the corona discharge for 3 different values of the opening distance (d = 1, 3 and 5 cm) a) Positive polarity; b) Negative polarity.

each experiment, a mass of 3 g was spread more or less uniformly on the same delimited surface on the solar panel of dimensions 30 × 16 cm^2.

The cleaning efficiency was estimated by calculating the following ratio:

$$\eta=(M_c/M_t)*100 \quad (1)$$

M_c: removed dust mass

$M_t = 3$ g: total mass of dust spread on the panel surface

The efficiency was determined as functions of the applied voltage and the movement speed of the actuator. All the experiments were conducted twice, and the mean value was used for plotting. Additionally, the experimental study was conducted under stable conditions of temperature (25 °C ± 5 °C) and humidity (45% ± 5%).

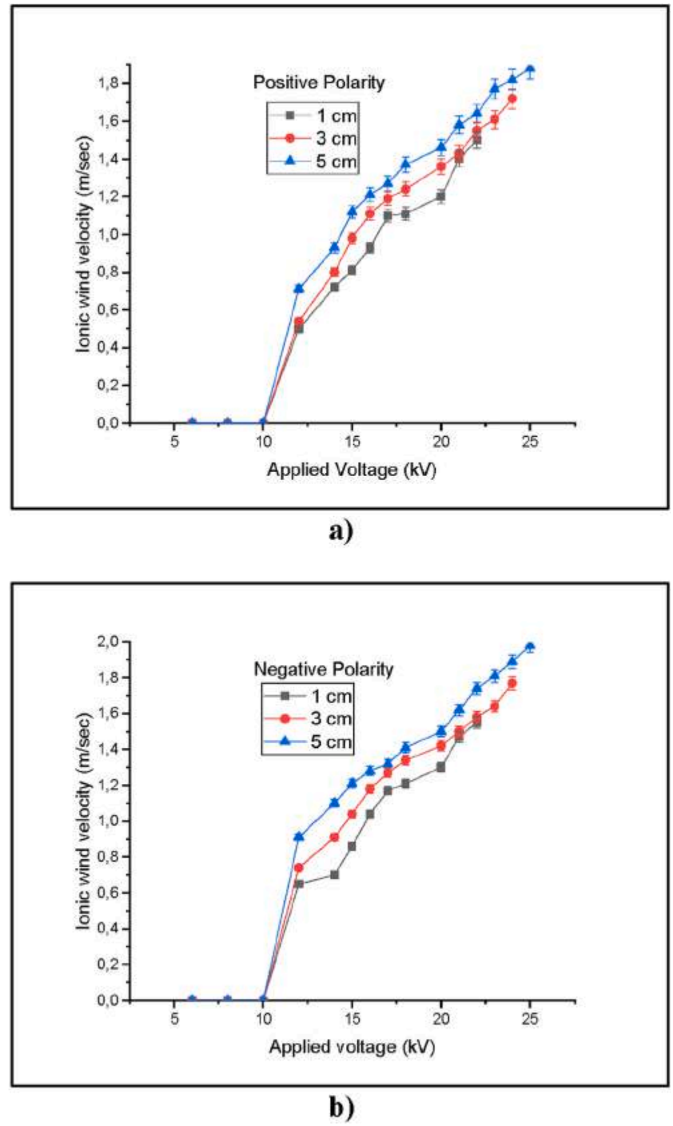

Fig. 7. Variation of the wind velocity as a function of the voltage for 3 different values of the opening distance (d = 1, 3 and 5 cm)
a) Positive polarity; b) Negative polarity.

3. Results and discussion

a) "Current-voltage" characteristic:

The current-voltage characteristics are plotted in Fig. 6, for both positive and negative polarities. The obtained results show that the corona discharge current in negative polarity is higher compared to the positive polarity. This difference is due to the fact that the current in negative polarity is mainly caused by the movement of electrons whose mobility is higher than that of positive ions.

Additionally, the current corresponding to the largest opening (d = 5 cm) is higher when compared to d = 1 cm and d = 3 cm. This is because the electric field lines have a larger collecting surface for d = 5 cm, which is a result of the increased surface area of the ground electrode as d is increased.

b) Measurement of the wind velocity v

The obtained results regarding the variation of the ionic wind velocity produced by the actuator as a function of the applied voltage are plotted in Fig. 7. The variation of the wind velocity according to the applied voltage is quasi-linear, with values reaching up to 2 m/s

Table 1
Comparison of measured and calculated ionic wind values (d = 1 cm).

	Positive Polarity			Negative Polarity		
Applied voltage (kV)	10	15	20	10	15	20
Measured velocity (m/s)	0.46	1.01	1.28	0.59	0.96	1.35
Estimated velocity (m/s)	0.23	0.92	1.59	0.27	0.78	1.66
Error (%)	50.00	8.91	24.22	54.24	18.75	22.97

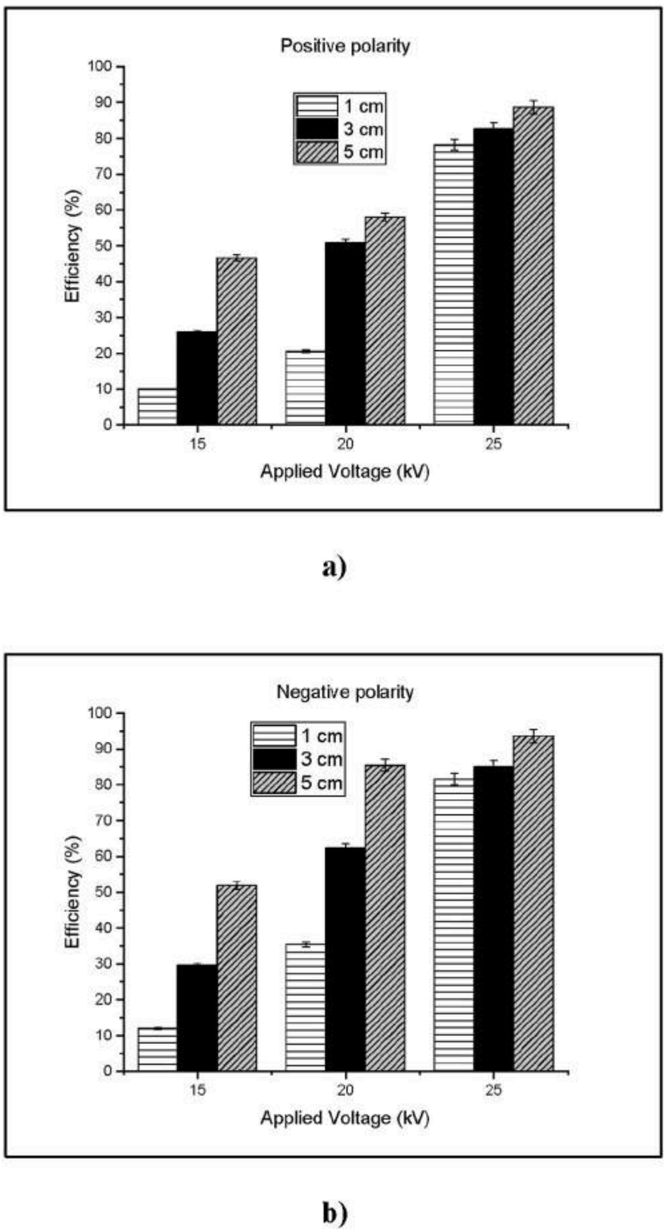

Fig. 8. Variation of the cleaning efficiency for 3 different voltages (15, 20 and 25 kV) and 3 values of the opening distance *d* (v = 0.7 cm/s) a) Positive polarity; b) Negative polarity.

for a maximal voltage of 25 kV which is the highest value that can be applied without breakdown risk. Moreover, the onset voltage that initiates the electric wind is about 12 kV for which *v* increases abruptly from zero to about 1 m/s. As observed previously for the *i* (*V*) characteristics in the two polarities, in a similar way, the ionic wind is slightly higher in the negative polarity due to the greatest current in this polarity. Furthermore, the experiments confirmed that the use of the negative polarity is much better because it allows the

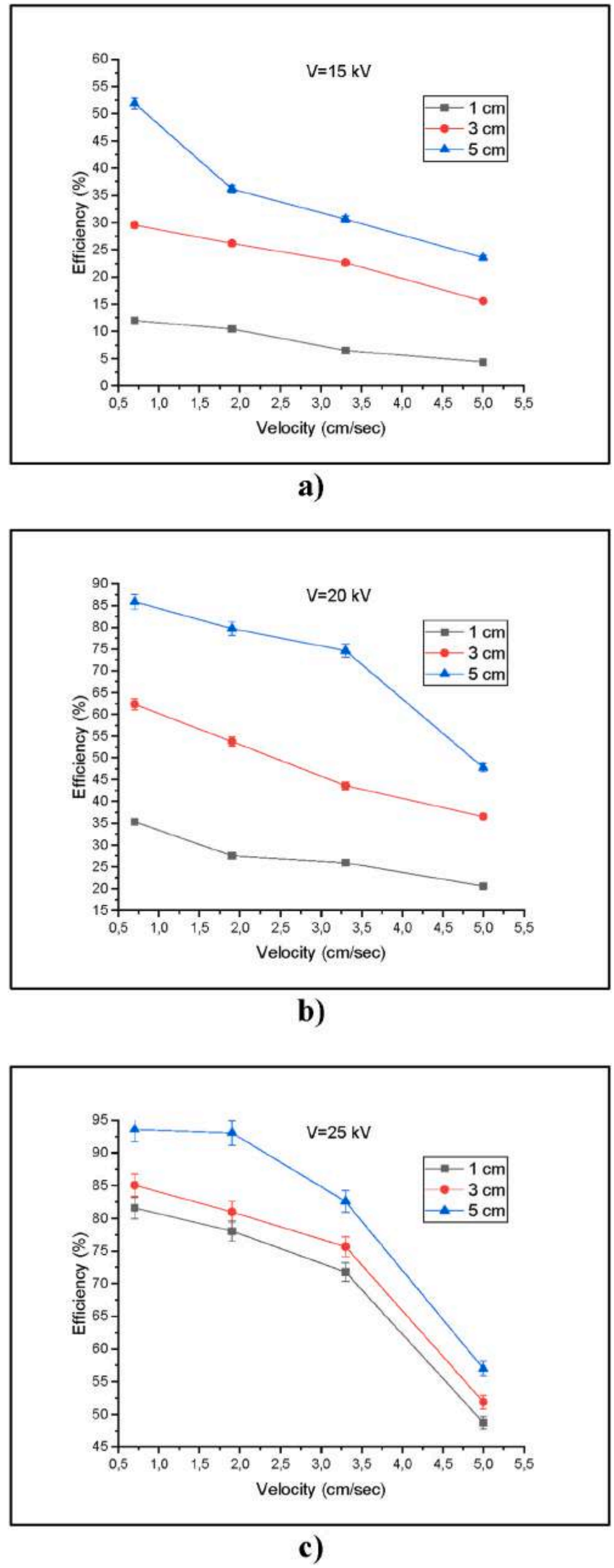

Fig. 9. Variation of the cleaning efficiency as a function of the device movement speed for 3 values of the opening distance (d = 1, 3 and 5 cm) and for 3 different voltages (15, 20 and 25 kV) a) V = 15 kV; b) V = 20 kV; V = 25 kV.

application of higher voltages without risk of breakdown in comparison of the positive polarity for which the breakdown occurs at smaller values.

We notice on the other hand that the opening distance *d* has more or less significant effect on the wind velocity, with higher values for greater distances. This dependence is concordant with the variation of the *i*(*V*) characteristics for which the electrical current is greater for $d = 5$ cm.

In corona discharge, the direction of the electric wind depends on the polarity of the applied voltage. When the voltage is positive, the wind is caused by the transfer of momentum from positive ions to neutral particles. However, when the voltage is negative, the main source of the wind is the transfer of momentum from electrons and negative ions to neutral particles, with positive ions contributing only in a small area near the electrode corona [57]. The velocity of the electric wind depends thus on the polarity of the corona discharge, which is determined by the types of particles involved in its generation. This variation can be illustrated by comparing the mobility of positive ions in positive polarity, which is about 2×10^{-4} $m^2V^{-1}s^{-1}$, to the mobility of negative ions in negative polarity, which is 2.2×10^{-4} $m^2V^{-1}s^{-1}$ [58].

The ionic wind is influenced by multiple factors, as evidenced by the equation below [59]:

$$v_g = \sqrt{\frac{Id}{\rho_g \mu A_g}} \quad (2)$$

Where d is the inter-electrodes distance, I is the electric current intensity, ρg is the air gas density, μ is the ionic mobility and A_g the section crossed by the electric current discharge.

Table 1 presents a comparison between the ionic wind velocity calculated using previous relation and the experimental measurements for three different applied voltages. It is evident that relation 2 provides a reasonable estimation of the wind velocity, when compared to the results obtained from the cleaning device.

Relation 2 shows that the difference in ionic wind velocity between the positive and negative polarities is related to the ratio I/μ, which is dependent on the nature of the particles that generate the electric wind.

c) Cleaning efficiency

The results plotted in Fig. 8 describe the variation of the cleaning efficiency of the solar panel in both polarities, for 3 different voltage levels (15, 20 and 25 kV) and a constant movement speed of the device equal to 0.7 cm/s.

The plotted results show that a cleaning efficiency higher than 90% was achieved with the device at negative high voltage value, in accordance with those obtained previously related to the variation of the current and the wind velocity. Moreover, a better cleaning efficiency was obtained in the negative polarity with an opening distance of 5 cm, corresponding to higher values of the ionic wind velocity. As an example, for $d = 5$ cm, the efficiency in negative polarity equal to 93% is higher compared to the positive polarity which is equal to 88%. Note that these results were obtained after a single pass of the device, and that a second pass allowed reaching an efficiency of almost 100%. Moreover, it's possible to apply a medium voltage (20 kV instead of 25 kV) and to make two consecutive passes on the surface of the solar panel to obtain a maximum efficiency with minimum energy consumption.

Furthermore, the results of the variation of the cleaning efficiency as function of the movement speed of the device for three different voltages, are shown in Fig. 9. A better efficiency was obtained with the lowest movement speed *v*. The efficiency decreases with increasing velocity due to the diminution of the wind energy on one side and the inertia of the sand particles on the other side. Therefore, with a lower velocity, a larger amount of dust is moved. The optimal speed in our case was equal to 0.7 cm/s, corresponding to duration of a one cleaning pass equal to about 140 s for a 1 m length panel. On the other hand, by analogy with the *i*(*V*) characteristics obtained previously, it can be seen that a better cleaning efficiency is achieved with largest opening distances.

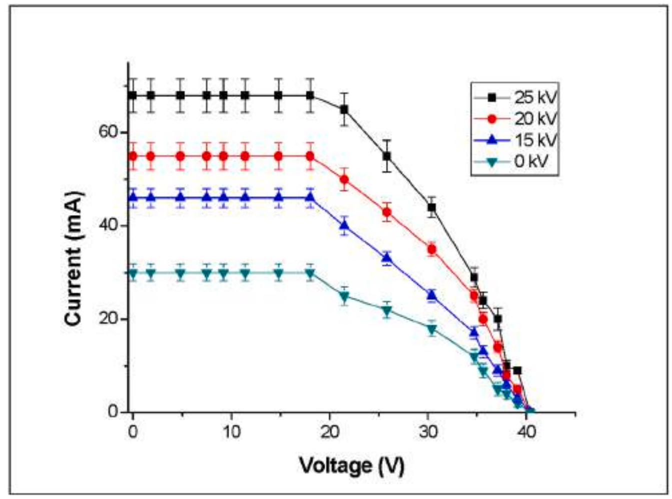

Fig. 10. Current-voltage (I–V) characteristics of the PV module before (0 kV) and after cleaning for different values of the applied voltage.

The illuminated current-voltage (I–V) characteristics of the PV module were evaluated before and after cleaning to assess its performance. Fig. 10 illustrates the module's performance before and after the cleaning operation, demonstrating the effectiveness of the cleaning process. The experiment involved cleaning the same 15 × 32 cm2 surface area, and the i(V) characteristics were measured with the panel surface covered, except for the studied surface.

The images shown in Fig. 11 illustrate the evolution of the cleaning operation at different times during the movement of the device. We notice the accumulation of dust at the front of the device as it progresses ensuring a "sweep" of dust that is almost uniform along the actuator.

The cleaning method that utilizes ionic wind generated by corona discharge has some advantages, such as low power consumption, typically around 20 W to clean a 1-m panel, and the ability to clean without making any physical contact with the panel surface. Additionally, this method does not involve the use of water. It is important to note that the specified power corresponds to the corona power alone and does not include the power needed to move the actuator. To ensure the cleaning device's independence and optimize its performance, it is advisable to incorporate a separate small photovoltaic panel with a maximal power output of 100 W. This solution guarantees that the cleaning device operates autonomously and efficiently by utilizing renewable energy for its power needs. By integrating a dedicated PV panel, the device remains self-sufficient and minimizes any potential impact on the electrical power yield of the overall photovoltaic system.

Moreover, the electric wind PV cleaner holds more potential in surpassing the limitations of mechanical fans. It utilizes EHD (electrohydrodynamic) technology to induce airflow, offering several advantages such as the absence of moving parts, silent operation, reliable performance, flexible design options, ease of maintenance, and the ability to produce a significant airflow volume.

However, there are also limitations that need to be addressed. The device's performance can be improved by optimizing its geometric configuration to produce wind velocities above 2 m/s, and it should be tested under real-world conditions of humidity and temperature to ensure its cleaning efficiency. The present study was limited to a small-scale laboratory model, and further research is needed to determine the reliability of the device when applied to a range of solar panels over an extended period. A techno-economic analysis should also be conducted to compare it with other cleaning systems currently in use. One of the major challenges of this technique is the high voltage supply needed to

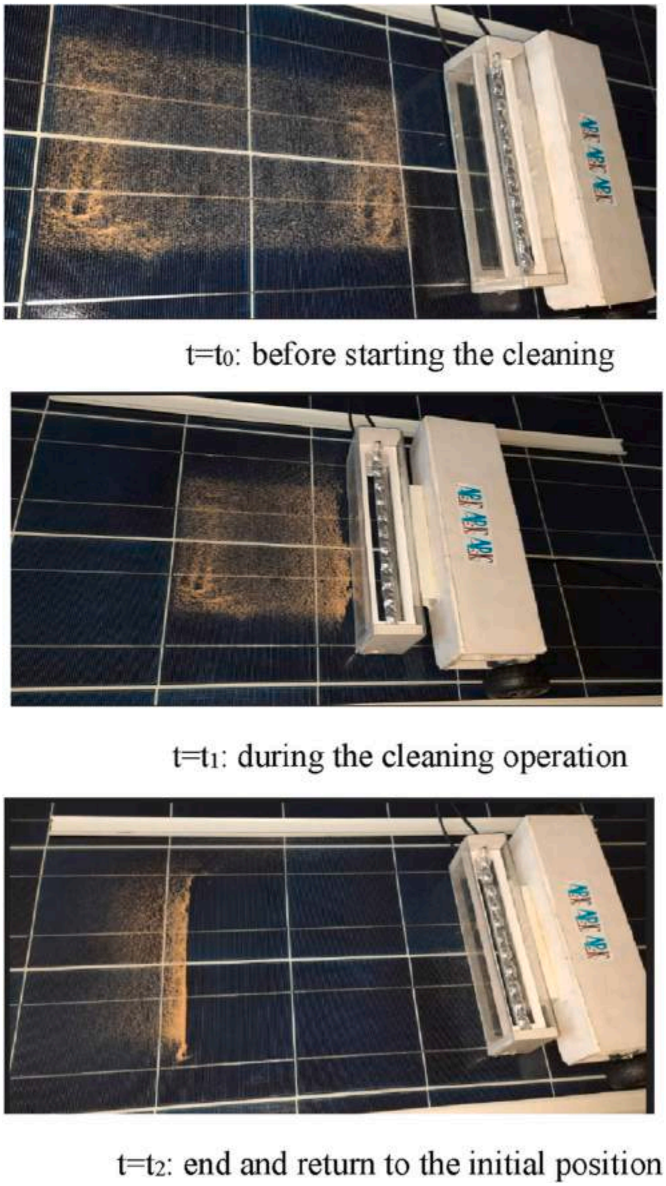

Fig. 11. Images taken at different times during the cleaning operation.

produce the corona discharge, as it must be powerful enough to create the required wind while also being compact and lightweight enough to be attached to an actuator and transported easily. In addition, it is important to regularly clean the corona electrodes to ensure efficient corona discharge and ionic wind, as sand particles tend to accumulate on the needle tips. This maintenance step is crucial for optimal performance [60,61].

Furthermore, to ensure resistance to ozone corrosion, it is essential to select appropriate materials [62,63]. For example, stainless steel can be used for the electrodes, while a polymer like PVC can be employed for the plastic framework. However, its impact is probably not so harmful considering the operation conditions, for instance:

- Typically, PV panels are installed in open spaces, allowing any ozone produced to rapidly disperse and decompose due to diffusion and decomposition reactions with other chemical species presented in the air.
- Due to the constant movement of air, the residence time of ozone in the device remains low, preventing its accumulation.
- The cleaning panel operates for approximately 140 s, resulting in a relatively low average ozone concentration.

To address concerns about possible damage from the corona reactor to the PV module, a grounded electrode serves as an electrostatic shield, preventing the electric field from affecting the PV panel. Furthermore, the electrical charges generated by the corona discharge do not come into contact with the PV module but instead are directed to ground through the grounded electrode.

In order to provide a thorough and precise comparison with other methods, we have included the ionic wind and the EDS techniques in the comparison table presented in Ref. [40] (Table 2). Nevertheless, to ascertain the efficiency of the electrostatic cleaning methods, experiments must be tested under actual environmental conditions of temperature and humidity to which the solar panels are exposed.

4. Conclusion

In this paper, a new solar panels cleaning device has been studied, this new technique is based on the use of ionic wind produced by a mobile corona discharge actuator. The device consists of a spiked electrode connected to a direct current high voltage source and a frame-shape grounded electrode. Experimental measurements, using sand dust, have confirmed a cleaning efficiency of over 95% and an electrical wind velocity of about 2 m/s. Furthermore, it was shown that the negative polarity gives better results given the higher corona discharge current compared to the positive polarity. Moreover, the cleaning efficiency is optimal for low actuator movement speeds of the order of 0.7 cm/s. More experimental and numerical studies should be carried out to obtain the best geometrical configuration of the actuator for increasing the wind velocity and the cleaning efficiency in more realistic conditions, and optimize the power consumption of the system.

Table 2
Comparative analysis of cleaning methods.

	Cleaned Surface Quality	Labors Injuries Risk	Electric Shock Risk	Panel Damage Risk	Water Wasting	Electricity Consumption	Cleaning Cost
Ionic Wind Cleaning	[a]High	No risk	No risk	No risk	No	Low	Medium
Electro Dynamic Systems EDS	[a]High	No risk	No risk	No risk	No	Low	Medium
Intelligent cleaning system	High	No risk	No risk	No risk	Yes	Very high	Very high
Manual Cleaning	High	Very high	No risk	High	Yes	Low	High
Vacuum Cleaning	High	Very high	No risk	High	No	High	Very high
Electrostatic Precipitator	[a]High	No risk	High	No risk	No	Low	Low
Automatic Wiper Cleaning	High	Very high	No risk	High	Yes	Very high	Very high
Coatings With Nanoparticles	Average	No risk	No risk	Very high	Yes	Low	High
Robotic Cleaning	high	No risk	No risk	No risk	Yes	High	Very high

[a] While these techniques have been tested in laboratory settings, they have not yet been confirmed for use in real panels. Further testing is necessary to determine their effectiveness in practical applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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