# Revisiting the Joshi effect

**Sanjay M. Wagh* and Dilip A. Deshpande**

Central India Research Institute, 34, Farmland, Ramdaspeth, Nagpur 440 010, India

**Here, we argue for the need of revisiting the Joshi effect, which is an important instance of the effect of light on matter, by developing an appropriate theory for the electrode-less discharge that underlies this effect.**

**Keywords:** Electrode-less discharge, Joshi effect, metal electrode discharge, plasma formation.

## Historical perspective

STUDIES of discharge in gases under high electric voltages led to discoveries in physics such as those of X-rays, electrons, etc. These studies had electrodes placed in 'direct contact' with the gas undergoing discharge, and such configurations were referred to as metal electrode discharge systems.

Following Warburg's studies[1–4] during 1909–1925, an electrode-less discharge too had attracted considerable attention. In such studies, a closed glass tube having gas is placed between the plates of a capacitor across which an alternating voltage is applied. In this case, the gas is not in 'direct contact' with the electrodes, and such configurations were referred to as electrode-less discharge systems. Warburg suggested that the surface charges on the inner walls of the glass tube controlled, at least partly, the features of the electrode-less discharge.

In 1928, Penning and co-workers[5–9] discovered an increase in the discharge threshold potential of the argon–neon mixtures when the discharge tube (of the electrode-less system) was irradiated by an external neon light. In this case, irradiation was from times prior to plasma formation in the discharge. This increase in the threshold potential, the Penning effect, had also been explained as being due to the destruction of the meta-stable states of neon as a consequence of the irradiation of the gas by neon light, affecting secondary ionization processes due to collisions in the gas undergoing discharge.

In 1937, Klemenc *et al.*[10] too had supported the relevance of the surface charges on the walls of the discharge tube.

In 1940, Joshi and Narasimhan[11] discovered that the RMS value of the stabilized discharge current in an ozonizer (Figure 1), filled with chlorine (at 3.2 mm of Hg, 30°C and operated at 50 Hz for the applied AC voltage) diminishes, almost instantaneously, following the irradiation of the ozonizer by light from an incandescent lamp. This effect of light was also found to be completely reversible: on stopping the irradiation, the 'dark' value of current restores in the ozonizer.

Following this discovery, called the Joshi effect, these observations got extended to different values of gas pressure, to other gas systems, to various frequencies of the AC voltage, and to different types of irradiation. See Kher[12] and Arnikar[13] for early bibliography of these studies, and for the details of the theory postulating the important role of surface layer of charges on the walls of the ozonizer. In contrast to the Penning effect, the irradiation of the tube was done after the discharge plasma formed in the container, and not from times prior to its formation.

Notably, the Joshi effect was never observed with the metal electrode discharge systems then, but was observed only with the electrode-less discharge systems.

The Joshi effect is described as the positive or negative change in discharge current passing through an electrode-less discharge tube, i.e. a high voltage electrodeless alternating current corona discharge, when external radiation is allowed to fall on the tube.

But, certain important features of the Joshi effect are missed in this description. Thence, in 1971, the Joshi effect was described as[14]: 'When the voltage across a discharge tube is gradually increased, under certain conditions and in certain regions, feeble and intermittent but successive discharges that are visible to the naked eye can be seen. Under this condition, illumination from outside can stop such discharge instantaneously; as soon as the illumination is cut-off, the discharge begins to start again. Its response to putting-on and shutting-off of the illumination is instantaneous and repetitive. … when there is no visible glow discharge, illumination from outside initiates the discharge instantaneously; as soon as the illumination is cut-off, the discharge stops, thus revealing that external radiation is under certain conditions an indispensable factor… .'

These important aspects of the Joshi effect are not captured by the above simple description.

The Joshi effect had been studied in tubes of varied designs and electrode geometry like: (i) all-glass ozonizer from Siemens; (ii) wire-in-glass cylinder semi-ozonizer or the maze type GM counter; (iii) a tube with external electrode sleeves; (iv) a Geissler tube with plane parallel metal electrodes, and (v) a combination of some of these types.

*For correspondence. (e-mail: waghsm.ngp@gmail.com)

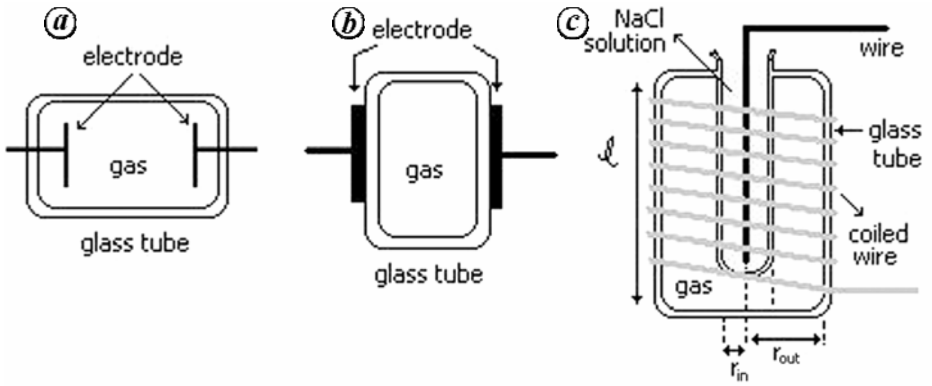


**Figure 1.** ***a***, Metal electrode; ***b***, Electrode-less planar and ***c***, An ozonizer as discharge systems.

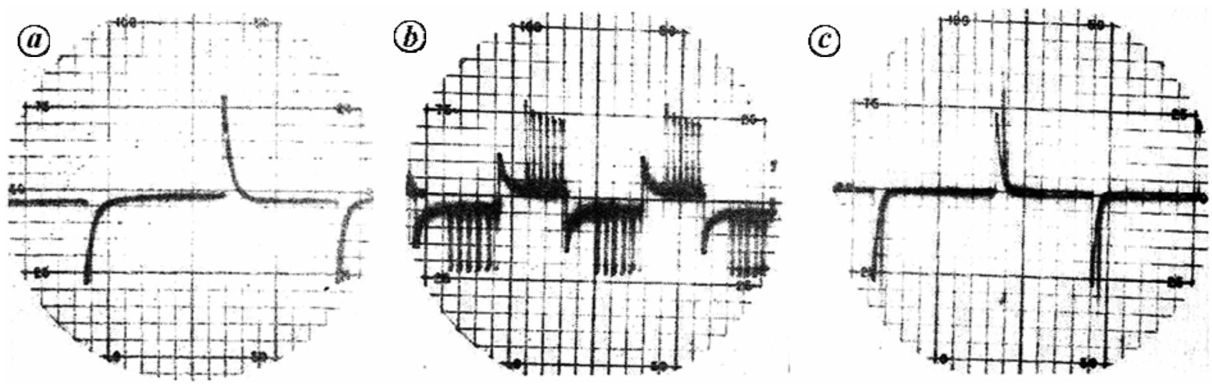


**Figure 2.** Current 'pip' and pulses under square wave voltage (from Kher and Kelkar[15,16]).

For the sake of completeness, we note below some characteristics[15,16] of current pulses in metal electrode and in electrode-less discharge systems.

Under square wave excitation of the discharge tube with peak value of the applied voltage being below that leading to plasma formation in the discharge, a single current pip passes through the tube (Figure 2 *a*). (The duration of this pip was approximately, 5*RC*, with *R* being the resistance in series with the tube.)

The relaxation pulses in metal electrode discharge system under its square wave excitation and the current pulses in an electrode-less system were obtained[15] as shown in Figure 2 *b* and *c*.

For the metal electrode discharge system under its sine wave excitation, current pulses were obtained[15] as shown in Figure 3 *a*. With slow increase of peak voltage beyond the threshold $V_m$, secondary pulses result[15] for an ozonizer excited by sine voltage (Figure 3 *b*). One part of Figure 3 *a* and *b* shows the 'stable' waveform of current over a complete cycle, while the other part (Figure 3 *c*) shows five discharge current pulses of the first half cycle as 'resolved' by the expansion sweep of cathode ray oscilloscope (CRO). A 'triangular' shape with 'rounded' top is characteristic of the secondary pulses of current, but not of the first 'major' current pulse.

As an instance of the Joshi effect, we reproduce one observation from Kher and Kelkar[15,16] in Figure 4. Figure 4 *a* shows the 'dark' waveform at 2 kc/s with exciting voltage of 360 V, and Figure 4 *b* shows the waveform under illumination by 'white' light from an incandescent lamp. Notice the decrease in the height of 'only' the first pulse, but not of the secondary pulses in Figure 4 *b*. That is, only the major current pulse is light-sensitive and the secondary current pulses are light-insensitive.

This Joshi effect gets quantified by the change $\Delta i$ of current or by the percentage change $\Delta i/i$ with respect to the peak value of the dark current pulse. That is, we have the quantification of the Joshi effect as

$$\frac{\Delta i}{i} = \frac{i_{\mathrm{d}} - i_l}{i_{\mathrm{d}}}, \quad (1)$$

with $i_{\mathrm{d}}$ being the dark current and $i_l$ the current with irradiation. Then, $\Delta i > 0$ is called the positive Joshi effect and $\Delta i < 0$ the negative Joshi effect.

It is worth pointing out here that the irradiation of the 'entire' ozonizer tube was made in these studies and not any specific region of the space within the ozonizer[13]. Nevertheless, an important observation was made that only the first major current pulse is light-sensitive and not any of the secondary pulses of current in the ozonizer.

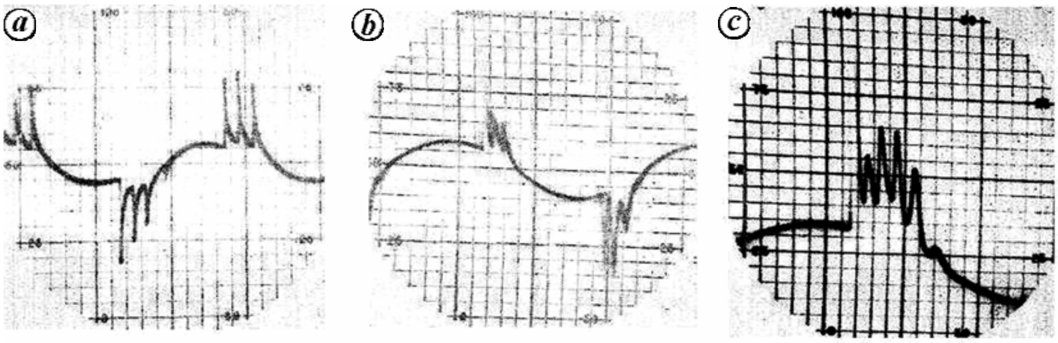

**Figure 3.** Current pulses under sine wave voltage: peak value above threshold (from Kher and Kelkar[15,16]).

Observational features of the Joshi effect, i.e. of the effect of irradiation on electrode-less alternating current corona discharge, were then summarized as follows[12,14]:

- In the beginning, the applied voltage is set to be the threshold potential, $V_m$ (the RMS value of the applied AC voltage at which discharge is initiated in the gas) for about 30 min so as to give the ozonizer an initial period of ageing, that is, exposure to discharge. This ageing is necessary to obtain 'reproducible' results. Therefore, current through the device is a steady-state pattern.
- As the voltage reaches the value $V_m$, only one large discharge current pulse occurs. This pulse is hazy and could not be photographed.
- $V_m$ is practically independent of the frequency of the applied AC voltage.
- On increasing the voltage above $V_m$, the first large discharge current pulse appears, along with additional secondary pulses of smaller current rise.
- The smaller pulses can be resolved by the sweep expansion device of the CRO. A 'triangular' shape with 'rounded' top is noticeable for the secondary pulses, but not for the first 'major' pulse.
- The Joshi effect is observed in all parts of the spectrum, including infrared to $\gamma$-rays, and is not limited to the region of selective absorption.
- The Joshi effect is observed using $Cl_2$, $Br_2$, $NO_2$, $I_2$, $O_2$, $H_2$, air, organic vapours, $N_2O$, $H_2O$, HCl, $SO_2$, $N_2$, rare gases, as well as using vapours of Hg, Se, Te, Zn, Na, K and $Cu_2O$.
- The change of current, decrease to its increase, can be brought about by mere change in the light intensity at all frequencies.
- The magnitude and the sign of the Joshi effect are affected by electrode filming and also by continued discharge. This indicates that the electrode–gas interface is the seat of the phenomenon.
- Increase of applied peak voltage and that of its frequency diminish the magnitude of the Joshi effect. It is small under DC excitation.
- The effect of the rise in temperature of the system is to increase the positive Joshi effect and to inhibit the negative Joshi effect.
- With the increase of gas pressure, $\Delta i$ first increases to a maximum and then decreases.

The Joshi effect is a more widely seen phenomenon than the Penning effect, and is instantaneous, reversible, and occurs with many gaseous systems.

In an attempt to explore the details of the optical excitations in the corona discharge, pulsed irradiation was also attempted[17].

Kher and Kelkar[15,16] established that the 'effective time for the light (Joshi) effect' is restricted to the duration of occurrence of the 'first major pulse' (Figure 4). But, they also showed that pulsed irradiation is not the main ingredient of the Joshi effect.

Recently, it has been experimentally demonstrated that a superconducting nano-wire single-photon detector is deterministically controllable by bright (continuous) illumination by noting that the current through the device drops under illumination[18]. This is nothing but the negative Joshi effect.

In another recent such study, increase in current through the nano-array film has been noted on its irradiation[19]. This is nothing but the positive Joshi effect, we wish (see note 1) to emphasize here.

It may be noted that the above-mentioned studies[18,19] also use continuous and not pulsed illumination. Basically, only the energy of the incident light quanta is of fundamental importance to the Joshi effect and whether these quanta are incident continuously or in a short pulse. That is, whether irradiation of the discharge plasma is continuous or pulsed does not determine the light sensitivity of the first major current pulse of the steady-state waveform. The issue of 'continuous' versus 'pulsed' irradiation is not basic to the mechanism of the Joshi effect.

A proper understanding of the plasma formation in a discharge system is, undoubtedly, a prerequisite for the explanation of the Joshi effect, that is, of the effect of irradiation on the discharge current.

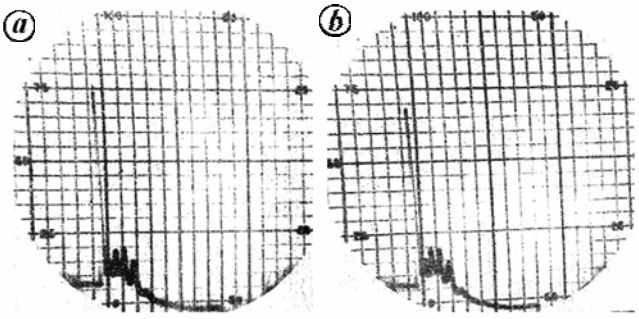

**Figure 4.** The Joshi effect in an ozonizer under its sine wave excitation (from Kher and Kelkar[15,16]).

Notably, the coating or filming of the electrodes was found to be affecting the magnitude and sign of the Joshi effect. We recall that the Joshi effect was observed with only the electrode-less discharge systems.

The parallel-plate electrode-less discharge system was used by Kher *et al.*[20]. Its discharge current under sine wave excitation had a current pulse group in each half cycle with a steady, wide, low-amplitude pulse at a constant phase angle and a flickering, narrow, high-amplitude pulse erratic in phase angle. Only the flickering pulse was found to be affected by external illumination of the tube, i.e. to display the Joshi effect (see later in the text).

However, it was neglected in the aforementioned literature that an ozonizer is a cylindrical capacitor and that the geometry of the capacitor affects the process of formation of the discharge plasma in it. The effect of geometry of the discharge system on plasma formation is clearly evident by the nature of the pulses in Figures 2 and 3.

In what follows, we turn first to plasma formation in cylindrical geometry of the system. Cylindrical shape of the plasma container will then be seen to have a major electric field effect explaining many aspects of the Joshi effect. The role of the involved optical excitation processes will also be discussed.

## Plasma formation in a cylindrical discharge system

The electric field in the space between the electrodes of any cylindrical capacitor, like an ozonizer, is

$$E(r,t) = \frac{V(t)}{r\ln(r_{out}/r_{in})}, \tag{2}$$

where

$$V(t) = V_o \sin\omega t, \tag{3}$$

is the instantaneous value of the applied AC voltage with

$$r_{in} \le r \le r_{out}, \tag{4}$$

with $r$ being the 'radial distance' from the common axis of the cylindrical electrodes of the capacitor.

If $E_s$ is the dielectric strength of the material (gas) contained between the electrodes, then the voltage $V_b$, the breakdown threshold, at which discharge begins in the gas is

$$V_b = E_s r_{in} \ln\left(\frac{r_{out}}{r_{in}}\right). \tag{5}$$

The breakdown of the dielectric (gas) then begins at $r = r_{in}$ with $V = V_b$. When applied voltage increases beyond $V_b$ to its peak value $V_o$, breakdown of the (homogeneous) dielectric extends to radius.

$$r_b = \frac{V_o}{E_s \ln(r_{out}/r_{in})} = r_{in}\left(\frac{V_o}{V_b}\right). \tag{6}$$

A 'breakdown zone' around 'only' the inner tube of the ozonizer has thickness

$$\Delta r(t) = r - r_{in} = r_{in}\left(\frac{V(t) - V_b}{V_b}\right), \tag{7}$$

and we have

$$\Delta r_{max} = r_b - r_{in} = r_{in}\left(\frac{V_o - V_b}{V_b}\right), \tag{8}$$

with $\Delta r_{max}$ being its 'maximum' value for a chosen peak value $V_o$ of the applied voltage.

Importantly, the above 'breakdown zone' is not a 'surface layer' because $\Delta r_{max}$ can be of the order of a centimetre for $V_o = 1.5 \times V_b$.

Further, we can expect that the breakdown of the dielectric occurs within a volume, and not as a 'sectional surface' of the medium, even at $V_o = V_b$. Free charges accelerating in the electric field cause secondary creation of free charges, by Townsend avalanches, in some volume or (elemental) zone.

The extent of the consequent 'elemental zone' of dielectric breakdown will depend on the density, nature of the dielectric material and other relevant factors. But, when dielectric breaks down at $V_o = V_b$, we can expect around the inner tube an elemental breakdown zone of certain thickness $\Delta r_e$, say.

For $V_o = V_b$, let the 'number density of positive charges' reaching the anode be $n_+$ and that of negative charges reaching the cathode be $n_-$. (We neglect here ionization 'outside' the elemental zone.)

As the 'dielectric breakdown zone' is centred around the inner tube of the ozonizer, negative charges are rapidly swept away by the inner tube when acting as a cathode. Charge on the cathode then 'lowers' by $\Delta Q = -q(2\pi r_{in})\ell(n_{-}\Delta r_e)$ rapidly, and consequently the potential across the electrodes 'lowers' by

$$\Delta V = \frac{\Delta Q}{C} = -\frac{q}{C}(2\pi r_{in})\ell(n_{-}\Delta r_e), \quad (9)$$

instantaneously, because change in potential travels at the speed of light in the medium. Here $\ell$ is the length of the cylindrical capacitor or the ozonizer.

But, notice here that the positive charges move to the anode through the 'unbroken' dielectric. Then, the 'moving front' of positive charges undergoes variable acceleration in the electric field $E(r, t)$. It 'drifts' at varying velocity $u_d = \mu E(r, t)$, with $\mu$ being the mobility of charges, to the anode while covering a distance $r_{out} - (r_{in} + \Delta r_e)$; and the current pulse 'exists' for the corresponding time. Amount of charge $\Delta Q = +q(2\pi r_{in}) \times \ell(n_{+}\Delta r_e)$ now gets deposited at the anode, 'lowering' the potential further by $\Delta V$, instantaneously.

Then, due to the dielectric breakdown within the zone of thickness $\Delta r_e$ near the inner tube, voltage changes across electrodes by $2\Delta V$ with associated sharp and large 'major' current pulse.

But, the accelerated motion of the front of charges creates disturbance of pressure in the dielectric (gas). If the frequency of the applied voltage is such that the 'next' front of charges is created before the 'earlier' one has reached the anode, a new disturbance of pressure will simultaneously travel through the dielectric. (We are considering here the case of dielectric breakdown only at the peak voltage $V_o = V_b$.) The drift velocity also changes with the electric field $E(r, t)$.

There are therefore different kinds of disturbances creating pressure waves, travelling at the speed of sound $v_s$, within the dielectric (gas).

Ageing of the ozonizer is 'required' to 'stabilize' the above processes and to obtain a 'stable' waveform for current in the ozonizer. Now, the ageing time depends on the frequency $\omega$, the length $r_{out} - r_{in}$, as well as on factors like viscosity of the gas. We are not so much concerned about these transients here.

Our interest here is in the stabilized pattern of the above processes, and it will then correspond to 'standing waves' of sound, within the cylindrical geometry of the capacitor, like those of an open pipe (Figure 5). Major creation of charges due to secondary ionization will then occur at the corresponding pressure maxima.

Let us then consider a 'stabilized' waveform after the ageing of the ozonizer has taken place. The major pulse of current is provided by the dielectric breakdown near the inner tube of the ozonizer. It corresponds to 'primary' charges of current within the ozonizer. These charges cause further ionization 'outside' the dielectric breakdown zone.

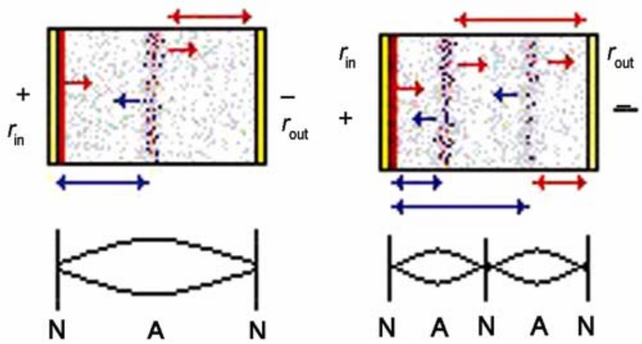


**Figure 5.** Standing wave(s) of pressure in an ozonizer.

The fundamental mode of standing waves will be the first to be excited in the (dielectric) gas and the 'first' secondary pulse of current will correspond to the collisional ionization at its pressure maximum by primary charges. This, the first secondary, pulse will have a 'symmetric triangular' form, for its pressure maximum is located half way between the electrodes.

With the slow increase of the peak voltage $V_o$ beyond the breakdown threshold $V_b$, a subsequent 'bunch' of secondary pulses will result from the excitation of the corresponding mode of standing waves.

The widths of the pressure maxima provide for the 'rounded top' feature of secondary pulses in the stabilized discharge pattern. The secondary pulses can also be expected to be 'triangular' in shape. The strengths of these pulses will depend on the degree of ionization (caused mostly by the primary charges created during the dielectric breakdown).

These theoretical 'features' of current pulses agree quite well with the observations of Kher and Kelkar[15,16], as reproduced in Figure 3 *b* and *c*.

The number of secondary pulses can be predicted. Kher and Kelkar[15] provide it empirically as:

$$N = \frac{V_o - V_e}{V_i - V_e}, \quad (10)$$

where $V_i$ is the ignition voltage at which the current pulse begins and $V_e$ is the extinction voltage at which the same current pulse ends. The empirical formula (eq. (10)) can now be substantiated with the underlying theory developed in the present work.

Now, it is important to note that the charge carriers of current in the ozonizer are 'positive' when its inner tube is acting as a cathode, while they are 'negative' when the inner tube is acting as an anode. The characteristics of the discharge current pulses in the 'upper half' cycle and those in the 'lower half' cycle are then those of 'different' charge carriers.

The aforementioned difference in charge carriers is clearly recognizable from the differences in the observed pulses, as in Figure 3. Corresponding theory, then, leads to measurement of the mobility of charge carriers using the characteristics of pulses.

If the charges flow with drift velocity $v_d$ over the distance $d$, and if their number density at the anti-node of standing wave of pressure is $n_c = \eta n$, then the current density is

$$j_c = q\eta n \frac{v_d}{d} \equiv q\mu\eta n \frac{E(r,t)}{d}, \tag{11}$$

where $n$ is the number density of molecules at the anti-node, $\eta$ is the fraction of these molecules getting ionized, and $\mu$ is the mobility of carriers of charge $q$.

The total current density is then

$$j = j_+ + j_- = q\eta n \left[\frac{\mu_+}{d_+} + \frac{\mu_-}{d_-}\right] E(r,t) \tag{12}$$

where $d_+$ and $d_-$ are distances travelled by the positive and negative charges respectively. In general, $d_+$ and $d_-$ differ, depending on the location of the anti-node within the discharge space. For the first mode of the standing wave of pressure however, $d_+ = d_-$.

When electrons are the dominant charge carriers, as is the case when electrons produced in ionization at the anti-node travel to the anode, we have $\mu_- >> \mu_+$. When increasing (decreasing), the current exhibits sharper rise (fall) in this case.

When ions dominate as the charge carriers, electrons produced at the anti-node having reached the anode, the term with $\mu_-$ is to be neglected; and when increasing (decreasing), the current then exhibits comparatively less sharper rise (fall).

The transition from electron dominance to ionic dominance as charge carriers in the discharge tube is gradual, and this explains the observed[15,16] 'rounded top' feature of the current pulses.

Therefore, notice here that for the upper half cycle of the current waveform, the rising portion has electrons as dominant charge carriers and the falling portion has ions as dominant charge carriers. For the lower half cycle however, electrons are the dominant charge carriers. Also, notice that the amplitude of the current pulse(s) is 'larger' during the lower half cycle than in the upper half cycle. This is because of the 'larger' value of $\eta$ during the lower half cycle.

Now, measuring area under (linear) portion of a current pulse (Figure 3 *c*), we obtain the (total) charge flowing in the device for the corresponding time duration. From this experimental information and that of the strength of the electric field determined on the basis of the measurement of voltage across the discharge tube, it is then possible to measure the mobility of charges in the discharge tube.

Having established the origins of the 'stabilized' waveform of current pulses in the ozonizer as well as the 'information' that can be extracted from these pulses, let us now turn to the effect of irradiation of the tube on the current pulses, i.e. to the Joshi effect.

## Plasma and its irradiation

The process of formation of plasma in an electric discharge has the following aspects[21–26].

(i) First, a moving electron causes ionization in the gas. With Townsend's first ionization coefficient, $\alpha$, the corresponding current, $i$, is

$$i = i_o e^{\alpha d}, \tag{13}$$

where $d$ is the size of the discharge gap and $i_o$ is the initial value of current in the system.

(ii) Within a self-sustained discharge, secondary electron emission takes place in many ways. All these ways can be described by a single Townsend's second ionization coefficient, denoted by $\gamma$, which provides for the number of secondary electrons produced per positive ion. The corresponding discharge current, $i$, is given by

$$i = \frac{i_o e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}. \tag{14}$$

At high voltage, the denominator becomes close to zero and very large current flows through the system. Large current through the device signals the dielectric breakdown. The electric discharge then maintains itself at this 'breakdown' value of the voltage and at values higher than it.

Any change in current, $\pm \Delta i$, may now be interpreted to be the 'decrease/increase in the breakdown voltage' of the dielectric. This can happen, in general, due to increase/decrease of $\alpha$ or $\gamma$, or both. However, $\alpha$ is not known to vary considerably. Thus, the change in $\gamma$ is the main determining factor here for the change in the discharge current.

Mechanisms removing electrons from the discharge space can be expected to be greatly affecting the change in current through the device.

- Adsorption of molecules on electrode surface often decreases $\gamma$ appreciably by increasing the 'effective' work function of the surface. This decreases the discharge current. The ionization potential of the gas molecules has a role in deciding the coefficient $\gamma$; but not any decisive role in determining the sign and magnitude of the change in the discharge current through the device.

- As another example, electron attachment to molecules of high electron affinities lowers the discharge current. This is because electron avalanches are prevented by such an attachment. Mobility of charges also decreases in such an attachment.
- In electron–ion recombination processes, electrons get removed from the discharge space. This also lowers the discharge current. In gaseous mixtures, electrons attach themselves to molecules of higher electron–ion recombination coefficient.
- Charge transfer also takes place in the collision between an ion and a neutral molecule. For gases *A* and *B*, with the ionization potential of species *B* being lower than that of the species *A*, the charge transfer reaction

$$A^+ + B \rightarrow A + B^+, \tag{15}$$

occurs readily. The $B^+$ ion so formed has much higher electron–ion recombination coefficient than the $A^+$ ion. Appreciable number of electrons can then be removed from the discharge space. Therefore, charge transfer processes decrease the discharge current through the system.

Of importance now are the mobilities of charge carriers. In the case of discharge, large numbers of ion pairs are produced in the discharge space.

- Due to their high mobility, electrons reach the anode quickly. But the positive ions lag behind in their motion towards the cathode. Majority of positive ions also travel relatively longer distances than electrons. This arises due to the spatial disposition of 'conically shaped' electron avalanche, with its tip directed at the cathode. An appreciable time is then required for the positive ions to reach the cathode and clear the space charge. The lower ionic mobility then introduces an increase in the statistical time lag between the discharge pulses. Thus, the discharge current decreases.
- If the molecules in the gas are polar, they form clusters. Due to increased mass, the mobility of charges decreases in cluster formation, leading to decrease in the discharge current.

Electronic number can also get enhanced due to some processes. The following is such an example.

- A meta-stable state $A^*$ of the species *A*, say, can, on collision with a molecule of species *B*, lead to the interaction

$$A^* + B \rightarrow A + B^+ + \text{e}. \tag{16}$$

This leads to the enhancement of discharge current in the tube containing the plasma.

When the plasma container is electrically excited at the plasma formation voltage for sufficiently long time, that is, it is aged, a steady state is reached within the dielectric (gas) inside it. Under ageing, the aforementioned processes occur under equilibrium. This equilibrium state has a steady pattern of current pulses flowing through the circuit of the capacitor. As discussed before, the characteristics of steady-state current pulses are dependent on the geometry of the capacitor.

Now, any external illumination of the plasma container changes the conditions of the equilibrium of the aforementioned processes.

For example, under external illumination, the reaction of photonic de-excitation of atomic state of the following kind can take place

$$A^* + \varepsilon \rightarrow A, \tag{17}$$

with $\varepsilon$ being the (energy of the) incident light quantum. The process of collisional ionization thus gets inhibited in the plasma, and discharge current decreases under illumination. (Such reactions in neon–argon mixtures underlie the Penning effect in them.)

Under external illumination, 'new' values of the equilibrium parameters of the dielectric get established. The 'new' equilibrium values, now correspond to 'increased' or 'decreased' value for the discharge current pulse. As was emphasized before, only the first major current pulse is light-sensitive.

In view of the theory underlying plasma formation in cylindrical configuration as developed here, it is then important to notice that irradiation does not affect the process of (secondary) collisional ionization at the pressure maxima of the standing waves of pressure within the ozonizer. It then affects only the processes taking place within the zone of dielectric breakdown close to the inner tube of the ozonizer.

Reasons[14,21,26] for only the first major current pulse as being light-sensitive, or showing the Joshi effect, and the secondary pulses being light-insensitive are thus atomic. On the basis of the earlier discussion, it is now clear that the effect of irradiation is primarily limited to the dielectric breakdown zone centred only around the inner tube of the ozonizer; it is this zone that harbours the origin of the first major current pulse.

Thus, irradiation disturbs only the processes of dielectric breakdown zone; and these disturbances involve affecting the meta-stable states of the gas. Furthermore, the meta-stable states of the gas occurring only within the dielectric breakdown zone are affected by irradiation and not those, if any, within the pressure maxima of the standing mode. This fact is then important for the explanation of the Joshi effect.

As we are not considering any specific dielectric here, we also do not deal with specific quantitative estimates. But, we do stress the following implications of the theory developed here.

It is convenient to model the first major discharge current pulse by

$$i = \alpha \frac{v_d}{Z}, \tag{18}$$

where $v_d$ is the 'drift' velocity of electrons and $Z$ is the coefficient of electron removal/addition (see note 2).

Recall that, under suitable conditions, the decrease $\Delta i < 0$ was observed and was called as the negative Joshi effect; while the increase $\Delta i > 0$ was also observed and called as the positive Joshi effect. Explanation of the Joshi effect must account for both of them.

As percentage Joshi effect, it is noteworthy indeed that 100% negative Joshi effect and about 500% positive Joshi effect were observed. A sharp reversal from positive to negative Joshi effect for a small rise of the peak value of the applied voltage was also noted[20,27–29]. For such studies, the inner tube of the ozonizer was coated with a variety of materials with the intention of establishing the presence of surface layer of adsorbed meta-stable states of the gas used in the ozonizer tube.

Equation (18) may then be used with $Z$ changing under external illumination. For the negative Joshi effect, the coefficient $Z$ increases and for the positive Joshi effect the coefficient $Z$ decreases under the external illumination of the plasma. Under typical experimental situations[15,16], we may not expect both the velocity $v_d$ and Townsend's coefficient $\alpha$, to be greatly affected by any external illumination.

## Concluding remarks

The glass material of the tubes of the ozonizer has no role to play in the aforementioned theoretical considerations. Therefore, we can consider a cylindrical capacitor of two coaxial metallic cylinders filled with dielectric, and apply alternating voltage across its electrodes.

Alternatively, we may also consider (see note 3) a glass system with the inside filmed with a transparent coating of conducting material like ITO or silver. The 'dielectric breakdown zone' will also be created in this case and the above considerations will be applicable, equally well, to such a capacitor.

Aspects of discharge pulses and Joshi effect can be then studied using such designs for a cylindrical capacitor, then.

In this context, we emphasize that the Joshi effect was not observed in (parallel plates) metal electrode discharge systems and the suggested cylindrical systems are metal electrode systems.

However, the theory developed herein unequivocally predicts that the Joshi effect will be observed using a cylindrical metal electrode discharge system. Cylindrical configuration may also be advantageous for a variety of applications of the Joshi effect.

In the case of a parallel-plate electrode-less system as was used by Kher *et al.*[20], the wide, steady, low-amplitude pulse at a constant phase angle is due to secondary ionization at the pressure maxima of the standing wave of pressure within the tube. The flickering pulse with erratic phase is then due to dielectric 'breakdown'. As noted before, only the flickering pulse is light-sensitive and the related details are specific to the dielectric under use.

Now, in the context of similar studies conducted during 1976–1978, the optogalvanic effect was also discovered[30–44]. This deals with the effect of irradiation of the ozonizer on the voltage across it, rather than with the current in it. Studies of optogalvanic effect have led to optogalvanic spectroscopy.

Arnikar[45] pointed out the 'close similarity' between the Joshi effect and the optogalvanic effect discovered during 1976–1978. However, these two effects are not identical, as the voltage rise (whenever it happens) requires conditions of charge separation; but current rise requires only those of charge creation. 'Information' contained within the voltage changes and the current changes should be 'complementary' to each other. However, related issues have not been studied even to this date.

In conclusion, we suggest revisiting the Joshi effect, for many of its theoretical and experimental aspects are unexplored; and so also its applications.

## Notes

1. However, the authors[18,19] do not refer to the effect of illumination on current through the respective devices as being the instances of the Joshi effect. Indeed, the community at large does not, though being unaware of it, refer to the effect of illumination on current through the device as the Joshi effect.
2. When electron–ion recombination is the dominant process, the coefficient $Z$ is the coefficient of ionic recombination.
3. We are grateful to one of the referees for this suggestion.


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