Chapter 5

Development and characterizations of atmospheric plasma devices
5.0 Introduction

Atmospheric pressure micro-plasma jets have become hot issues of current low-temperature plasma research because of their immense potentials for material processing and biomedical applications [1]. The micro-plasma jets generate plasma plumes in open space and thus, they can be used for direct treatment [2]. They do not require vacuum systems not the expensive instruments. This makes the atmospheric plasma, a convenient and user friendly tool for innovative experiments. They have been operated at an excitation frequency either in the several tens of kilohertz ac range or in the radio-frequency (RF) range [3-5].

The plasma generation in micro-plasma jets relies mainly on two mechanisms; corona discharge and dielectric barrier discharge (DBD) [6-8]. A corona discharge appears as a luminous glow localized in space around a point tip (or wire) in a highly non-uniform electric field, whereas the DBD discharge is produced in the region surrounded by two dielectric surfaces backed by metallic electrodes to prevent any arcing. DBDs are becoming common micro-plasma devices, particularly, when operating at higher pressures (hundreds of Torr and above) due to their intrinsic stability against arcing. In fact, commercial plasma display panels use a DBD configuration on scales of hundreds of microns [9].

It is surprising that the first exploitation of dielectric barrier discharges (DBDs) was started in Europe as early as 100 years ago. It was basically used for ozone production for the treatment of drinking water [10,11]. Since then, the number of industrial applications of this type of discharge started to grow. However during the last few years their importance has been further exemplified and attempts are being made worldwide to use the DBD devices for pollution control at large scale and also to polymer surface treatment for promoting wettability, printability, and adhesion.

The reason behind such a huge success lies in the fact that DBDs are developed as stable, high-pressure, and non-thermal plasma sources [12]. The plasma in DBDs are sustained between electrodes of which one is (or both are) covered by a dielectric. The electrodes are driven with alternating voltages of tens of Hz to as high as radio frequency (rf), MHz. Conventional DBDs with large area electrodes sustained at atmospheric pressure typically have gap spacing of a few mm. At low frequencies, the plasma in these devices operates in a filamentary mode with each individual filament having a diameter of tens to hundreds of µm. When operating at a high frequency (tens of kHz or above) or with rapidly rising voltage pulses in mildly attaching gas
mixtures, DBDs often visually appear to be a uniform plasma since the rapid onset of voltage and pre-ionization from the prior pulse tend to work against the formation of large filaments [13,14].

They are also proved to be inexpensive and easy to operate. Recently, the uses of DBD reactors have been explored in the automobile industries for removing the pollutant gases. Micro-plasma torches have been developed for the medical applications more commonly for the purpose of sterilization. Looking to the immense applications of DBD plasmas in the field of environmental pollution control, for controlling the water pollution, by removing the organic impurities and for modern biomedical applications, we have decided to develop DBD reactors by indigenous fabrication in the laboratory.

The chapter describes the details of basically two kinds of DBD reactors and their characterizations in terms of the plasma species and their energies. Out of these two devices the first one consisted of an extended dielectric barrier atmospheric plasma reactor, which was suitable for removing the pollutants from the exhausts of automobiles. Its design was specifically modified to suite the requirements of a medium scale four wheeler vehicle. The second DBD reactor was devised for sterilization in the dental industries. Keeping this in view the micro plasma was designed to form a fine plasma plume and was capable of functioning like a non-thermal plasma torch. Its applications for endodontic treatment are described in chapter 6. It was also found suitable for treating the polluted water by removing the dissolved organic pollutants. The experimental results of such applications are also described in chapter 6.

Several other designs were tested by fabricating laboratory scale models. Brief descriptions of these devices are also summarized in this chapter. The excitation source was a pulsed ac commercial supply and was commonly used for exciting all the DBD devices. The output waveform of the pulsed power supply was recorded on an oscilloscope when connected with the DBD plasma device assembly as shown in Fig 5.1(a)-(b). It was also noticed that all the DBD plasma reactors could efficiently generate ozone as a reaction product starting from air. The smell of ozone was taken as identification for proving that the DBD reactors can be used in applications where, ozone is reactive oxygen species (ROS). It is worthless to say that, recently, the importance of ROS has been realized in the field of antimicrobial studies.
**5.1 Development of cylindrical DBD plasma device (DBD-1)**

The sectional schematic diagram of cylindrical DBD plasma device is shown in Fig 5.2. This reactor consisted of cylindrical geometry having annular flow of air producing the discharge. The inner electrode was a 24 mm dia and 150 mm long copper cylinder, which was completely covered by a cylindrical borosilicate glass tube having a wall thickness of 1.6 mm. The inner electrode was also sealed from both the ends as shown in the Fig 5.2. The outer electrode was a cylindrical stainless steel wire mesh having a thickness of 1mm with 100 mesh size and was covered with outer glass cylinder. The inner diameter of the cylindrical mesh was 36 mm having a length of 280 mm. The annular region, available for the plasma discharge was 6 mm thick as shown in the diagram. Both the ends of the cylindrical device were terminated by flanges made up of PMMA (Polymethyl methacrylate) and were provided with slots facilitating the insertion of glass tubes for flowing the required gases. The connections for both electrodes were also made available on the PMMA flanges. The air gap between the two cylinders was adjusted so that an ac voltage of 6-7 kV would generate sufficiently bright plasma discharge and could sustain without any difficulty. The operating parameters and dimensions of the device are shown in Table 5.1.
gases like NOx,

**Fig 5.2**: Schematic diagram of cylindrical DBD plasma device (a) vertical section (b) Cross section (DBD-1)

**Fig 5.3**: Photographs of DBD plasma device (a) in operation and (b) without operation (DBD-1)

**Fig 5.3** shows the photograph of the device. The device could operate without any risk of the tube being heated for minimum period of one hour. The discharge was produced by flowing different gases and it was observed that an intense glow can sustain for argon with a minimum flow rate. However the intensity of the glow is reduced with increasing flow rate. The DBD device also produced discharge when no gas was flown. However for the application in the automobile exhaust a flow rate of oxygen/air has to be maintained in order to convert the toxic gases like, NOx, into the atmospheric gases.
Table 5.1: Detail specifications of cylindrical DBD plasma device

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Components of device</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total length of the device</td>
<td>280 mm</td>
</tr>
<tr>
<td>2</td>
<td>Inner diameter of the outer cylinder</td>
<td>36 mm</td>
</tr>
<tr>
<td>3</td>
<td>Outer diameter of the inner cylinder</td>
<td>24 mm</td>
</tr>
<tr>
<td>4</td>
<td>Electrodes materials</td>
<td>SS mesh and copper cylinder</td>
</tr>
<tr>
<td>5</td>
<td>Voltage Applied</td>
<td>6 – 7 kV AC</td>
</tr>
<tr>
<td>6</td>
<td>Frequency</td>
<td>50 – 60 Hz</td>
</tr>
<tr>
<td>7</td>
<td>Power Requirement</td>
<td>10 – 15 W</td>
</tr>
<tr>
<td>8</td>
<td>Optimum gas flow</td>
<td>0-4 lpm</td>
</tr>
</tbody>
</table>

5.1.1 Current characteristic of plasmas

![Graph showing the variation of output current of DBD plasma device with gas flowrate.](image)

Fig 5.4: Variation of output current of DBD plasma device with gas flowrate
The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. The plasma current was monitored for different gases and different flow rates (0 to 4 lpm) and is plotted in Fig 5.4. The current remains almost constant when varied in this range. A maximum current of 14.3mA for argon, 13.2 mA for nitrogen and 12.5 mA for oxygen plasma was obtained for this device. Here, output current achieved is directly proportional to the ionization of the respective gas. Argon has the highest output current even its ionization energy is 15.75eV higher than that of oxygen (13.61eV) and nitrogen (14.54eV), it is because both oxygen and nitrogen gases are diatomic so that their ionization take place followed by dissociation of molecules; dissociation energy of oxygen is 5.15eV and of nitrogen is 9.79eV. hence argon has the highest current output.

5.1.2 Diagnostics of the cylindrical plasma device using Optical Emission

Spectroscopy

The plasma excited in the DBD reactor was studied with the help of optical emission spectroscopy. The spectra recorded for air, argon, oxygen and nitrogen are shown in Fig 5.5 (a-d), respectively. All the gaseous species were identified by using the NIIST database. Since the plasma is excited at atmospheric pressure and the system is not evacuated, the lines corresponding to the nitrogen and oxygen are also seen to occur along with argon as shown in Fig 5.5.

The molecular bands for nitrogen as well as oxygen are seen to occur as indicated in the spectra. While exciting the air plasma the presence of NO and ozone could also be observed. The mechanism which is responsible for producing different species in such kind of DBD plasmas has been explained in chapter 1 (section-1.5.4.2). Due to the high electric field strength which is sufficient to produce discharge in the gaseous medium at atmospheric pressure, the electrons generated because of the ionization events undergo acceleration and deceleration during every half cycle of the applied sinusoidal potential. This causes multiple ionization of molecules present in the vicinity of energetic charged species. Although the complete mechanism of ionization and production of stable plasma is quite complicated, some of the reactions which can produce atomic oxygen and atomic nitrogen in air are given below.
Similarly the formation of O₃ molecules in micro-discharge in oxygen and air is explained mainly due to the following reaction [15],

\[ e + O_2 \rightarrow O + O \] ...........................................(5.0)

\[ O + O_2 + M \rightarrow O_3 + M \] ...........................................(5.1)

(where M = O₂ or M = N₂) and reactions responsible for O₃ destruction are:

\[ O_3 + O \rightarrow 2O_2 \] ...........................................(5.2)

Formation of atomic oxygen follows as,

\[ O_3 + M \rightarrow O_2 + O + M \] ...........................................(5.3)

(where, M = O₂, M = N₂, or M = wall; homogeneous or heterogeneous destruction in the reactor volume and on the surface of the electrodes). Also the electrons take part in the reaction leading to the formation of atomic oxygen,

\[ O_3 + e \rightarrow O_2 + O + e \] ...........................................(5.4)

\[ O_3 + e \rightarrow O_2 + O^- \] ...........................................(5.5)

\[ e + N_2 = N + N \] ...........................................(5.6)

\[ e + O_2 = O + O \] ...........................................(5.7)

Finally,

\[ O + N = NO \] ...........................................(5.8)
Fig 5.5: Optical emission spectrum of (a) air plasma (b) argon plasma (c) nitrogen plasma (d) oxygen plasma

Since atmospheric pressure plasmas are considered to be in local thermodynamic equilibrium (LTE) [16], the electron temperature can be determined from the absolute intensity of any atomic or molecular emission, or from Boltzmann plots of population distributions.

The recorded spectra were utilized to calculate the electron temperatures using the equation of straight line given by equation 1.17 in chapter 1. The fitting of straight line for the plots of $\ln \left( \frac{I_{\lambda}}{gA} \right)$ as a function of $E_u$ provides the value of the electrons temperature from the slope $\left( \frac{1}{kT} \right)$. The electron excitation temperatures for argon, nitrogen and oxygen plasmas were calculated by using the OES spectra recorded by maintaining nine different flow rates (0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 lpm of the gases). Typical Boltzmann plots corresponding to OES spectra recorded for argon, nitrogen and oxygen flowing with flow rate of 0.5 lpm are shown in Fig 5.6 (a-c) respectively. Similar plots were obtained for all the recorded spectra corresponding to the plasma generated at different flow rates and different gases. These values are compiled together and are plotted in Fig 5.7 to represent the variation with the flow rates for different gases.
Fig 5.6: Boltzmann plots for (a) Argon plasma (b) Nitrogen plasma (c) Oxygen plasma
It is observed that, the electron temperature in the plasma varies indirectly with gas flow. As gas flow increases electron temperature initially increases up to a flow rate of 0.5 lpm and then starts decreasing consistently. For argon plasma, at the minimum flow rate of 0.5 lpm electron temperature was found to be 2.13 eV; however for maximum flow rate of 4 lpm it is calculated to be 1.77 eV. For nitrogen plasma variation of electron temperature varies from 4.6 eV for 0.5 lpm to 1.77 eV for 4 lpm. However in case of oxygen plasma electron temperature varies from 4.17 eV for 0.5 lpm to 1.34 eV for 4 lpm. The overall trend seems to be similar for all the gases used. However the values of electron temperatures for oxygen and nitrogen are seen to be much higher as compared to that of argon.

This can be explained on the basis of the stability of the ionic states of the noble gases. The positive ion of noble gases (Ar+) is in a metastables state. The accumulative ionization due to collisions between metastable atoms and electrons is important. The electrons after collision and newly produced electrons by ionization belong to low energy electrons [17]. As a result the
electrons loose energy after collision and hence the electron temperature is low in case of argon plasma.

5.2 Development of DBD plasma torch (DBD-2)

The second kind of DBD plasma devise was the micro-plasma torch which could produce a fine plasma beam for the medical applications. The DBD plasma device with flat plate cathode and wire anode geometry was indigenously developed in the laboratory. The schematic of this device is shown in Fig 5.8. This device consisted of tungsten wire electrode (cathode) with a glass tube as dielectric barrier. The assembly of cathode is enveloped in a glass tube, which has a narrow opening at one end, and forms the tip of the plasma torch. The other end of this tube is open for gas input. The anode used in this device was made up of stainless steel plate, which was placed normal to the tip of the torch. This anode plate was covered with a glass plate as a dielectric barrier material to avoid the direct arcing. Fig 5.9 shows the actual photograph of plasma torch assembly.

The plasma was excited with ac power supply. The maximum power delivered while carrying out all the experiments was observed to be 750 mW. Different gases were made to flow from one end of the torch with different flow rates for measuring the electron temperature and the characteristics of the plasma by using OES analysis.
Fig 5.8: Schematic diagram of DBD plasma device with flat plate and wire geometry (DBD-2).

Fig 5.9: Photograph of the plasma torch setup (DBD-2)
5.2.1 Current characteristics of the device (DBD-2)

The plasma was excited with a ac power supply (BRAHMA TC2SVCS) having pulse AC voltage of 12kV, 20Hz pulse frequency and 50% duty cycle. The power delivered to the torch was measured by recording the current waveform across a series resistance during the operation of the plasma. The plasma current varied from 1 to 6 mA when the distance between the tip of the torch and the anode varied from 1 to 3 cm. The variation in the resulting power at different separations of cathode and anode is shown in Fig 5.10.

![Figure 5.10](image)

**Fig 5.10**: (a) I-V characteristics of the device with distance of separation of electrodes. (b) Variation of output power as a function of separation between the electrodes.

5.2.2 Diagnostic of the device DBD-2 by using OES

Optical emission spectroscopic method has been employed to investigate electron temperature of the plasma generated by DBD torch.
Fig 5.11: Variation of electron temperature with gas flow for different gases

Fig 5.11 shows the variation of the electron temperature with gas flow for different gases like, argon, nitrogen and oxygen. It is observed that, the increase in the gas pressure decreases the electron temperature and it is found to be true for argon, nitrogen and oxygen gas plasmas. The decrease in electron temperature with increase in gas pressure is because, increase in gas pressure increases the density of species this enhances the collision rate. As collision rate increases, electron does not get sufficient time for gaining energy and effective temperature of electron decreases. Initially the electron temperature increases for gas flow rate of 0.5 lpm; afterwards it starts to decay constantly with gas flow rate. The variation of electron temperature with gas flow rate for argon plasma is from 2.99 eV for 0.5 lpm to 1.8 eV for 4 lpm, for oxygen plasma it varies from 4.5 eV for 0.5 lpm to 1.44 eV for 4 lpm flow rate, while for nitrogen 4.56 eV for 0.5 lpm to 1.57 eV for 4 lpm. In case of oxygen and nitrogen plasmas, the electron temperature is found to be closer for all the gas pressures but in case of argon plasma the electron temperature is calculated to be lower as can be seen from Fig 5.11.
The effect of the cathode material on the electron temperature has also been investigated for tungsten, nickel, copper and iron cathode materials. For every cathode material emission spectra were recorded and corresponding electron temperature were calculated for different gas flow rate. The variation of electron temperature is plotted with the gas flow rate for different cathode materials as shown in the Fig 5.12. The electron temperature in case of tungsten is seen to be higher than all the other materials. It is due to the higher electron emission property of tungsten. For all applications studies of this device tungsten has been used as a cathode material.

5.3 Other DBD plasma devices developed

5.3.1 Flat parallel plate anode and flat plate cathode geometry (DBD-3)

Flat parallel geometry of both anode and cathode were developed for the purpose of generating plasma which can be easily accessible for testing any chemical reaction. Moreover changing the dimension becomes much more convenient in such a configuration. Also any dielectric material can be chosen as barrier layer much more easily in the form of a sheet. Therefore the parallel plate DBD was fabricated by changing the thickness as well as the nature
of the dielectric material. Since glass is easily available in all the sizes and shapes and also cost effective, it has been selected as suitable dielectric material in the first such device. However thin glass sheets did not provide a high breakdown strength and therefore they were disregarded. The separation between the plates was kept fixed at 6 mm. **Fig 5.13** shows parallel plate DBD reactors with single and multi stacking arrangements with alternate cathode and anode electrodes connections. This provides the more plasma volume for same power source and it facilitates simultaneous multisampling treatments.

**Fig 5.13**: Fundamental Dielectric Barrier Discharge Process Configurations (a) single anode and single cathode geometry (b) Multiple electrodes geometry

**Fig 5.14**: Photograph of Flat plate anode and flat plate cathode geometry devices (a) stacking of multi electrodes (b) single anode and single cathode geometry

**Fig 5.14** shows the actual photographs of the flat plate cathode and flat plate anode DBD devices with stacking arrangement of electrodes. The spacers were made up of quartz and the
dielectric material was chosen as alumina in the second assembly. Thin alumina sheets (0.2mm) were used as the barrier material and were found to be superior to that of glass.

The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. The plasma current was monitored for different flow rates (0 to 4 lpm) of oxygen and is plotted in Fig 5.15 for single and multistacking geometries. The current remains almost constant for flow rates at and higher than 0.5 lpm. This DBD reactor was found to be suitable for surface treatment of polymer foils which could be easily inserted inside the reactor. A maximum current of 2.3 mA for single stacking, whereas it was 2.6 mA in case of multistacking arrangement for this device.

![Graph](image)

**Fig 5.15**: Variation of plasma current as a function of oxygen flow rate for DBD-3

### 5.3.2 Cylindrical anode and wire cathode geometry (DBD-4)

A DBD plasma device with cylindrical anode and wire cathode geometry was also fabricated. The schematic diagram of this device is shown in Fig 5.16. This device consisted of copper wire with enamel coating (dielectric) fitted centrally in a stainless steel (SS) cylinder.
This SS cylinder enveloped by glass tube of 25 mm outer diameter served the purpose of cathode. The SS cylinder cathode had the inner diameter of 23 mm with a wall thickness of 1.2 mm. An enamel coated copper wire of 0.5 mm diameter and 50 mm length was fitted in the center of the cathode with the help of teflon bushes. Glass envelope has inlet and outlet openings for passing polluted gases and plasma forming gases.

**Fig 5.16:** Schematic of DBD plasma device with cylindrical anode and wire cathode (DBD-4)

Photograph of this cylindrical anode and wire cathode geometry device has been shown in the **Fig 5.17.** The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. To avoid the direct arcing between two electrodes a ceramic tube was fitted inside the cathode which serves as a dielectric barrier. The plasma achieved by using this geometry was found to be weak or less intense and was suitable for only production of small amount of ozone.
Fig 5.17: Photograph of DBD plasma device with cylindrical anode and wire cathode geometry (DBD-4)

The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. The plasma current was monitored for different flow rates (0 to 4 lpm) of oxygen and is plotted in Fig 5.18. The current remains almost constant when varied in this range. A maximum current of 1.4 mA was obtained for this device.

Fig 5.18: Variation of current with gas flow rate
5.3.3 Cylindrical anode and coil cathode geometry (DBD-5)

The schematic diagram of cylindrical anode and coil cathode geometry of DBD plasma device was fabricated, for particulate matter (PM) removal as shown in Fig 5.19. It consisted of a metallic tube of diameter 46 mm exactly equal to the diameter of the road vehicle exhaust. This is chosen to avoid the back pressure of exhaust gases development while vehicle is in motion. A tube of ceramic material as a dielectric barrier of inner diameter of 28 mm was fitted inside the metallic tube. A coil electrode made up of stainless steel (SS) was suspended exactly at the centre of this assembly by tapping the metallic as well as ceramic tubes. Outer SS cylinder is considered to be the one of the electrodes. Plasma was excited by applying the high voltage between SS cylinder and coil electrodes. The constituents of the device with detail specifications are given in Table 5.2.

![Fig 5.19: Schematic of first design of DBD plasma device with cylindrical anode and wire cathode geometry (DBD-5).](image)

**Table 5.2:** Detail specifications of design of DBD plasma device (DBD-5) with cylindrical anode and wire cathode geometry
<table>
<thead>
<tr>
<th>Sr. no</th>
<th>Constituents of device</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length of the device</td>
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<tr>
<td>2</td>
<td>Inner diameter of the device</td>
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<td>3</td>
<td>Outer diameter of the device</td>
<td>43 mm</td>
</tr>
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<td>4</td>
<td>Electrode material</td>
<td>SS spring wire and SS cylinder</td>
</tr>
<tr>
<td>5</td>
<td>Voltage applied</td>
<td>6 – 7 kV A C</td>
</tr>
<tr>
<td>6</td>
<td>Frequency</td>
<td>50 – 60 Hz</td>
</tr>
<tr>
<td>7</td>
<td>Power requirement</td>
<td>10 – 15 W</td>
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</tbody>
</table>
The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. The plasma current was monitored for different flow rates (0 to 4 lpm) of oxygen and is plotted in Fig 5.20. The current remains almost constant when varied in this range. A maximum current of 1.6 mA was obtained for this device.

### 5.3.4 Wire anode and wire cathode geometry (DBD-6)

A DBD device with wire anode and wire cathode geometry was developed to extend the time of exposure of the plasma with polluted gases. The schematic diagram of this device is shown in the Fig 5.21.

This device consisted of aluminum wires with teflon coating and acrylic material was used as dielectric barriers. Acrylic plate of thickness 10 mm of length 9.5 mm and breadth of 9.5 mm was drilled along the plane. The holes were of 6 mm in diameter. Teflon coated wires were fixed through the holes by one side and alternate wires were connected to the power source so that plasma gets excited between the wires. Multiple stacking of such assembly was achieved for increasing the volume of plasma. Fig 5.22 shows the photographs of the device with its stacking geometry.
The plasma was excited by applying pulsed ac voltage source having a frequency of 50Hz. The plasma current was monitored for different flow rates (0 to 4 lpm) of oxygen and is plotted in Fig 5.23. The current remains almost constant when varied in this range. A maximum current of 3.52 mA was obtained for this device. The complete current characteristic of all the devices is shown in Table 5.3 with applications of device.

![Fig 5.22: Photograph of (a) DBD devices (b) with stacking arrangement (DBD-6)](image)

![Fig 5.23: Variation of current with gas flowrate](image)
Table 5.3: Electric characteristics and applications of DBD plasma devices

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type of DBD device</th>
<th>Nomenclature</th>
<th>Max. plasma current (mA) achieved for flow rate of 0.5 lpm</th>
<th>Comparison with literature</th>
<th>Applications reported</th>
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<tbody>
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<td>1</td>
<td>Cylindrical DBD plasma device</td>
<td>DBD-1</td>
<td>14.3</td>
<td>6mA for 20kV at 1.005mb [18] 1.5mA, for 2kV at 1mb [19]</td>
<td>Air pollution control</td>
</tr>
<tr>
<td>2</td>
<td>DBD plasma torch</td>
<td>DBD-2</td>
<td>6</td>
<td>10mA, 1.7kV, 50Hz [20] 4A 8kV, for 1 mb [21]</td>
<td>Water purification, dentistry</td>
</tr>
<tr>
<td>3</td>
<td>Flat parallel plate cathode and flat plate anode geometry</td>
<td>DBD-3</td>
<td>2.6</td>
<td>450mA, 11kV at 1 mb [22]</td>
<td>Surface modifications of polymers and thin films</td>
</tr>
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<td>-</td>
<td>Ozone production</td>
</tr>
<tr>
<td>5</td>
<td>Cylindrical anode and wire cathode geometry</td>
<td>DBD-5</td>
<td>1.4</td>
<td>15mA, 6kV, 35kHz for air pressure [23]</td>
<td>Ozone production</td>
</tr>
<tr>
<td>6</td>
<td>Wire anode and wire cathode geometry</td>
<td>DBD-6</td>
<td>3.52</td>
<td>0.5mA, 600W [24]</td>
<td>Ozone production</td>
</tr>
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</table>

5.4 Summary
Dielectric barrier discharge plasma devices have been developed including cylinder-cylinder geometry, which was used for NO\textsubscript{x} removal. The above mentioned geometry is optimized one amongst many other geometries namely plate-plate, wire-cylinder, wire-wire, wire-plate and cylinder-cylinder geometry. This can easily fit into the exhaust of the vehicle and have sufficient clearance to keep the flow of the exhaust gas. Optimized geometry of device consists of two concentric cylinders made up of metal and mesh. Both the cylinders are enveloped with glass observing certain separation.

The second optimized geometry amongst above mentioned geometries was the wire plate geometry, which also called as DBD plasma torch. This plasma torch device was indigenously developed for water purification and endodontic treatment applications. Detail diagnostics of both the optimized devices have been done by optical emission spectroscopy method. All other geometries as mentioned above are described in brief.
References

17. Ru-Juan Zhana, Xiaohui Wena,b, Xiaodong Zhua,b, Aidi zhao, Adjustment of electron temperature in ECR microwave plasma, Vacuum 70 (2003) 499
21. CAO Yingguang, Yang Ping, LU Xinpei, Xiong Zilan, YE Tao, Xiong Qing, Sun Ziyong, Plasma Science and Technology, Vol.13, No.1, (2011) 93

182
22. Jai Hyuk Choi, Inho Han, Hong Koo Baik, Mi Hee Lee, Dong-Wook Han, Jong-Chul Park, In-Seob Lee, Kie Moon Song, Yong Sik Lim, Journal of Electrostatics 64 (2006) 17