High-tension corona controlled ozone generator for environment protection

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Abstract. Engineering details of a high voltage driven corona-plasma ozone generator are described. The plasma diode of generator has coaxial cylindrical geometry with cathode located inside anode. Cathode is made of a large number of radial gas nozzles arranged on central tubular mast which admits oxygen gas. The sharp endings of the nozzles along with a set of corona rings create the high electric field at the cathode required for formation of dense corona plume responsible for O$_3$ evolution. A model of coronal plasma generation and ozone production is presented. The plasma formation is strongly dependent on the electric field and temperature in side diode where a high electron density in a low temperature negative corona is suited for high ozone yields. These are established by suitable regulation of A-K gap, voltage, oxygen pressure, and cathode-nozzle population.

1. Introduction
Ozone is a powerful disinfectant and oxidant important for purification of drinking water, room air, and environment [1, 2]. So also it is used for fumigation and sterilization in operation theatres in hospitals, disinfecting food products to increase shelf life, ozone therapy [3], and many more important applications. Plasma route of ozone generation is highly efficient [1] than other routes such as ultraviolet method. This work discusses the important features of a high-voltage (HV) corona controlled plasma-ozone generator which is under development presently in Pillai’s Institute of Information Technology, Engineering, Media Studies and Research (PIIT) New Panvel. Engineering details of this generator are described in present work. A model of corona plasma generation as well as that of ozone production is also described and results presented along with discussions. The generator so developed will be used in many of above various applications.

The generator makes use a negative corona discharge formed over the surface of cathode (K) of plasma diode where cathode is raised to a high negative potential (-1 to –60 keV) with respect to anode cup (A). Molecular oxygen O$_2$ is admitted in the anode-cathode (A-K) gap region and O$_2$ is split into atomic radicals O through collisions by electron emissions from cathode. Alongside the radicals combine with free molecules O$_2$ and form ozone (O$_3$) the allotrope. The process is illustrated below is reversible having half-lives of tens of minutes at the ambient temperature and reduces with increase in temperature.
Plasma formation inside diode is strongly dependent on the electric field and temperature. A high electron density in a low temperature negative corona gives rise to high ozone concentrations. Details of theory on these are given in companion paper [4] and further details elsewhere [2].

2. Description of generator cum processor

Figure 1 illustrates schematically the entire generator cum processor [2]. Ozone is generated in the corona-plasma generator and led into the rectangular shaped reactor vessel of 300 liters capacity where water is processed and purified for human consumption. In this there is option for treating either tap water or pond water. The pond water option can be exercised to benefit the potable water scarcity areas. Many producers of ozone generators make use oxygen from open air for ozone generation. So we have kept the option open for using oxygen either directly from open air or from an oxygen cylinder.

Water from the input source is first filtered of solid impurities over \( \mu \)m size and collected in a circulator tank of 50 liters capacity. This water is pumped into a 12 mm venturi line which leads to the reactor vessel. An ozone compatible water pump of 30 liters/min capacity is used for this. Meanwhile, ozone from generator is forced normally into water in venture-line using a diaphragm pump of 20 liters/min to enable rapid mixing of ozone in water. Ozone is only partly dissolved in water in the process. The conglomeration of water and ozone bubbles is then forced into a 1 meter long diffuser line having numerous side holes of 1 mm size. The diffuser line is introduced into the reactor tank through one of the bottom ports on the longer side end of tank. This forced entry in to water tank allowed better mixing and homogenization of dissolved ozone in water. Mixing is further improved by stirring the water with a motor driven stirrer suspended from tank cover.

Figure 1. Schematic of corona-plasma ozone-generator cum processing unit.
plate. The dissolved ozone is the main disinfectant here that acted on the harmful bacteria, virus, etc and destroyed them making the water potable.

A major part of ozone is still not dissolved in water, emerged from water and accumulates over the surface. When this ozone concentration over the surface exceeds 10 ppm, the same is recycled into the reactor fluid through a second diffuser line introduced from a bottom port opposite to the forward diffuser line, and drawn by a second diaphragm pump. Also for further improving the degree of water purity, the processed water in reactor vessel is recycled and reprocessed further. For this, the circulator tank is emptied of input water and filled with the processed water in reactor of earlier cycle. The processing is repeated till the required purity is attained.

3. Corona plasma diode

The plasma diode is of r-z geometry made of an anode cup and a cathode structure all of which are coaxially housed inside generator vessel of 330 mm nominal ID and 400 mm height as in figure 2. The cathode which is kept at the system ground potential is made of a large number of radial gas nozzles coaxially arranged on a central tubular mast which admits the oxygen gas. The sharp endings of the nozzles create the high electric field over cathode required for formation of a dense negative corona plume responsible for \( O_3 \) evolution. The anode cup is kept at a high positive voltage \( (\phi_a) \) with respect to cathode and varied in the range 0-60 kV. Anode is insulated from the system ground and held by a HV Teflon bushing, and connected to the HV power supply through a shielded coaxial HV cable. Overall HV electrical shielding of the generator is made complete with a SS shield dome covering the HV Teflon bushing where all shielding along with generator vessel is connected to the electrical ground of the system for ensuring safe and user friendly operations of complete system. The cathode, anode, the generator vessel, and all other metal parts which are in contact with ozone are made of the most ozone resistant metal, viz.

![Figure 2. Corona-plasma ozone-generator scheme.](image-url)
stainless steel (SS-316). Similarly all other components in contact with ozone are also made of ozone resistant other materials, such as, Teflon.

The cathode assembly which is connected to the negative terminal and electrical ground of HV supply is directly held on the bottom flange of generator vessel. The cathode assembly serves the dual purpose of (1) injection of gas into the A-K gap and (2) creation of electric field needed for corona discharge formation. As stated earlier, oxygen is injected into the gap by large number of gas nozzles (of 1 mm nominal bore) held on (for example in scheme-1) six equally spaced (20 mm spaced) radial planes on the tube mast of 50 mm diameter which is part of bottom flange and coaxial to the generator vessel. Each of these planes has equally spaced 16 nozzles each so that in all there are 96 nozzles. The nozzle-pinnacles face the anode inner wall and create the high electric field envelope over the cathode emitting surface as required. For same reason corona rings with sharp saw cuts on periphery are positioned alternatively on side of each nozzle plane in a different scheme. All the gas nozzles and corona rings together with the tube mast as shown in figure 3 (for example, with 12 nozzle planes in scheme 3) form the cathode assembly.

In presence of HV applied across A-K and oxygen gas pervading the annular gap, a corona plasma discharge aided by field emissions from cathode is formed encircling the cathode. Ozone is formed in this discharge at a rate decided by the background electron density \(n_e\) and temperature \(T\) in the region where \(n_e\) and \(T\) are determined by the chosen control parameters. In general a maximum \(n_e\) and a minimum \(T\) favor maximum ozone production. This is presently sought to be fulfilled by varying the voltage \(\phi_0\), A-K gap distance \(d\), gas pressure \(P\) and cathode configuration. A-K gap is varied here by adjusting the lengths of cathode nozzles and suitably choosing the corona ring sizes. Accordingly current in the gap is controlled and power dissipation kept to a minimum level so that \(T\) is low. Theoretical analyses were carried out on these lines in different schemes and results compared and discussed in a companion paper [4].

4. Corona and Ozone Generation Model
High voltage applied across the A-K gap results in high electric field \(E = -\nabla \phi\) surrounding cathode nozzle/corona-ring tips and gives rise to local field emissions which heat up the tips and
initiate thermionic emission. The emission thereafter is sustained by both field $E$ and
temperature $T$ and T-F emission [5] so rendered from cathode is given as:

$$I_{TF} = 2\pi AT^2 \exp\left(-\frac{e\phi}{k_BT}\right) r_f I_f \exp\left(\frac{cE_r^{3/2}}{T}\right)$$

(3)

where $e$ is electronic charge, $\phi$ is work function of cathode, $k_B$ is Boltzmann constant, $r_f, l, f$
appearing cathode emitter radius, cathode length, and a factor describing the effective emission area, $A$
is thermionic constant, $E_r = \frac{d\phi}{dr}$ is the radial field and $c$ is T-F constant. Whereas for extremely
high $E_r$, field emission (FE) is dominant [5] and described as:

$$I_f = 2\pi r f A r F K E c E \exp^2 - \frac{2}{\phi \pi}$$

(4)

where $A_F$ and $c_F$ are respective FE constants. The electrons from (3), (4) as the case may be
engage in collisions with the oxygen molecules and produce $O^-$ as in (1) and in the process
produce negative corona plasma. As $O^-$ are dragged towards the anode along with electrons, $O^-$
meet free $O_2$ molecules en-route and form $O_3$ the allotrope as in (2). As noted earlier ozone has a
short half life that reduces with temperature increase and causes early reversal of $O_3$ to $O_2$ and $O^-$.

Out of emissions (3), (4) the part that is drawn by plasma diode is only $I_b$ given by the
modified Child-Langmuir law [5] written as

$$I_b = 2.34 \times 10^{-2} a \phi^{3/2} / [(d - x)^2 + R \phi^{1/2}]$$

(5)

where $a = 2\pi r_A l$, $r_A$ and $l$ are radius and length of anode respectively, and $x$ is corona plume depth. Potential $\phi$ in (5) is substituted on relaxation of Poisson equations in r-z space:

$$\frac{\delta^2 \phi}{\delta r^2} + \frac{1}{r} \frac{\delta \phi}{\delta r} + \frac{\delta^2 \phi}{\delta z^2} = -\frac{\rho}{\varepsilon}$$

(6)

where space charge density $\rho = J/v$, $J = I_b/a$, $v$ is electron velocity, $\varepsilon = \varepsilon_r \varepsilon_0$, $\varepsilon_r$ is relative permittivity of oxygen gas, and $\varepsilon_0$ is permittivity of free space. Equation (6) is described
in a five-point finite-difference form [6] and solved employing MATLAB [7] and successive
over-relaxation. Potential and field distributions were determined inside the plasma diode in
various schemes and the details of studies and results reported elsewhere [4]. Of these the
computed potential distribution in scheme-1 having 6 nozzle planes alone on cathode is illustrated
in figure 4. In this, for applied voltage $\phi_0 = 10$ kV in A-K gap, the electric fields over cathode
surface exceeds 10 MV/m for small d of a few mm and field emission exceeds MA. The charge
density created in such conditions in gas pressure of 1 bar or more are also close to the gas
density, i.e., $10^{25}$ m$^{-3}$. Oxygen radicals described through (1) and (2) are hence high and observed
in some of the experiments with over 20 per cent efficiency as reported [1].
Figure 4. Diode geometry in scheme - 1 having six nozzle planes, along with computed potential distribution in the r-z axial plane of symmetry.

5. Summary
This work describes details of corona-plasma ozone generator cum processor under development. The generator so developed will be employed for various important applications such as purification of ambient air, drinking water, ozone therapy, and so on. The generator plasma diode has cylindrical geometry with a cathode assembly coaxially situated inside the anode. The cathode assembly is made of a large number of gas nozzles arranged radial symmetrically on a central tubular mast which admits the oxygen gas. The sharp endings of the nozzles create high electric field over the cathode surface and aid in formation of an oxygen negative-corona plume. This in turn results in dense O$_3$ production. A model of coronal plasma generation and ozone production is presented. High electron density coupled with low temperature favors ozone production and its yield.

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