Journal of Electrostatics 129 (2024) 103934

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Electrostatic charging of material webs in production machines and how to eliminate it

Wolfgang Schubert [a,*], Atsushi Ohsawa [b]

[a] IP3-Leipzig Institute for Printing, Processing and Packaging, Leipzig University of Applied Sciences (HTWK), Leipzig, Germany

[b] Department of Electrical and Electronic Engineering, Tokyo Denki University, 5 Senju Asahi-cho, Adachi, Tokyo, 120-8551, Japan

ARTICLE INFO

Keywords:
Charging phenomena
Charge profile
Material web
Active ionizer
Passive ionizer
AC ionizer
DC ionizer
Discharging methods
Placing of ionizers
Ignition hazard
Electrostatic field meter
Personal hazard
Film web
Paper web
Composite material
Brush discharge
Super brush discharge

ABSTRACT

The elimination of electrostatic charges, especially on material webs is critical to preventing ignition hazards and personal injury hazards in industry. The use of discharge bars (called "ionizers") is an important method for eliminating electrostatic charges.

The possibility of electrostatic discharge in a production machine is real. The metrological detection of charges on material webs is also discussed and the special phenomenon of a super brush discharge is described. A useful arrangement for active ionizers is described and justified.

1. Introduction

If static electricity were truly static, we could ignore it. But when it shows its dynamic side, we experience it as electric shocks as well as ignitions of flammable atmospheres in industry. Every day, millions of meters of the most diverse materials are coated, printed, and converted, as roll-to-roll webs all over the world. The natural laws of physics and chemistry are omnipresent, and the contact and separation of materials generates electrostatic charges at countless points in machines and systems. These are not only disruptive and detrimental to quality but can also lead to serious fires and personal injury. In this paper, problems commonly encountered in web processes are reviewed with their experimental demonstration. A particular feature of the problems is isolated conductive web surfaces or fragments that can cause a discharge to ignite combustible materials. For this purpose, we use the measurements of the electric field on the web surfaces and the visualization of the positive and negative charge distribution on the web surfaces. Visualization dates back to 1777 when G. C. Lichtenberg recognized that electrostatic discharges were fascinating phenomena that could be made visible as closely spaced positive and negative surface charges [1].

To successfully prevent these production disruptions and damage, it is important to understand the factors that influence the generation of electrostatic charges, as this is the only way to eliminate them. The charge elimination using passive and active ionizers is also recommended by the standards IEC TS 60079-32-1 [2], and NFPA 77 [3]. Not every ionizer on the market is suitable for every application. The purpose of this paper is to describe the effective use and the placement of the ionizers, as consideration of the electric field lines will help to understand the results of measurements with an electrostatic field meter and to position ionizers properly for safe charge elimination of webs.

Super brush discharge [4,5] is also introduced to explain the strong electrostatic shocks that often occur during web winding. We propose its discharge mechanism, definition and how such strong discharges can occur.

* Corresponding author.
E-mail address: schubertgmd@t-online.de (W. Schubert).

https://doi.org/10.1016/j.elstat.2024.103934
Received 1 May 2023; Received in revised form 29 January 2024; Accepted 13 May 2024
Available online 29 May 2024
0304-3886/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

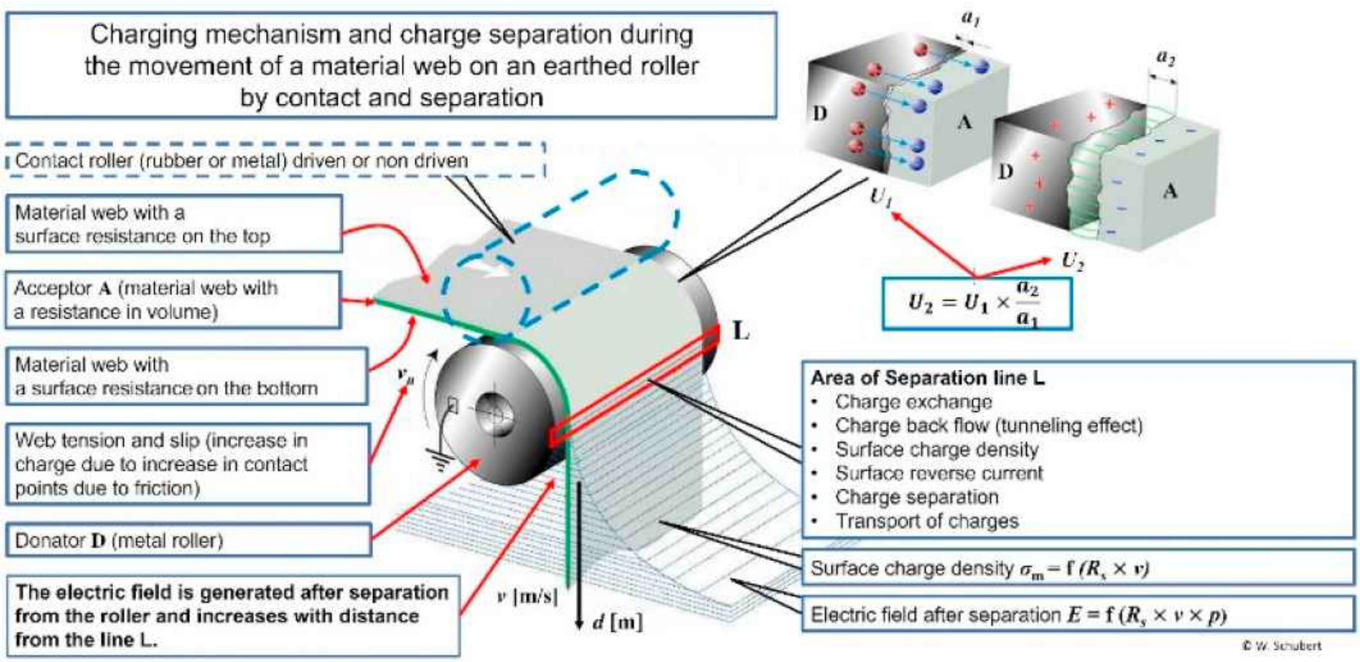

Fig. 1. Separation of the material web from a roll.

2. Electrostatic discharge on material webs

2.1. Fundamentals and influencing factors

In order to understand how charging occurs on a web, it is necessary to describe the influencing factors in detail (see Fig. 1). This mechanism between the donor D (in this case the roll) and the acceptor A (in this case the material web) occurs at each separation line L of a web, from the unwind through the guide rolls and coating units [6]. However, the web can also be a donor and the guide roll an acceptor.

When the web is rewound, other phenomena occur, which are described below (see Section 2.2). In web processes, we have the influences of the material with its thickness, the surface and volume resistances (R_s and R_v), the surface roughness, the constituents of the material web and the web tension. Contact pairs to the web, such as rubber, coated rolls, or bare metal rolls, also influence the process.

One of the most important factors is web speed, but temperature and relative humidity should also be considered. The web is guided by driven and non-driven rollers, among others, for guidance or stabilization. There is usually a speed difference between the web speed v and the peripheral speed v_u of the guide roller ($v_u < v$ or $v_u > v$). The relative motion between the surface of the web and the surface of the roll results in more contact points and more electrostatic charges, depending on the web tension. The greater the difference between v and v_u the greater the slip or friction and therefore the higher the charge.

Intensive contact of the material web with the roll (e.g., due to a large contact angle or a very smooth surface) results in a high number of contact points, which always cause electrostatic charges due to contact and separation. Press rollers with a downforce p are also often used to guide the web.

The six processes that occur at the contact surface are essential to the generation of electrostatic charge. This is where the charge exchange between the metal roller and the web takes place.

At a distance of $a_1 < 10^{-9}$ m between two materials, there are usually no clean surfaces. They are always contaminated with particles and molecules from the environment, and thus have different emission energies distributed over the surface, which are responsible for the dimensions and polarities that occur. The surface charge density σ_L is formed at the contact line. This charge density can be higher than σ_{max} due to charge binding at an earthed roller, where the surface charge density σ_{max} is the maximum one on a flat surface at atmospheric pressure in air, above which breakdown can occur.

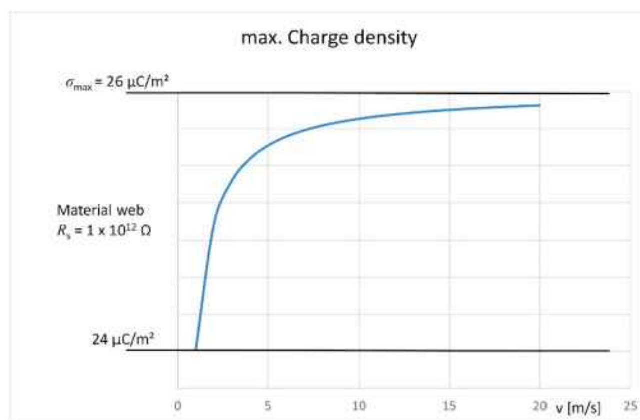

Fig. 2. Charge density with different speeds.

As shown in Fig. 1, depending on the speed v and the contact pair a surface reverse current I_R occurs at this line, while further investigation of the cause of the reverse current at this separation line is required.

After leaving the separation line L, the charge is no longer bound and does not exceed the value $\sigma_{max} = 2.6 \times 10^{-5}$ C/m^2 [7]. The surface charge density σ_L at the separation line L decreases to the value σ_m as long as a surface reverse current I_R is possible, depending on the conductivity of the guide roller, the speed v, the web surface resistivity ρ_s, and the distance d. Surface resistivity can be quite different on the top side of the web than on the bottom side. For example, a composite of aluminum, wax, and parchment paper may have a resistance of $10^4\ \Omega$ on the aluminum side and $10^{14}\ \Omega$ on the parchment side. Nevertheless, high charges become possible even at low speeds.

Here σ_m is defined as the average surface charge density transported away with the material web. It is a function of the surface resistance R_s and the web speed v. Assuming a resistance of $R_s = 10^{12}\ \Omega$ and a speed of

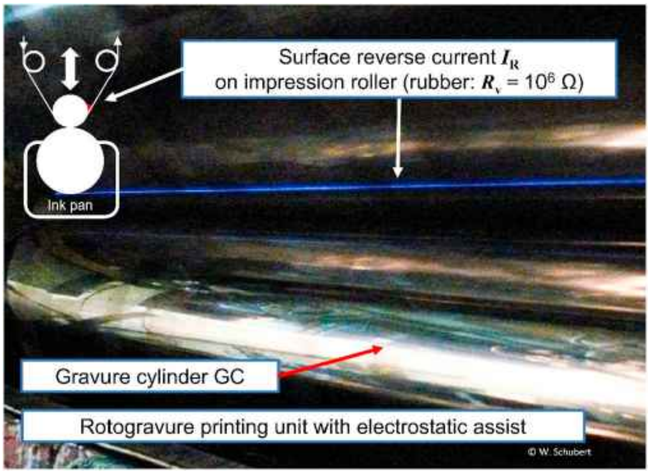

Fig. 3. Surface reverse current (Photo: H. Künzig ca. 2002).

only $v = 1$ m/s are assumed for the material web, 24.6 μC/m² is generated according to equation (1) derived in Reference [7].

$$\sigma_m = \frac{\sigma_{max}}{1 + \frac{1}{2\, \varepsilon_0\, R_s\, v}} = 2.46 \times 10^{-5}\mathrm{C/m^2} \tag{1}$$

If we calculate this for more web speeds, we get Fig. 2.

The situation shown in Fig. 1 illustrates the many factors that influence charge generation on a material web. The potential difference between the contacts is in the [mV] range at a separation distance of 10^{-9} m and less. For example, if the potential difference $U_1 = 1$ mV between the roller and the web with distance $a_1 = 1$ nm and with distance $a_2 = 2$ cm, U_2 becomes a much larger potential difference of 20 kV using equation (2), where the roller is earthed.

$$U_2 = U_1 \frac{a_2}{a_1} \tag{2}$$

The charge Q_1 between the pair of the web and the roller can be calculated by the formula:

$$Q_1 = C_1 U_1 \text{ and } C_2 U_2 = Q_2 \tag{3}$$

Ideally, the charge on the web after the separation line should be constant, but in practice this is never the case. However, it is a function of the reverse current I_R and therefore also depends on the material properties of the contact pairs and the separation speed. The surface reverse current depends on the conductivity of the contact pairs. Further investigation is needed.

Here, the charge $Q = CU$ is constant; but if you add energy to separate the materials, the capacitance C decreases and the potential U increases, as described by equations (2) and (3).

In Fig. 3, as a result of the surface reverse current I_R at the separation line of the material web from the impression roller is clearly visible as a blue line like a glow discharge. This is a typical situation of the web path in a gravure press. This photograph was made possible because the material web was a transparent one. The web speed was about 8 m/s. The properties of the film cannot be reconstructed. At present, no studies have been carried out on the reverse current, so no data are available.

2.2. Super brush discharge on material web

Material webs, including textile, composite, or fabric webs, are typically rewound after a production process. These highly resistive webs are charged at each line of separation (e.g., coating unit, guide rollers, tension groups, etc.). Without the elimination of the electrostatic charge, the individual charges of the web are accumulated in the finished coil by the mechanical force of the web tension.

Experience has shown that these coils are often so highly charged that the unavoidable contact during handling of the rolls, i.e., usually by an earthed person, causes strong electrostatic discharges when approaching, even if only a few kilovolts of potential are measured on the web surface before winding. Such discharges on people can lead to secondary accidents. Not only are personnel at risk[1] of shock, but the product is at risk of production rate as well.

Experience has also shown that the accumulation of electrical charges during winding can cause the already finished and stored roll to telescope and become unusable.

Internal charges in the roll material occur regularly because even minimal fluctuations in web tension cause relative movement between the individual layers of the finished film roll. The high mechanical pressure between the layers causes friction and an increase in contact points for electron exchange, which always results in a high separation charge when the roll is unwound. Punctures inside the roll have also been observed, resulting in material damage.[2]

As the web is rewound, the surface charge of the front and back of the web for each polarity is added and mechanically compressed. The field measured on the outside of the roll is composed of the fields due to the surface charges and those due to the charges inside the roll (superposition principle). The total amount of internal charges contributing to the electric field on the outside of the roll can be greater than that due to the surface charges.

Due to the high resistance of the material, the charge on the material surface cannot be dissipated. This can cause the charge on the material surface to accumulate to an undesirable level. The accumulation of surface charge can cause a discharge when the electric field due to the surface charge exceed the breakdown field.

The surface charge density for the initiation of discharge is therefore well known as the maximum surface charge density ($\sigma_{max} = 26$ μC/m²). This yields to

$$E_b = \frac{\sigma_{max}}{\varepsilon_0} \approx 3\ \mathrm{MV/m} \tag{4}$$

where E_b is the breakdown electric field of air.

In this situation, equation (4) expresses the maximum surface charge density limited by air breakdown. In practice, however, the charges are present on both sides of insulating surfaces, so σ_{max} cannot be achieved. The vector sum of the electric fields due to the charges on both side surfaces can cause a discharge on a surface.

Therefore, at this time, the surface charge density on one side can be lower than σ_{max}. This means even a surface charge is not high, a discharge can occur due to the charge on the opposite side. In addition, the accumulation of the surface charges can cause many local discharges, which are as low as invisible, on the web, resulting in complicated surface charge distributions with locally positive and negative polarities on both side surfaces, as described later. In this case, the surface charge density that initiates a discharge becomes much lower than σ_{max} (see Fig. 6). In the case of winding webs, charges existing inside the roll can contribute to the initiation of a discharge even at the surface charge densities much lower than σ_{max}, on the winding webs.

Partial discharges can also occur on the side of the roll to the winding axis. In both types of discharges, most of the charge remains inside the roll because it can only be partially discharged due to the high resistance of the materials [5]. In addition, the charge inside the wound roll is difficult to discharge because it is closely surrounded by the web materials, leaving no space for discharge to occur. As a result, the electric

[1] Note: The influence of electrostatic fields or flashovers on persons is discussed in IEC 60479–2 [8].

[2] Personal communication of H. Künzig: "*During an investigation, the coating of a film was found to be defective near the core of the roll or the winder axis. Optical inspection of the uncoated film showed dendrites ending in a small pore. When the layers were overlaid, the pores could be traced to the winding axis.*"

field on the surface due to the charge inside the roll is maintained during discharge. This can result in a high energy discharge that can cause a strong electrostatic shock and an ignition of flammable atmospheres. In this situation, the polarity of the surface charge on the roller can be reversed. This is because when a discharge occurs, only the surface charge is discharged, and the surface charge density is less than σ_{max} due to the charges accumulated inside the wound roller which can superimpose to create the electric field for breakdown at the surface.

For example, the process of stacking electrostatically charged plastic trays is similar. During the investigation of an industrial incident, it was found that the process of "stacking" trays resulted in an accumulation of charge. A person caused a strong discharge by moving his hand close to the tray and fell to the floor.

A definition of the process of charge accumulation by mechanical forces, especially on material webs, is not known. To explain the mechanism of accumulation of charges of the same polarity, gravity is introduced to overcome the repulsive Coulomb forces. The charge accumulation of poured insulation granules in an FIBC is such an example. A coiled web is also a typical example where gravity is replaced by mechanical force.

The following definition of super brush discharge is proposed:

> An external force (gravity or (applied) mechanical force) overcomes the repelling Coulomb forces of a large number of individual charges of the same polarity, that are present on insulating materials, resulting in the formation of a "system" with an accumulation of charges of the same polarity.
>
> The presence of a distant earthed conductor[3] binds the charge.
>
> Super brush discharge also occurs when the breakdown field strength (>3 MV/m) is reached. However, the following points differ from other types of discharge: the presence of the accumulated charges of the same polarity can help to initiate and sustain the discharge. In addition, the accumulated charges are almost maintained because the discharge does not occur where the accumulated charges are present. Therefore, when a discharge occurs near the location where the accumulated charges are present, the electric field due to the accumulated charges is then maintained at the location where the discharge occurs during the discharge. In such a situation a super brush discharge can occur, releasing a high energy that can cause an electrostatic shock and an ignition in flammable atmospheres.

Examples of the discharge are that which occurs on the roll surface during web winding and that which occurs on the surface of Type A FIBCs containing charged granules where many intermittent electrostatic shocks occur when approaching an earthed conductor (a person). In these cases, the charges inside the winding webs and FIBCs are maintained and only the surface charges on them can be discharged. The polarity of the surface charges may be reversed.

As the electric field is maintained due to the accumulated charges during the discharge, this can lead to higher ionization rates and higher electron drift velocities at higher electric fields at atmospheric pressure in air [18]. This results in a high discharge current and therefore high energy release. This is the reason why the super brush discharge can release high energy and cause many electrostatic hazards.

The transition from a brush discharge to a super brush discharge and to a propagating brush discharge can be demonstrated with the recording of current waveforms of the respective discharges [9, p. 89 ff.]. When an insulating sheet with an earthed backplate far away on the backside is charged with a monopolar ionizer, a brush discharge occurs when an earthed electrode approaches. If the earthed backplate is closer

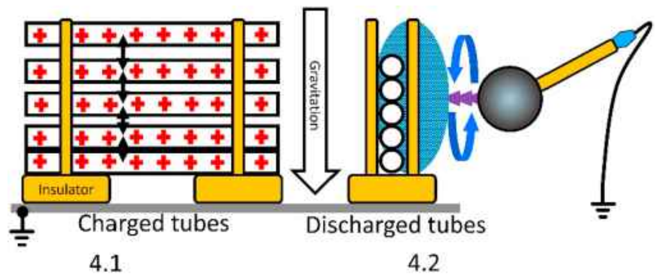

Fig. 4. This experiment is a model of how objects accumulate charges of the same polarity [10, p. 358].

(e.g., 10 … 1 cm), a super brush discharge occurs when the earthed electrode approaches, and if the earthed plate is much closer (e.g., ≪ 1 mm), a propagating brush discharge occurs.

The best way to determine the mechanism of a super brush discharge is to record the current flow of the discharge oscillographically. This can be done experimentally with the following setup: Five or more thin-walled plastic tubes of the same material, charged to the same polarity by rubbing, e.g., with a lambskin, repel each other when placed between two insulating forks [5]. The Coulomb force causes the tubes to float on top of each other (see Fig. 4.1).

While the maximum surface charge density σ_{max} cannot be achieved on each tube, the accumulation of charge due to the gravity or the mechanical force to overcome the repulsive Coulomb force causes a much higher electric field resulting in a much stronger brush discharge when an earthed electrode is approached, hence the name "super brush discharge" was derived from this [4]. When this discharge is triggered, the tubes in the forks collapse (see Fig. 4.2).

Lüttgens and Wilsons [4] reported that when this discharge is triggered, the tubes in the forks fall on top of each other and the discharge current results in a more energetic brush discharge than normal, which may include an electromagnetic pulse that can be detected with a radio receiver. If this discharge current is high enough to produce a high magnetic field, it causes the pinch effect that leads to gas heating [11]. At present, however, there is no obvious evidence that the pinch effect, which can cause gas heating to yield to ignition, has occurred. Nevertheless, the super brush discharge can be a possible ignition source in flammable atmospheres [5].

3. Types of ionizers

3.1. Passive ionizers

Discharge bars (ionizers) can be divided into passive and active electrodes (ionizers). All solutions based on the corona discharge principle and earthed sharp pins, that can be placed opposite a material web, are referred to as "passive" ionizers. Each pin can be earthed via a series resistor. They can also be dissipative brushes with low or high brush density.

When using passive ionizers, the user should always be aware of the path of the field lines (see Fig. 5). This means that the smaller the number of pins, the higher the concentration of field lines for the corona inception voltage, and therefore the higher the discharge effect.

The optimum number of individual free-standing pins per centimeter depends on the distance of the area (surface) to be discharged and on the mutual influence between adjacent pins.

3.2. Active ionizers

Discharge ionizers are called "active" when their emission pins are connected to a sufficiently high voltage [kV] through a current limiter (usually resistors). They are connected either by an external high-voltage supply or by an internal high-voltage generator.

[3] In our case, this is e.g., the earthed winding axis. As you know for a corona discharge you need no earthed conductor. For brush and super brush discharges you need a distant earthed conductor and for a propagating brush discharge your need a very close earthed conductor.

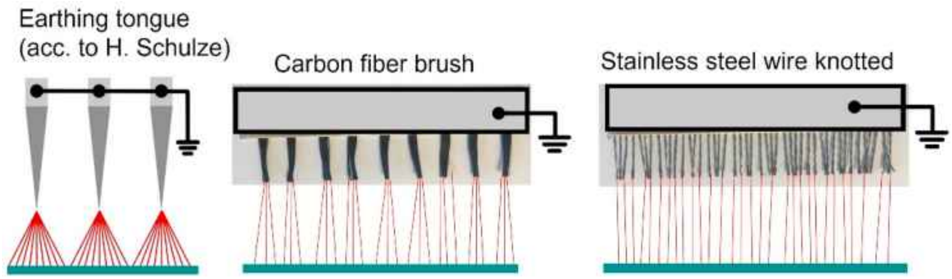

Fig. 5. Field line concentration at passive pins with different tongue/brush densities [9, p. 205 ff.].

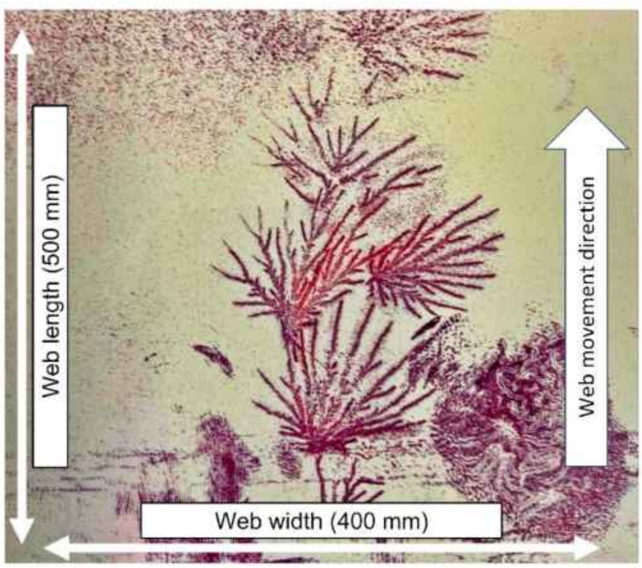

Fig. 6. Charge distribution on a polycarbonate film after being unwound by hand, with prominent dendrites, characterizing the positive charges. The "cloudy" area indicates negative charges.

The principle of operation of the ionizer at normal pressure is based on the fact that when the dielectric strength of the air (3000 V/mm) is exceeded, charge carriers escape at the pin of the ionizer and thus initiate impact ionization, which results in collisions with other particles. Valence electrons are lifted out of their outer orbits by electron impact ionization, the environment begins to glow blue; the air is ionized - the electrons are available for charge transport and the air becomes conductive.

There are many different variants on the market. Either the tip rows are supplied with AC (AC ionizer) or separately with ± DC. The active ionizers have different characteristics, that can be used individually or in combination:

- Changing the frequency of the AC high voltage manually on the power supply,
- Changing the AC high voltage frequency by measuring the discharge current,
- Changing the AC or DC high voltage 5 kV … 50 kV manually or automatically by measuring the discharge current or by measuring the distance,
- Changing the ratio of positive and negative voltage applications to control positive and negative.

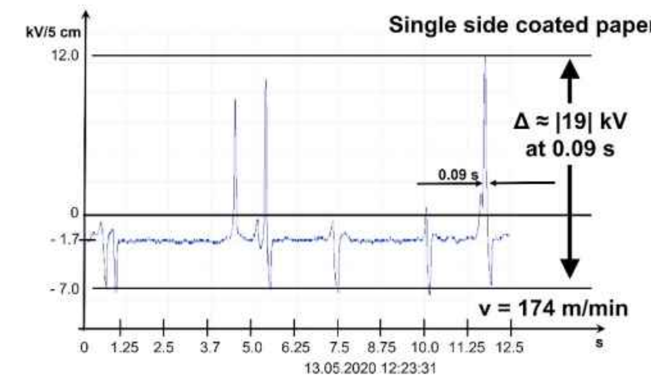

Fig. 7. A trace of the electric field measured on the web after a guide roller [6].

4. Arrangement of ionizers

4.1. Basic requirements

In a production machine that processes material webs, ionizers are required to be installed in many positions, where production difficulties or ignition hazards are expected. Experience has shown that ionizers are often missing, incorrectly placed, and/or placed in positions where malfunctions or ignition hazards due to electrostatic charging are not to be expected. Empirical solutions for proper placement have prevailed in the past and can now be justified by measurement technology.

After unwinding from a reel or separation from a guide roll, charge distributions with different amounts and polarities lie close together on the material surfaces. By walking across the web width with an electrostatic field meter (EFM with the influence principle[4]) at a constant distance, anyone can quickly see the different field strengths. The EFM can also be used for continuous measurements. [11, p. 61 ff.]

4.1.1. Charge distribution on surfaces

The charge distribution on a film can be seen by dusting the surface with fine powder (see Fig. 6).

To also show the charge polarity distribution, a powder mixture with two differently colored components (in this case, sulfur powder colored with carmine red (+) and lycopodium powder colored with methyl blue (−) [10, p. 245 ff.]) are used.

When such a mixture is sprinkled on a charged surface, negatively charged particles are attracted to positively charged parts of the surface and vice versa. It can also be shown that the positive and negative charges are very close to each other, and that a discharge occurs between them.

A trace of the electric field measured on the web after a guide roller [6,12] has shown that charge profiles of different polarity and

[4] This is usually translated as "induction".

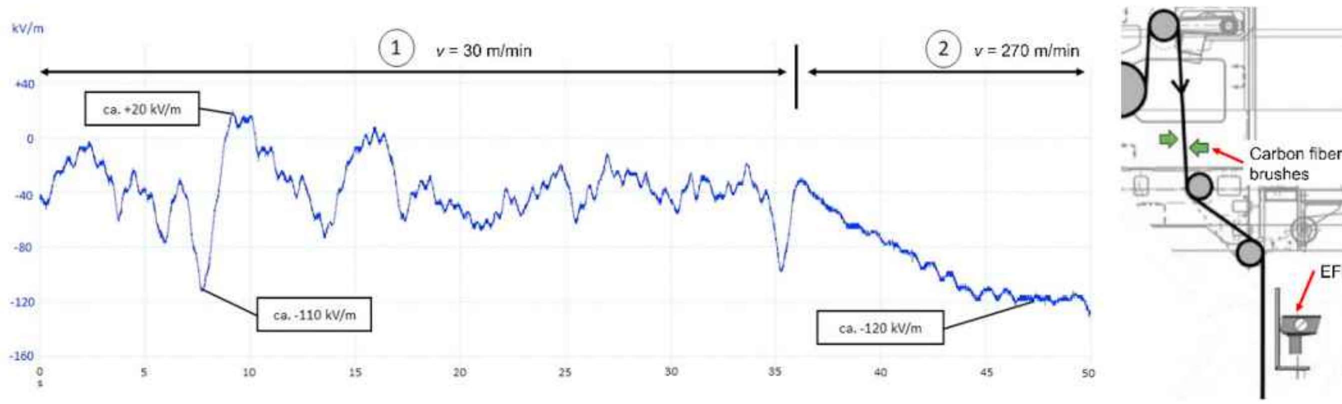

Fig. 8. Field strength at a PET film [13].

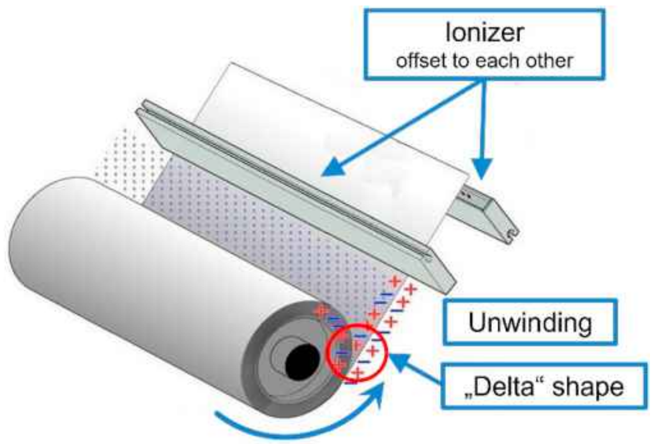

Fig. 9. Arrangement of the ionizers during unwinding [14].

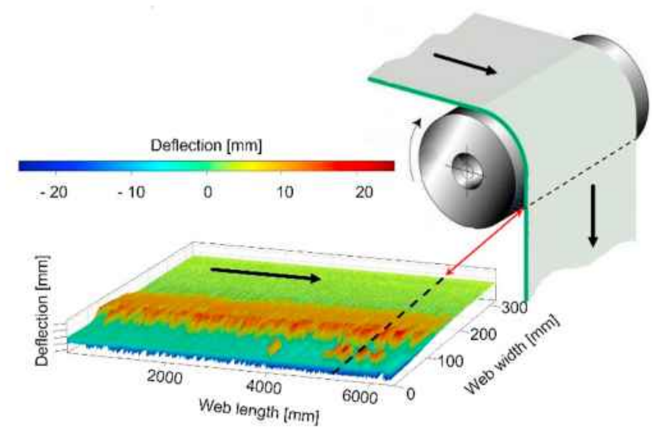

Fig. 10. Measurements with oWTP-Scanner from Fraunhofer IVV, Dresden [15].

distribution occur in close proximity and at sub-second or sub-millimeter intervals along the web path (see Fig. 7), both in the web width and in the running direction.

In this context, the effect of ionizers, such as those offered e.g., with “closed loop” or with “in-line measurement”,[5] must be questioned: *It is impossible for an ionizer to respond to such a frequently fluctuating electric field on a web, and if you add a sensor (field meter) near the ionizer - this sensor can only detect a narrow strip of the web and cannot detect different polarities of an electric field that are close together as described above.*

Many ionizers on the market advertise that it is possible to detect electric fields with a measurement built into the ionizer and to achieve a better discharge by adjusting the ion emission.

The charge distribution on the web as shown above does not allow for such a system. Therefore, the claim of “a better discharge” of the web is not physically tenable.

The large variance in the spread of electric field strength during start-up (1) and acceleration (2) of production in a gravure press was clearly demonstrated on a 12 μm PET film with an EFM measuring distance of 100 mm, as shown in Fig. 8. In this gravure press, earthed carbon fiber brushes were installed as a passive discharge. These could not be removed for safety reasons (risk of fire and explosion).

After this passive ionizer, the web still had to pass through two guide rollers up to the measuring point, with the front and back of the film enclosing the guide rollers at an angle of about 60°.

The electric field values are not so low, while the international standard recommends the maximum permissible electric field of 200 kV/m to avoid ignition in flammable atmospheres [2]. This is because the web was in contact with rollers after the passive ionizers until it reached the position where the electric field was measured. Fig. 8 shows that proper placement of the passive brushes is necessary to avoid high charges.

4.1.2. Charge distribution at separation line

As a web passes through a machine, particles (water molecules, dust, rubber abrasion, etc.) are constantly deposited and removed from the rollers and web surface. As a result, the conditions at the separation line are completely chaotic and produce a wide variety of adhesion and release conditions that can be detected with the oWTP scanner (see Fig. 10). This separation line is called “delta” and represents any triangular shape (see Fig. 9). [10, p. 85].

The web tension profile scanner (oWTP) for optical determination of the web tension distribution (see Fig. 10) can be used to determine material-dependent release conditions. [11, p. 243 ff.], [15]. Very strong oscillation deflections or separations between the roll and the film can be found on the release line (Fig. 10: deflection visualized by color from −20 mm to +20 mm). From the visualization of separation behavior (different separation conditions), it can be concluded that the polarity and potential of the surface charge vary strongly. This confirms the practical experience gained with the EFM. Further investigation should verify this.

It is often attempted to neutralize the surface charges on both sides of the web simultaneously by aligning the ionizer with the web separation

[5] “Closed-loop” or “in-line” is a marketing term that describes a feedback control system in which the ionizers are supposed to be controlled by the measured electric fields.

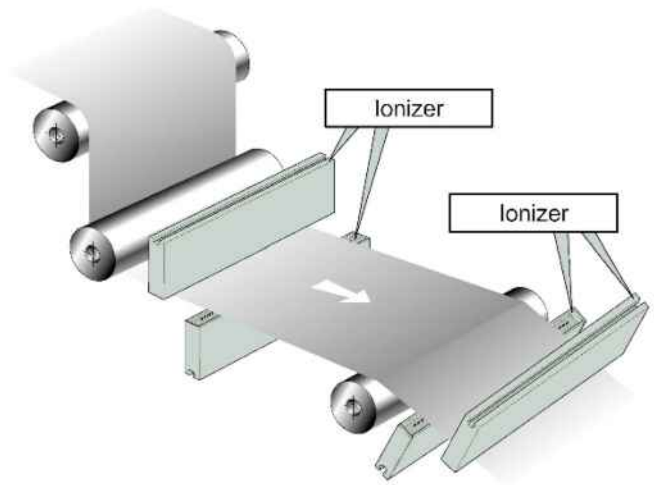

Fig. 11. Ideal placement of the ionizers [14].

line of a coil. If the working direction of an ionizer is exactly at the delta separation line, the rapidly changing release conditions of the web from the roll would be superimposed by the alternating field of the AC ionizer; thus, the positive and negative ions emitted by the ionizer would hardly be attracted for neutralization.

4.1.3. Effect of the material

The arrangement of the ionizers is inevitably influenced by the main material used (paper, film, nonwoven or composites). This means that for normal paper and film, active ionizers are usually used even in potentially explosive atmospheres. For composites with conductive layers and in the presence of flammable solvents, only passive ionizers may be used (see Section 3.3).

Materials must always be classified according to their electrostatic properties and their contact and separation behavior. For example, in the case of partially coated or printed paper, charge neutralization on one side may be sufficient. This is because the finite resistance of the substrate causes both sides to reach charge equilibrium in a relatively short time. The same applies to porous webs.

But the properties and behavior can be completely different depending on the manufacturing step. For example, a surface coated with black ink (carbon black) must be considered as an insulated conductor.

In the case of films or other non-porous materials, e.g., fully printed or coated on both sides, experience has shown that both sides must be discharged with staggered ionizers (see Fig. 11). When installing ionizers in flammable atmospheres, ignition hazards (Ex zone) must be considered.

4.2. Optimum placement

It is well known that the elimination of electrostatic charges is a challenging task in almost all areas of industries. The electrostatic charge on a web can be optimally eliminated or greatly minimized if the ionizers are placed as shown in Fig. 11. For all materials, it is usually necessary to position ionizers on both sides of a web when it is insulating [12,16]. This illustration is an example that must be adapted to specific conditions.

In processing operations where flammable solvents are used, the correct placement of ionizers to prevent ignition hazards due to electrostatic charges is of the utmost importance. This is also described in IEC/TS 60079-32-1, [2, p. 12.5.3] and the German TRGS 727 [16].

The first ionizer in the running direction should be located on the side after the last separating line (see Fig. 11). This can be the separation line of a coil or of a guide roller. The strength of the electric field on the

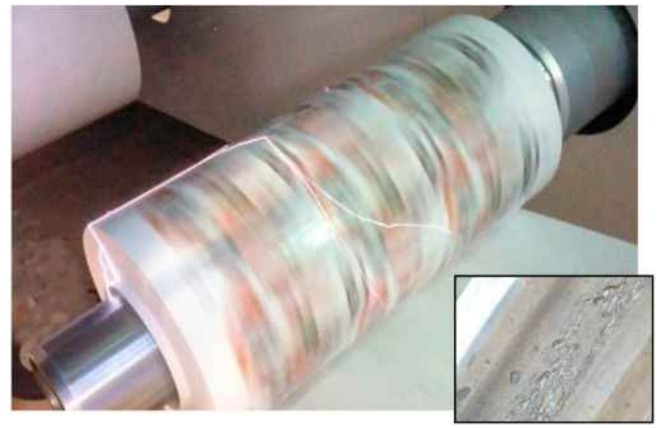

Fig. 12. Super brush discharge during winding on an earthed shaft at a web speed of 40 m/min. Small picture: electro-corrosion in a bearing.

Fig. 13. Composite material with embedded aluminum.

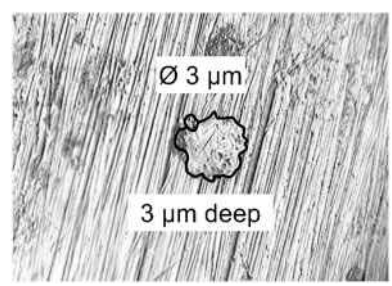

Fig. 14. Electro-corrosion by composite material on a guide roller.

web is always higher on the side of the separation line than on the outside of the material web (see Fig. 1). As already mentioned, it is always best to discharge both sides of non-porous materials (e.g., foils or fully printed paper webs), since it is often not known on which side the highest static charge has accumulated. Earthed machine components near the material web can reduce the effectiveness of an ionizer by altering the field is changed causing most of the ions emitted by the ionizer to be attracted to the earthed machine components. Therefore, only the remaining “remnant” of the ions can be used to neutralize the charge on the surface. In other words, when analyzing the installation conditions of ionizers, it is necessary to think in terms of “field lines” so that the electric field emanating from the charged material can see the pins of the ionizer.

It should be reiterated that it is imperative that both sides of the web be sufficiently discharged prior to winding to prevent dangerous super brush discharges at the winding point (see Fig. 12).

The discharge can occur on the outside of the reel as well as on the inside directly to the earthed winding axis. It can become a propagating brush discharge. This discharge will cause sparking in the shaft bearing, resulting in electro-corrosion (see Fig. 14).

4.3. Electrostatic discharge of composite materials

Electrically conductive layers are increasingly used in composite materials. These can be aluminum foils as a barrier layer or other

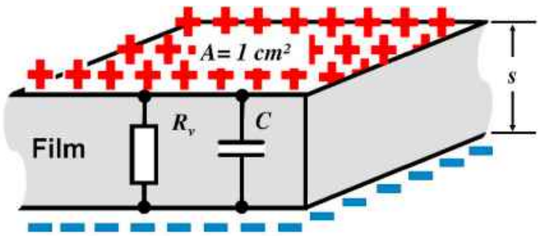

Fig. 15. Equivalent circuit diagram of bipolar charge layers [10, p. 60] (R_v: volume resistance, *C*: capacitance, *s*: film thickness).

For example, an aluminum label (7 × 10 cm) commonly used for automatic roll change has a capacitance of 15 pF (distance to ground: 1 cm). If the capacitance is charged to "only" 5000 V, an energy of ≈1.9 mJ is released, resulting in an ignition hazard for many flammable liquids. Therefore, the so-called "5000-V-Rule" must be questioned [17].

If a wide variety of materials are to be processed in web presses, active ionizers must be provided for insulating materials and passive ionizers for composite materials.

This can be achieved by using active discharge bars with the electrode pins connected to the high voltage supply via resistors, or by providing another passive discharge path (see Section 3.1). However, ionizers with a built-in high voltage supply connected directly to the pins do not meet this requirement; therefore, these ionizers may cause ignition in flammable atmospheres. The built in voltage supply act with a high voltage cascade and this part is not "open" back to earth, so that no passive function is possible.

Material webs with open conductive side edges can also be contacted laterally with grounded conductive tongues/brushes (see Fig. 5) if there are no insulated conductive fragments in them.

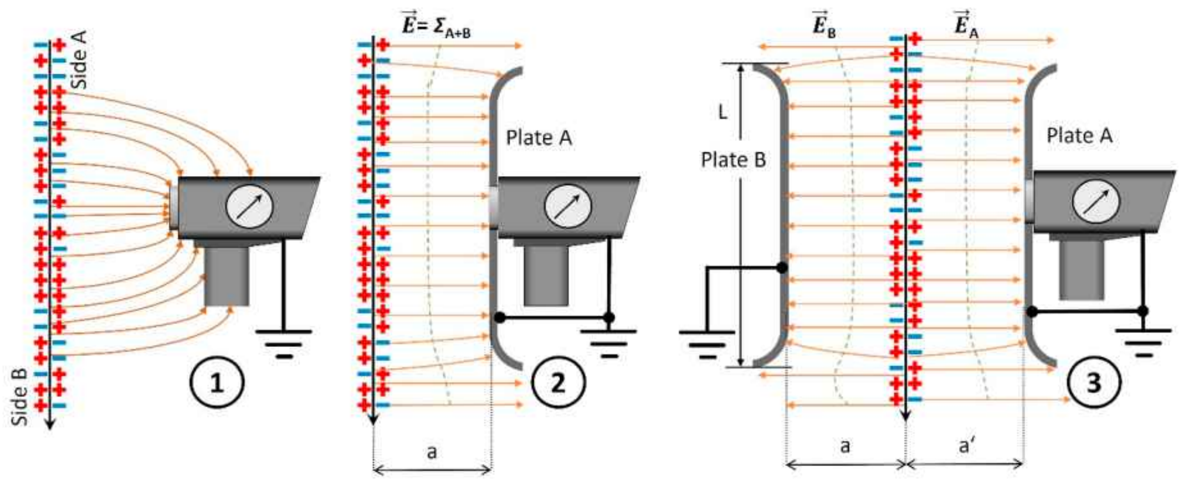

Fig. 16. Ideal homogenization for electric field measurement [10, p. 189].

electrically conductive layers, such as foils with ITO (indium tin oxide) functional layers in the field of flexible electronics. It does not matter whether the metal foil or metallized layer is on the outside or embedded in the composite (see Fig. 13). When active ionizers are used, the air in front of the pins becomes conductive, so that charge is introduced into the large electrical capacitance of the conductive layer via the exposed edges of the web. The same is true when corona pre-treatment equipment is used to change the surface energy.

Regardless of whether the conductor is inside or outside, the charge on that conductor is affected and generates a capacitive displacement current, which can then lead to periodic (e.g., 50 Hz) spark emission to very close earth. This usually occurs at the open edge of the trimmed web to a bare metal surface (e.g., guide roll). These discharges cause electro-corrosion. Fig. 14 is the result of a damage investigation by Schubert.[6]

Therefore, active ionizers should not be used on composites with conductive layers. This is especially true for manufacturing processes that use flammable solvents.

A particular hazard exists if parts of the conductive layers (metal fragments) are electrically isolated, i.e., not earthed, due to defects in the composite material. Another hazard exists when only parts of the surface are metallized or have conductive metal pigment layers. These electrically isolated segments or fragments store charge and can produce ignitable sparks if they have sufficient capacitance, as has been found in a fire investigation.[7]

Electrically, these metallic surface fragments act like a capacitor with a capacitance *C* whose stored charge is rapidly discharged by a high-energy spark discharge. Therefore, when processing materials containing solvents, solvent vapors can be ignited by a spark.

5. Measurement detection

When a material web is fed through a machine, both the top and bottom sides of the web pass through several separation lines with very different characteristics (rubber, coated surfaces etc.). This creates electrostatic charges on both sides of the web, which may be of different magnitude and polarity or of the same polarity (see Figs. 7 and 8). In the case of film webs, we now speak of "bipolar charge layers", which are separated from each other by the thickness of the film as a function of its permittivity and thus form a capacitor (see Fig. 15).

An EFM is used to measure the values of the electric field. The measured electrostatic field is always the vectorial sum of the electric fields from both sides that the EFM detects. [11, p. 60 ff.]. If these fields were to be measured separately, it would be necessary to measure on both sides of the web using homogenization plates with the distances a = a' as shown in Figs. 16–3 (where $L \times L >> a$). In practice, however, this ideal homogenization can almost never be achieved in production machines.

Since the body of the E-field meter is earthed, the electric fields caused by the surface charges on both sides of the insulating web are directed to the field meter (Figs. 16–1) and/or to the earthed measuring person. Such a measurement without homogenization cannot provide real values (Figs. 16–1), but only an indication of what dimensions can be expected. Or only what is available to the EFM as a field mixture at that moment on a moving web.

[6] The details of these investigations are confidential.
[7] The details of these investigations are confidential.

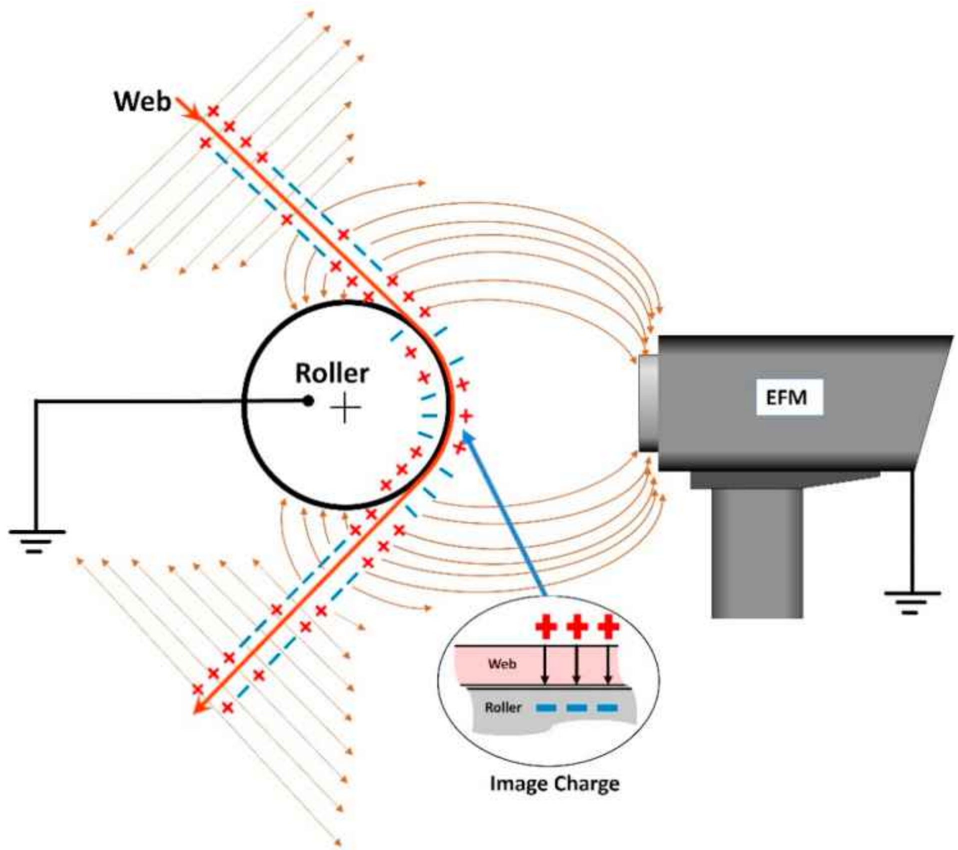

Fig. 17. Detection range of an E-field meter opposite an earthed roller (Through influence (induction), the charge of the overlying web is mirrored with reversed polarity on the roller).

If an earthed plate A is placed on the EFM, the vector sum of the EFM can be detected (Figs. 16–2), but the measured field strength is too high - or too low (vector addition). If another earthed plate B is placed on the opposite side (Figs. 16–3), the electric fields of the opposite surface are mainly directed to this plate B. The electric fields of the side facing the field meter are directed towards the earthed plate A of the field meter (Figs. 16–3). This means that only the E-field on one side of the web is detected if the distances a = a' are maintained!

Note: Two homogenizing plates are also used to calibrate field meters and electrostatic voltmeters. The instrument to be calibrated is placed in the opening of plate A and is thus earthed. A defined voltage is applied to plate B opposite the instrument, which is then matched to the instrument.[8]

Already at low web speeds, the distance between the web and the plates varies so that the essential condition $a = a'$ for homogenization is not met.

Therefore, a measurement setup is often chosen in which the E-field meter or other measuring device is placed exactly opposite the roll (Fig. 17). With such an arrangement, it will always be possible to obtain readings for running webs. However, these readings are usually not meaningful because the detection range of the EFM extends well beyond the contact area between the web and the roller and all fields of the incoming and outgoing web are included in the displayed readings.

The field emanating from a web is calculated using formula $E = U/a$ and is always aligned with the nearest earth potential. When the web touches the earthed roller, the distance a is reduced to the thickness of the material and the field is only within the thickness of the material.

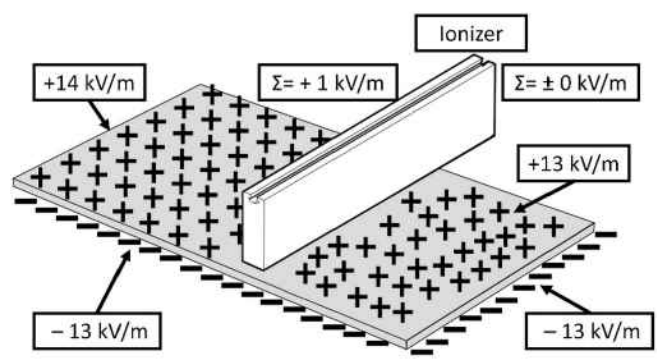

Fig. 18. Single-sided discharge – unfavorable – you get a bipolar charge layer.

The field emanating from the charged web generates an image charge on the conductive roller in the contact area between the web and earthed roller through influence. [11, p. 37].

Understanding electrostatics means thinking in terms of "field lines". The field lines are always directed toward the nearest ground, which in our case is within the material thickness. Therefore, the charging of a web can only be measured as shown in Fig. 16, with the disadvantages of the chosen measurement setup.

Fig. 18 shows an example of an idealized possible situation where a one-sided discharge is insufficient. For example, if +14 kV/m can be measured separately at the top of a web and −13 kV/m at the bottom (as per Figs. 16–3), the electrostatic field measured at the top of the web will be only +1 kV/m. Therefore, the ionizer will only emit enough negative particles to neutralize +1 kV/m. If one side surface is positively charged and the other negatively charged, the zero means that the vectorial sum

[8] See IEC TR 61340-1-1 CD:2024-01.

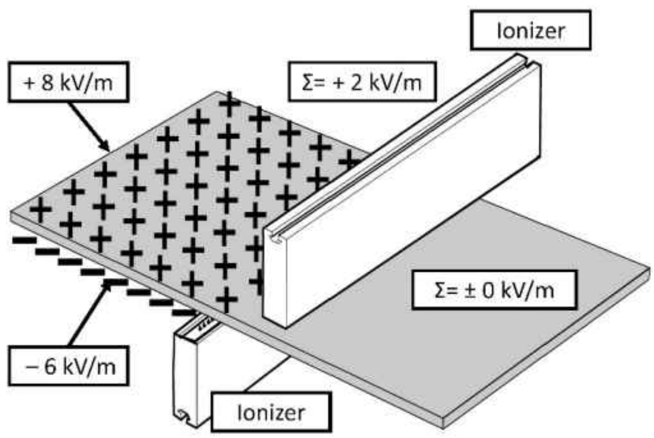

Fig. 19. Discharge on both sides – optimal.

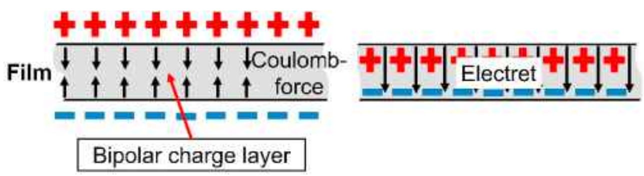

Fig. 20. Bipolar charge layer.

common in the industry. Often more than one ionizer is connected to a single power supply. It does not matter whether the AC or DC ionizer is. This means that all ionizers have the same voltage and polarity at their tips. If two of these ionizers are facing each other, they will both emit the same polarity of ions at the same time. This creates a repulsive Coulomb force, and the discharge effect goes to zero.

When the difference between the bipolar charged layers is zero, as shown in Fig. 20, or the charge difference between both sides of the film is small, discharging becomes difficult for insulating films with very high resistance.

For a better understanding, it is useful to work with the potential on a web, because it is easy to measure with the EFM. To measure charges on a web, you need a coulomb meter, which, unlike the EFM, is not available everywhere.

For example, imagine that the potential difference between the top side and bottom side of a web is only a few kilovolts/m, say −15.3 kV/m and +15.1 kV/m. Thus, only the small potential difference of 200 V is available to neutralize the charged surface. Therefore, even a discharge with ionizers on both sides has no effect in most cases.

> “Such a high field strength is unmeasurable, almost impossible to discharge, this field is bound within the film thickness! But can still be life threatening if an extremely high resistive film carries an extremely high charge on both sides of equal but opposite polarity during processing. For example, one side +20 kV, opposite side −20 kV (vectorial sum 40 kV). Not measurable from the outside, with a film thickness of 100 μm $E = U/a = 4 \times 10^4 V/10^{-4}$ m this corresponds to an electric field strength of $4 \times 10^8 V/m$, or more simply

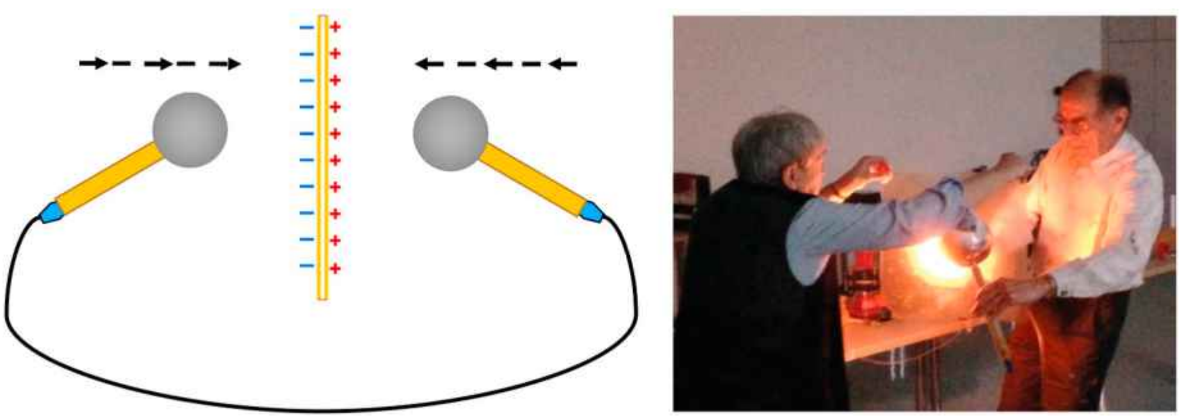

Fig. 21. Demonstration of a propagating brush discharge at a bipolar charge layer by Günter and Sylvia Lüttgens [11, page 167]. In this case, this highly insulating film carries the bipolar charge only in the center region, so it can be held by hand, as shown in the picture.

between the two side charges is zero, i.e., charges of the same absolute value remain on each surface.

If we now measure the effectiveness of the discharging ionizer with an EFM, we can see that the measured value in front of the ionizer is +1 kV/m and behind the ionizer is ideally ±0 kV/m, but it is not discharged.

Fig. 19 is also an idealized illustration of web charge neutralization. With the arrangement of ionizers shown, practical experience and measurements have shown that effective neutralization of the web is possible down to a few volts. Further research should be done to determine how different types of ionizers can be used.

In a staggered arrangement, the ionizers should be at least two discharge bar widths apart. As mentioned in Section 4.1.1, ionizers with built-in power supplies can be damaged by charge peaks coming from the web (see Figs. 6 and 7). This arrangement can also prevent the discharge bars from influencing each other when they are placed opposite each other as described later.

The use of ionizers with a separate high-voltage power supply is

> 400 million V/m. If, for example, this film is inserted into a central cylinder flexographic printing (Fig. 23) press for printing and possibly touched on both sides with the fingers of the hand, an industrial accident with permanent paralysis is understandable. Inside the flexo press, propagating brush discharges are also very likely![9] (see Fig. 21)

The high field strength acts within the small film thickness. Therefore, it cannot be measured with an EFM (see Fig. 19). The authors are not yet aware of any practical approach to solving such problems.

In the case of composites with aluminum foil, for example, electrostatic charges are hardly measurable with the EFM if the aluminum is sufficiently earthed via a contact in another area of the machine. The electric field lines are then directed to the earthed aluminum foil.

[9] Private information by H. Künzig, closest employee of H. Kleinwächter.

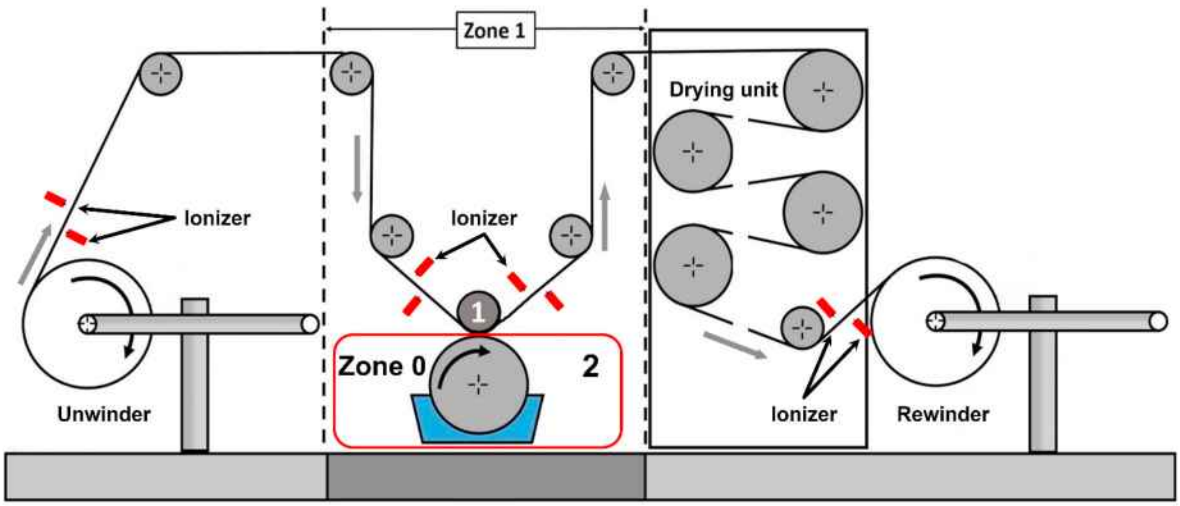

Fig. 22. Processing machine for material webs (according to Ref. [16]).

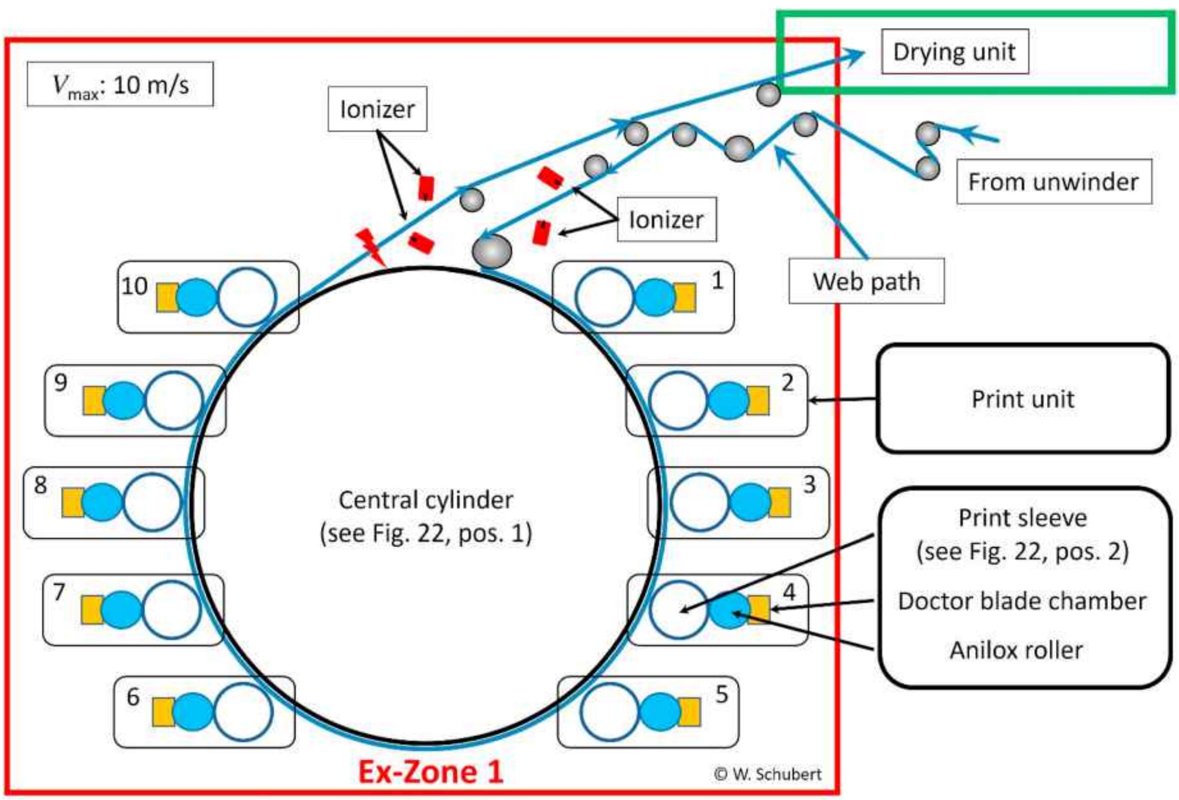

Fig. 23. Schematic of a central cylinder flexographic printing press.

6. Material webs and their potential hazards

The explanations in [9, p. 225] are to be amended because of the results from a fire-cause investigation.

The requirements from IEC/TS 60079-32-1 [2] and the German TRGS 727 [16] are shown in Fig. 22. Both documents refer only to films and paper webs.

In the opinion of the authors, all material webs must be considered. This is because not only film and paper webs are coated on a large scale, but also textile material webs. These textile materials usually consist of highly insulating plastic fibers and are coated with a wide variety of materials that dissolve in flammable solvents (e.g., aramid fabric for rubber gaskets and the like).

The key point for all users and designers is that the placement of the ionizers shown in Fig. 22 must be adapted to the specific conditions of a material web processing machine. For example, the designer of a central cylinder flexographic press (see Fig. 23), must provide the central cylinder with position 1 and the doctor blade with an anilox roller and impression cylinder at the coating unit 2 as shown in Fig. 22.

An arrangement of discharging ionizers between the printing units will not be successful because the electric field from the web will always be directed towards the nearest ground, in this case, the central cylinder. Thus, the “ions” emitted from an active ionizer will not be attracted to the charged web surface. Even a passive ionizer will have no effect because the electric field is directed toward the earthed central cylinder.

7. Summary and conclusions

Proper placement and selection of ionizers are the keys to web processing. The many factors that cause electrostatic charging during web processing are shown and the possibilities of electrostatic discharge in web processing machines are discussed. To understand the dangers and potential problems of rewinding charged webs, the mechanism of super brush discharge is described.

Further studies under production conditions are suggested, particularly on the distribution of electrostatic charges as the web separates from a guide roller. The same applies to the study of the operation of the numerous ionizers available on the market.

CRediT authorship contribution statement

Wolfgang Schubert: Methodology. **Atsushi Ohsawa:** Methodology.

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

No data was used for the research described in the article.

References

[1] C. Hermann, Das physikalische Kabinett zur Görlitz - Diss, Gunter Oertel Verlag (2016), 978-3-944560-27-4.
[2] IEC/TS 60079-32-1, *Explosive atmospheres – Part 32-1*: Electrostatic Hazards, Guidance, 2013.
[3] NFPA 77, Recommended Practice on Static Electricity, 2019. Edition, 2019.
[4] G. Lüttgens, N. Wilson, Electrostatic Hazards, Butterworth-Heinemann, 1997, https://doi.org/10.1016/B978-075062782-5/50003-7.
[5] S. Forestier, J.-M. Dien, M. Glor, Ignition of a cloud of dry powder using super brush discharges, Chemical Engineering Transactions 48 (2016). AIDIC, Italy].
[6] W. Schubert, L. Engisch, U. v Pidoll, Electrostatic Charging Phenomenon Material Web, Electro Field Meter Measurements in a Production Machine and Their Interpretation, 2022, https://doi.org/10.1016/j.elstat.2022.103681.
[7] M. Gabel, G. Schön, *Elektrostatische Aufladung von Papier beim Rotationsdruck*, Advances in Static Electricity, Vol. 1, in: Proceedings of the 1st Internat. Conference on Static Electricity, Österreichischer Verband für Elektrotechnik, Vienna, 1970, pp. 82–95.
[8] IEC 60479-2, *Effects of Current on Human Beings and Livestock* - Part 2 ED 2 (CD 2020): Special Aspects, 2019.
[9] G. Lüttgens, et al., Statische Elektrizität, WILEY VCH, 2020.
[10] W. Schubert, G. Lüttgens, *Praxislexikon Statische Elektrizität*, Expert Verlag, 2022, https://doi.org/10.24053/9783816985068.
[11] G. Lüttgens, S. Lüttgens, W. Schubert, Static Electricity, WILEY VCH, 2017.
[12] A. Ohsawa, Computer simulations of insulator charge neutralisations with a corona ioniser – influence of initial surface charge distribution, J. Electrost. (2013) 71287–71293.
[13] A. Götz, Electrostatic Charges on Moving Material Webs in Production Machines, Technical University of Applied Sciences, Amberg-Weiden, Germany, 2022. *Master thesis*.
[14] Eltex Elektrostatik GmbH, Training and Seminar Material, Weil am Rhein, Germany.
[15] Fraunhofer Institute for Process Engineering and Packaging IVV, 2013. Dresden, Germany).
[16] DGUV Information 213-060, TRGS 727 *Vermeidung von Zündgefahren infolge elektrostatischer Aufladung* (TRBS 213-060 Prevention of ignition hazards due to electrostatic charges).
[17] A. Seaver, Analysis of electrostatic measurements on non-conducting webs, J. Electrost. 35 (Issues 2–3) (1995) 231–243, https://doi.org/10.1016/0304-3886(95)00040-H.
[18] J.J. Lowke, R. Morrow, Theoretical analysis of removal of oxides of sulphur and nitrogen in pulsed operation of electrostatic precipitators, IEEE Trans. Plasma Sci. 23 (4) (1995).