Report on the different Plasma Modules for Pollution Removal

MO 03

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1. Plasma and plasma sources

1.1 Comprehension of plasma

Plasmas are ionized gases consisting of positive and negative ions and electrons, as well as neutral species. The plasma state is often referred to as the fourth state of matter. The ionization degree can vary from 100 % (fully ionized gases) to very low values, ranging from $10^{-4} – 10^{-6}$ (partially ionized gases). Besides the astroplasmas, we can distinguish two main groups of artificial (or laboratory) plasmas, i.e. the low temperature plasmas ($\leq 50 000$ K), and so-called the high-temperature or fusion plasmas ($50 000 – 10^{6}$ K) [1].

In general, a division could be made between plasmas which are in the thermal equilibrium and those which are not in thermal equilibrium (Table 1) [2]. The thermal equilibrium implies that the temperature of active species (electrons, ions and neutrals) is the same. In case of non thermal equilibrium plasmas, the temperatures of different species are not the same. To be more precisely, electrons are characterized by much higher temperatures compared to heavy ions.

The gas discharge plasmas can be also classified into local thermodynamic equilibrium (LTE) and non-LTE plasmas. The subdivision is typically related to the pressure in the plasma. High pressure implies many collisions in the plasma (i.e. short collision mean free path compared to the discharge length), leading to an efficient energy exchange between the plasma species. On the other hand, a low gas pressure results only few collisions in the plasma (i.e. a long collision mean free path compared to the discharge length). This leads to different temperatures of plasma species, due to inefficient energy transfer.

Electron temperature ($T_e$) of plasma in the equilibrium state usually is equal to ion temperature ($T_i$) or thermodynamic gas temperature ($T_g$). $T_e$ of non-equilibrium plasma may significantly exceed the temperature of heavy particles and thermodynamic gas temperature as well. The electron density ($n_e$) of non-equilibrium plasma usually is various in the bulk area of plasma ambient and increases toward the center of the over dense volume. To estimate thermodynamic non-equilibrium – the charged particle temperature and flux in the jet effluent
planar Langmuir probe may be used.

Table 1. Classification of plasma

<table>
<thead>
<tr>
<th>Plasma</th>
<th>State</th>
<th>Example</th>
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</thead>
<tbody>
<tr>
<td>Low temperature plasma</td>
<td></td>
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<tr>
<td>Thermal plasma (Quasi-equilibrium plasma)</td>
<td>$T_e \approx T_i \approx T_g \leq 2 \times 10^4 K$</td>
<td>Arc plasma, plasma torches, RF inductively coupled discharges</td>
</tr>
<tr>
<td></td>
<td>$n_e \geq 10^{20} \text{ m}^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Non-Thermal plasma (Non-equilibrium plasma)</td>
<td>$T_e &gt;&gt; T_i \approx T_g = 300…10^3 K$</td>
<td>Glow, corona, direct barrier discharge, atmospheric pressure plasma jets, hollow cathode discharges, electron beams, microwave and etc.</td>
</tr>
<tr>
<td></td>
<td>$n_e \approx 10^{10} \text{ m}^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Range of plasmas as function of electron temperature (eV)
In Fig. 1 the main characteristics (concentration of charged particles $n_e \approx n_i$ and temperatures $T_e$) for some natural and artificial plasmas are showed. The plasma can be found at very broad range of these parameters, but not all types of plasma could be used for environmental applications. There are some limitations concerning the pressure. In this case, the pressure of the medium where plasma is produced starts at atmospheric pressure (1 Pa). As the average particle energy is directly proportional to the temperature, the temperature is also often characterized by eV: $1 \text{ eV} \rightarrow 11600 \text{ K}$.

![Volt-ampere characteristics of low-pressure gas electric discharge regions](image)

Fig. 2. Volt-ampere characteristics of low-pressure gas electric discharge regions [4]

Most types of plasma which are created by other setups could be understood on the basis of simplest way. The electric discharge in the form of spark may appear between two
electrodes applying the voltage. With a certain amount of gas between these electrodes, the ionization starts in the discharge gap, and gas become conductive, thus are transited to plasma state. This transition is called as electrical breakdown. Depending on several factors, the discharge may radiate visible light. The electric discharge has three regions, with distinct current-voltage characteristics (Fig. 2) [3].

In the region of lowest voltages (A-B), the current depends on the concentration of charged particles which are produced by external sources like cosmic rays and/or by the illumination of the cathode (photoemission) and there is only a small increase of current with increasing voltage. This regime, called sometimes Geiger regime, are used in Geiger counters where high-energy rays will create current pulses which are proportional to the intensity of the radiation intensity. At higher voltage (B-C) the ionization in the electric field becomes significant and in a narrow voltage ranges the current increases super exponentially. This region in the current-voltage curve is Townsend discharge. Because only a small amount of light is emitted in this region, it is also known as dark discharge. It should be pointed that in this region, the discharge is still not self-sustaining, i.e. it exists only because of an external ionization source. In the region C-D, the Townsend discharge is self-sustained. In this region, the current increases several orders of magnitude almost at a constant plasma voltage value. The external resistor is necessary to control the current in this regime. In the region D-E the current growth is related to plasma voltage decrease. In this region the initially homogeneous electric field $E$ becomes distorted because of the space charges accumulated in the discharge gap and the Townsend discharge transits to normal glow discharge (E-F). The glow discharge has a distinct appearance with varying light and dark areas. With the growth of current the cathode region of the discharge widens and when all of the cathode area is filled with discharge, the plasma voltage starts to increase again (abnormal glow, F-G). Voltage drop in the region G-H is caused by the heating of cathode and the arc discharge forms [3].

1.2 Types of discharges and plasma sources

A large variety of gas discharge plasmas could be employed in a wide range of
applications. Various sources of atmospheric pressure plasmas will be introduced, and their working principles and applications for environmental protection, and approximate economics evaluation will be presented. We will concentrate on non-LTE and LTE atmospheric pressure plasma sources:

- Dielectric barrier discharge (DBD);
- Corona discharge;
- RF plasmas (capacitively, inductively);
- Microwave discharge;
- Hollow cathode discharges;
- Gliding-Arc discharges;
- Electron beams;
- Water vapour plasma.

1.2.1 Dielectric barrier discharge (DBD)

Dielectric barrier discharge (DBD) is referred to as barrier discharges or silent (inaudible) discharges. Due to the manifold possibilities of configurations and discharge parameters, there are often used different terms for the same type of discharge. Concerning the properties of the discharge, there is a rather complicated interconnection among all parameters. DBDs are known under different names like barrier discharge, silent discharge, ac-discharge, normal pressure glow discharge, ozonizer discharge and display discharge. It has been exclusively related to ozone generation for a long time. Its non-equilibrium discharge which can be handily operated at atmospheric pressure conditions. DBD is usually formed between two electrodes separated by an insulating dielectric barrier. The most important characteristic of barrier discharges is that non-equilibrium plasma conditions can be provided in a much simpler way comparing with other alternatives like electron beam, low pressure discharges, pulsed high pressure corona discharges [5]. Its flexibility allows efficiently scaling up from laboratory conditions to large industrial scale installations.

The process normally uses high voltage alternating current (AC), ranging from lower radio frequency (RF) to microwaves frequencies (MW). An experimental device for DBD
generally consists of two parallel electrodes separated by thin dielectric layer (Fig. 3). An AC voltage is applied to the electrodes at a frequency of several hundred hertz (Hz) to few hundred kilo hertz (kHz). A breakdown occurs in the gap between the two electrodes at a sufficiently high voltage enough to ionize the media around. As the charges collect on the surface of the dielectric, they discharge in microseconds, leading to their reformation elsewhere on the surface. Plasma is sustained if the continuous energy source provides the required degree of ionization overcoming the recombination process leading to the extinction of the discharge. The discharge process causes the emission of an energetic photon, the frequency and energy of which corresponds to the type of gas used to fill the discharge gap [6].

DBD devices can be made in many configurations, typically planar, using parallel plates separated by a dielectric or cylindrical; using coaxial plates with a dielectric tube between them. Common dielectric materials include glass, quartz, ceramics and polymers. The gap distance between electrodes varies considerably, from less than 0.1 mm in plasma displays, several millimeters in ozone generators and up to several centimeters in CO₂ lasers. The purpose of the dielectric barrier is to limit the electron current between the electrodes.

Fig. 3. Common dielectric barrier discharge configurations with one or two dielectric barriers [7]
1.2.1.1 Characteristics of DBD plasma source

Due to their nature, these devices have the following properties:

- \( T_e \gg T_i = T_g = 300 \ldots 10^3 \text{ K} \).
- Capacitive electric load: low Power Factor in range of 0.1 to 0.3.
- High ignition voltage 1 - 10 kV.
- Huge amount of energy stored in electric field - requirement of energy recovery
- Voltages and currents during discharge event have major influence on discharge behavior (filamented, homogeneous).
- Low density of electrons with high kinetic energy.

Also, DBD’s characteristics depend on the gas composition, type of dielectric material, its lifetime, and operating conditions. Than plasma forming gas is mixture of air, the dominant discharge mode at the ambient pressure is the short-lived filaments [8]. The efficiency of direct barrier discharge according to an energy balance study, the input microdischarge electric energy dissipates mainly in heating of electrodes (about 90%) and partially (about 10%) in the production of chemical active species (atoms and metastable molecules) [9].

Direct barrier discharge sources may be applied for various purposes not only in laboratory scale but for successful and economically feasible industrial scale. The gamma of applications can vary:

- **Generation of UV-radiation (indirect).** Produced UV light can be used to produce ozone for industrial scales. Ozone is extensively used in industrial air and water treatment.

- **Usage of the generated plasma.** The generated plasma itself could be used for modification (cleaning) of the surfaces of materials (e.g. polymers, semiconductors etc.). Semiconductor manufacturing, germicidal processes, high-power CO₂ lasers typically used for welding and metal cutting, pollution control.
- **Medicine (plasma medicine).** Could be useful for bio-medical applications such as sterilization of implants and surgical instruments. Also for therapeutic applications without affecting tissue and even stimulating tissue regeneration.

- **Water treatment (direct).** To remove chlorine organic compounds used for removal of bacteria and organic contaminates in drinking water supplies; treatment of public swimming pools and baths, aquariums.

- **Industry.** In textile industry to modify the surface properties of the textile to improve wettability, improve absorption of dyes, sterilization. Treatment of waste water after technological process of any field of industry. Removal of VOC\textsubscript{x} and NO\textsubscript{x}/SO\textsubscript{x} from flue gases.

- **Agriculture.** Reduction of odours.

Considering the DBD technology, this report mainly concentrates for DBD’s applications for environmental aspects such as removal of combustion products (SO\textsubscript{x}/NO\textsubscript{x}) out of flue gases, ozonation and treatment of water, and volatile organic compounds (VOC\textsubscript{x}) emitted from various industrial processes. Direct barrier discharge technology may offer some unique advantages over conventional technologies such as high removal efficiency, good energy yields and good economy.

### 1.2.2 Corona discharge

A corona is one type of a large diversity of non-thermal plasmas, where \( T_e \gg T_i = T_g = 300 \ldots 10^3 \) K. Corona discharges in general are relatively low power electrical discharges that take place at or near atmospheric pressure in non-uniform electric fields. A corona is generated by strong electric fields (E-field), associated with small diameter wires, needles, or sharp edges on a working electrode. The corona appears as a dim filamentary discharge propagating form high to low electric fields [10]. On the other words, corona is an electrical discharge brought on by the ionization of a fluid surrounding a conductor that is carrying a current. The name ‘corona discharge’ arises from the fact that the discharge appears as a lighting crown around the wire.
A corona is a process by which a current, perhaps sustained, develops from an electrode with a high potential in a neutral fluid, usually air, by ionizing that fluid so as to create plasma around the electrode. The ions generated eventually pass charge to nearby areas of lower potential, or recombine to form neutral gas molecules. To be more precise, to create the corona at atmospheric pressure a strong non-uniform E-field is needed. It is achieved by application of a high voltage to an asymmetric electrode configuration. To initiate the discharge an ion-electron pair is necessary. Due to electric fields generated electrons start moving towards the anode. In the initial phase of the discharge ions is considering being stationary due to mass difference between electrons. Velocities of electrons are much higher. Therefore taking energy from the electric field or external voltage source they move away from the ions creating a space charge. This is so called first avalanche electrons. During ionization a new electron is emitted which leads to exponential growth of electrons and creation of the secondary avalanche. [11-12].

Corona discharge usually involves two asymmetric electrodes (Fig. 4); one highly curved (such as the tip of a needle, or a small diameter wire) and one of low curvature (such as a plate, or the ground). The high curvature ensures a high potential gradient around one electrode, for the generation of plasma. The polarity of the corona can be either positive or negative.

The DC corona is called positive when the curved electrode has a higher potential than flat electrode. The character of the discharge, both positive and negative, highly depends on the applied voltage and electrode geometrical configuration [4].

The properties of corona discharge depend on corona geometry. Really distinguishing feature of coronas is the existence of a low field drift region connecting the ionization region(s) with the eventual low field, passive electrodes.

Applications

- Production of ozone.
- Sanitization of water.
• Removal of unwanted volatile organics, such as chemical pesticides, solvents, or chemical weapons agents.
• Scrubbing particles (particulate matter) from air streams.
• Surface treatment for tissue culture.
• Air ionizers.
• Surface treatment of materials to change properties (adhesiveness, hardness etc.).

Fig. 4. Simplified scheme of corona discharge

**Advantages**

• High removal efficiency.
• Energy yields.
• Low investment and operational costs compared to other technologies.

**Disadvantages**

• Audible noise.
• Power loss.
1.2.3 Radio frequency (RF) plasmas (capacitively, inductively)

Electrical discharges could be excited and sustained by high-frequency electromagnetic fields. RF (radio frequency) discharges usually operate in the frequency range 1 – 100 MHz. The corresponding wavelengths ($\lambda = 300 – 3$ m) are large compared to the dimensions of plasma reactor.

The power coupling in RF discharges can be accomplished in different ways, as:

- Capacitively coupled discharges, ‘$E$’ discharges;
- Inductively coupled discharges, ‘$H$’ discharges [13].

1.2.3.1 Capacitively coupled plasma

Capacitively coupled plasma (CCP) is generated with high-frequency rf electric fields, typically 13.56 MHz. A conventional RF system for sustaining a discharge consists of a generator and the reactor with electrodes (Fig. 5).

Fig. 5. Typical capacitively coupled RF plasma reactor
The electrodes in the RF discharge are covered by sheath regions, which are similar to the cathode dark space in a dc glow discharge. The space between the electrodes is filled with the bulk plasma. It essentially consists of two metal electrodes separated by a small distance, placed in a reactor. One of the electrodes is connected to the RF power supply, and the other one is grounded. As this configuration is similar to a capacitor in an electric circuit, the plasma formed in this configuration is called capacitively coupled plasma. Gas pressures in the reactor are typically in the range $1 – 10^3$ Pa [7, 14].

It is important to note that the term ‘capacitively coupled’ refers to the way of coupling the input power into the discharge, i.e. by means of two electrodes and their sheaths forming a kind of capacitor.

At the typical RF frequencies, the electrons and ions have a totally different behavior, which can be explained by their different masses. The light electrons can follow the instantaneous electric fields produced by the applied RF voltage [15,16].

Another important aspect of capacitively coupled RF discharges, which also results from the differences in mass between electrons and ions, is the phenomenon of self-bias. The ‘self-bias’ or ‘DC bias’ is a negative DC potential that develops between the plasma and the powered electrode as a consequence of (i) the use of a coupling capacitor between the RF generator and the powered electrode and (ii) the use of appropriately shaped areas of the (smaller) powered electrode and the (larger) grounded electrode. This feature can assume that the currents from the plasma to both electrodes must be equal. The higher current density at the small electrode demands a higher voltage between the plasma and electrode. In other plasma devices, the application of an additional RF bias to the sample holder produces a self-bias with higher ion energies [7].

In a capacitively coupled RF discharge, the electron density is in the range $n_e = 10^9 – 10^{10}$ cm$^{-3}$ and densities of up to $10^{11}$ cm$^{-3}$ are possible at higher frequencies [17]. The ion energy near the powered electrode can reach energies of a few hundred electron-volts due to the self-bias.
CCPs are successfully applied for a wide range of applications such as deposition of thin-films, plasma etching and sputtering of insulating materials as well as microfabrication of an integrated circuit manufacturing industries for plasma enhanced chemical vapor deposition (PECVD).

1.2.3.2 Inductively coupled plasma

Inductively coupled plasma (ICP) is similar to CCP but the electrode consists of a coil wrapped around the discharge volume that inductively excites the plasma. ICP is excited by an electric field generated by a transformer from a RF current in a conductor [15, 18]. The changing magnetic field of this conductor induces an electric field in which plasma electrons are accelerated. Simply speaking, the RF currents in the coil (inductive element) generate an RF magnetic flux, which penetrates the plasma region. Schematic representation of an inductively coupled plasma source is showed in Fig. 6.

Fig. 6. Scheme of an ICP source, (a) in cylindrical geometry, with a helical coil wound around the discharge, and (b) in planar geometry, with a flat helix or spiral wound from near the axis to near the outer radius of the discharge chamber [14]
As shown in (Fig. 6 a,b), basically, two different coil configurations can be distinguished in inductive discharges for processing applications, i.e. cylindrical and planar. In the first configuration, a coil is wound around the discharge chamber, as a helix. In the second configuration, which is more commonly used for materials processing, a flat helix or spiral is wound from near the outer radius of the discharge chamber, separated from the discharge region by a dielectric. Advantages of the latter are reduced plasma loss and better ion generation efficiency; a disadvantage is the higher sputter-contamination, UV-damage and heating of neutrals at the substrate. Multipole magnets can be used to increase radial plasma uniformity. The planar coil can also be moved close to the wafer surface, resulting in near-planar source geometry, having good uniformity properties, even in the absence of multipole confinement [15].

ICPs can achieve high electron densities \( n_e = 10^{12} \text{ cm}^{-3} \) at low ion energies. Another advantage is the simplicity of the concept, no requirements for DC magnetic fields, as it is in electron cyclotron resonance sources (ECRs) and helicons. Several applications of inductively coupled plasmas are reported such as thin-film deposition, plasma etching and lighting applications (electrodeless discharge lamps) as well as mass spectrometric analysis and some environmental applications for ozone production [19-21].

1.2.4 Microwave plasma

Plasmas that are created by injection of microwave power, i.e. electromagnetic radiation in the frequency of 300 MHz to 10 GHz, can in principle be called ‘microwave induced plasmas’. For microwaves the most commonly used wavelength is 12.24 cm, corresponding to a frequency of 2.45 GHz. This wavelength is roughly comparable to the dimensions of a typical microwave reactor [14]. A striking feature of microwaves induced plasmas is the wide range of operational conditions that can be applied: dependent on the plasma source, power levels can range from a few Watt up to several hundreds of kilowatts, the discharge pressure might range from less than \( 10^2 \) Pa up to several times atmospheric pressure, whereas many different discharge gases might be used (both noble and molecular gases) [22].
A microwave plasma reactor (Fig. 7) consists in principle of a power supply, a circulator, the applicator, and the plasma load. The transmission lines are rectangular waveguides or, at lower powers, coaxial cables. The applicator should optimize the energy transfer into the plasma and minimize the power reflection. The circulator protects the power supply from reflected power [7].

Fig. 7. Principle of microwave assisted plasma reactor

Basically, there are distinguished three types of microwave plasma reactors: discharges produced in closed structures, in open structures, and in resonance structures with a magnetic field [23]. In closed structures, the plasma chamber is surrounded by metallic walls. Resonant cavities of high quality with their high electric field allow an easy ignition of discharges, even at high pressures. Examples for discharges in open structures are microwave torches, slow wave structures, and surfatrons. Electron cyclotron resonance (ECR) plasmas are a typical example of microwave plasma in magnetic field [7].

The microwave discharge plasma generated at low pressure has been used in many industrial productions such as semiconductor and optical component production as a device for etching or deposition, because it is clean and has high chemical reactivity. It is also being
used as ion production, atomization and light, and excitation source in ion bombardment, nitrification and solar lamps as well as analytical chemistry, respectively [22]. Regarding the atmospheric microwave discharge plasma, it can be applied for waste treatment, such as decomposition and detoxification of detrimental gases (chlorofluorocarbon and nitrogen oxides) from industrial facilities and cars, and for the surface treatment and the electromagnetic coating at atmospheric pressure [24].

1.2.5 Hollow cathode discharges

The cylindrical hollow cathode discharge (HCD) is a kind of glow discharge. Two glow discharge regions are the most important: a dark space adjacent to the cathode surface, where the electric field is strong, which is called the cathode dark space (CDS) or sheath, and rather luminous part beyond it, where the field is weak and which is called the negative glow (NG) or plasma region. The cathode can be built in different shapes, for example as a spherical segment or as a pair of plane parallel plates or as a hollow cylinder. The anode is placed mostly at the end of the cathode cylinder and can be chosen in different shapes, such as a disc, a ring, a cylinder etc [25]. The schematic sketch of fused hollow cathode with integrated open structure and flowing gas is showed in Fig. 8. The principle is the same considering hollow cathode.

![Fig. 8. The schematic sketch of fused hollow cathode with integrated open structure and flowing gas is...](image-url)
HCDs are capable of generating dense plasmas. High-density plasmas typical of hollow cathodes discharges are based on efficient avalanche multiplication of electrons known as a hollow cathode effect – large increases in current density and light intensity with reduced separation of the two cathodes. Hollow cathode (HC) discharges have too an important characteristic that combines two important processes, i.e. sputtering and excitation/ionization of the sputtered atoms. The HC plasma properties can be enhanced through the use of various geometrics, magnetic field and discharge operating mode modifications [26].

A glow discharge is sustained by the cathode emission of secondary electrons and by the creation of new charged particles as results of electron, ion and metastable atom ionization collisions inside the discharge. The emitted secondary electrons are accelerated in the strong electric field of the cathode dark space to high energies, and ionize the neutrals there, creating a new pair of charged particles. Because the electrons move again in the direction of the electric field, and because of their low mass, they lose only a small amount of energy in collisions, and therefore they propagate to the region of low field (i.e. to the negative glow) having still enough energy to induce the inelastic collisions [25].

Hollow cathode discharges are widely used for the variety of applications, for instance in plasma processing (ion etching, thin film deposition, surface treatment) [28-30], in ion gas lasers and spectroscopic analysis [31], where the hollow cathode is used as an emission source, allowing direct excitation and analysis of samples, or as a light source in absorption spectrometry. Because hollow cathodes exhibit a high activation degree of species, it can be used for environmental applications, such as conversion of gases. The 100 % conversion rate of NO was achieved in NO\textsubscript{x} + N\textsubscript{2} system [27].

**1.2.6 Gliding arc discharges**

Gliding arc discharge (GAD) in one of the electric discharge plasma which can be generated at near atmospheric pressure. The GA is an intermediate system between thermal
and non-thermal discharges, and is able to provide simultaneously high plasma density, power and operating pressure with high level of non-equilibrium, high electron temperature, low gas temperature and possibility of stimulation selective chemical processes without any quenching [32].

Gliding arc generates regions of both thermal and non-thermal plasma at the conditions of atmospheric pressure and ambient temperature [33]. The plasma is weakly ionized and characterized by the lack of local thermodynamic equilibrium since the energy of the electrons is much higher than that of the heavy species.

Fig. 9. Scheme of gliding arc reactor with electric circuit

In general, the gliding arc plasma generator consists of two divergent electrodes (Fig. 9), where the arc starts at the shortest distance between the electrodes, then moves with the gas flow and the length of the arc column increases together with the voltage. The arc discharge disappear at arc maintenance voltage exceeds input voltage. This process of generating of an arc, movement (gliding), and disappearance is repeated continuously in the
high voltage discharge [34]. The GAD can be powered by a DC or AC power supply source. The DC gliding arc plasma generator is characterized by stability of discharge and a simple design. The main advantages of AC gliding arc discharge plasma generator are simplicity of the power supply system and its low cost [35].

GAD plasma is useful in many industrial applications that involve coating, painting, dying, and adhesion. In particular, the gliding arc combines a number of industrially attractive features of plasma based surface treatments [36]: it is environmentally much cleaner than mechanical and wet chemical processes; it operates well in air at atmospheric pressure with low cost. Being as torch-like plasma source, it can treat surfaces of bulky objects, and it allows fast processing [37].

### 1.2.7 Arc discharge

An electric arc is an electrical breakdown of a gas which produces an ongoing plasma charge, resulting from a current flowing through normally nonconductive media such as air. Its thermal plasma source, where $T_e \approx T_i \approx T_g \leq 2 \times 10^4$ K.

The arc occurs in the gas-filled space between two conductive electrodes and it results in a very high temperature, capable of melting or vaporizing most materials. An electric arc is a continuous discharge. The process normally uses high voltage alternating current (AC) or direct current (DC).

The most common example of the arc discharge could be plasma torch. It’s a device for generating a directed flow of plasma. The torch thermal efficiency in most cases is 50 – 90 % depending on the operating regime and construction [38].

The characteristics of thermal arc discharge plasma are as following [39]:

- Thermal plasmas are a processing medium with one of the highest energy densities; the results are high processing rates, high fluxes of radical species, the potential for smaller installations, and a wide choice of reactants.
- High chemical reactivity.
- High quench rates.
• Short residence time of treated materials.
  
  Thermal arc discharge plasma can be applied for a wide range of applications, considering industrial scale applications such as:
  • Welding.
  • Cutting.
  • Applications in metallurgy industry.
  • Plasma spraying for production of hard coatings with good resistance properties.
  • Production of catalytic materials.
  • Destruction of hazardous waste.
  • Plasma pyrolysis of organic materials producing synthetic gas.
  • Production of mineral fiber.
  • Application in medicine for sterilization.
  • Plasma treatment of medical waste.

  The best application of plasma arc and plasma torch from environmental point of view is plasma gasification/pyrolysis producing synthetic gas (CO+H$_2$). Plasma gasification/pyrolysis is able to get the energy it needs from waste-streams such as municipal solid waste (MSW) and even hazardous and toxic wastes, without the need to bury these wastes in a landfill.

  1.2.7.1 Plasma arc and plasma torch

  There are two methods used in plasma gasification/pyrolysis – the first one is a ‘plasma arc’ and second is called a ‘plasma torch’ (Fig. 10) [38, 39].

  A ‘plasma arc’ plasma gasification plant operates on principles similar to an arc-welding machine, where an electrical arc is struck between two electrodes. The high-energy arc creates a high temperature, highly ionized gas. The plasma arc is enclosed in a chamber. Waste material is fed into the chamber and the intense heat of the plasma breaks down organic molecules (such as oil, solvents, and paint) into their elemental atoms. In a carefully controlled process, these atoms recombine into harmless gases such as carbon dioxide. Solids
such as glass and metals are melted to form materials, similar to hardened lava, in which toxic metals are encapsulated. With plasma arc there is no burning or incineration and no formation of ash.

Fig. 10. Basic types of plasma arcs [40]

‘Plasma arc’ gasification plants have very high destruction efficiency. They are very robust; they can treat any waste with minimal or no pretreatment; and they produce a stable waste form. The arc melter uses carbon electrodes to strike an arc in a bath of molten slag. The consumable carbon electrodes are continuously inserted into the chamber, eliminating the need to shut down for electrode replacement or maintenance. The high temperatures produced by the arc convert the organic waste into light organics and primary elements.

Combustible gas is cleaned in the off-gas system and oxidized to CO₂ and H₂O in ceramic bed oxidizers. The potential for air pollution is low due to the use of electrical heating in the absence of free oxygen. The inorganic portion of the waste is retained in a stable, leach-resistant slag. In ‘plasma torch’ systems, an arc is struck between a copper electrode and either a bath of molten slag or another electrode of opposite polarity. The
inorganic portion of the waste is retained in a stable, leach-resistant slag. The air pollution control system is larger than for the plasma arc system, due to need to stabilize torch gas. Air pollution depends on the gas being used to stabilize the electric arc of plasma torch in the reaction chamber.

Despite the fact that these technologies are very efficient, but there are some limitations and concerns. A chief concern about plasma arc technology is ensuring that gaseous emissions are kept to a minimum and cleaned before being released to the atmosphere. Concerns have been raised regarding the reliability of ‘plasma torch’ technology. Parts of plasma torch must be replaced periodically to prevent burn-through at the attachment point of the arc and subsequent steam explosion due to rapid heating of the released cooling water.

### 1.2.7.2 Water vapor plasma torch

Recently, the new technology has appeared which is less explored. It is plasma torch stabilized with water vapor vortex [41, 38]. The use of water vapor as plasma forming gas enables to reduce the emissions compared to other gas being used, such as air, nitrogen etc. Double benefit is achieved: emissions are reduced, that means lower costs for pollution. Secondly, synthesis gas is being produced containing high level of hydrogen. This gas could be further burnt in a heat boiler producing electricity and heat. Also, in assistance of special catalysts, syn-gas could be liquefied and directly applied in the internal combustion engines. It is also may be used for production of pure hydrogen and methanol in chemical industry. These advantages render this technology very attractive, but more research must be done before applications for industrial scale.

The advantages and disadvantages concerning plasma arc, plasma torch and water vapor plasma torch devices are as following [42]:

**Advantages**

- High destruction efficiency of organic and inorganic materials.
- Production of synthetic fuels.
• One of the best existing technologies in plasma welding and cutting.
• Enables better pollution control comparing to conventional combustion technologies.

Disadvantages

• Erosion of the electrodes.
• Arc flash.
• Consumes quite lot electricity.
• Noise.

1.2.8 Electron beam generated plasma

Plasma generation using beams is most frequently accomplished by the use of electron beams and laser beams. A beam-produced plasma discharge is sustained by the interaction of an electron beam with gaseous medium [4, 14]. Collective effects produce turbulent plasma oscillations with high amplitudes. The heating of the plasma electrons in this turbulent field is sufficient to sustain the beam-produced discharge plasma. The energy transfer is very effective as up to 70% of the beam energy can be transferred to the plasma. It is possible to create plasmas with high degrees of ionization in low pressure environments. The plasma properties may be controlled be the electron beam current, the acceleration voltage, the gas pressure, and by the shape of the beam [4]. Scheme of electron beam gun for plasma generation is showed in Fig 11.

Electron beam comes from a filament, made of various types of materials. The most common is tungsten hairpin gun. This filament is a loop of tungsten which functions as the cathode. A voltage is applied to the loop, causing it to heat up. The anode, which is positive with respect to filament, forms powerful attractive forces for electrons. This causes electrons to accelerate toward anode [43].
Electron beam generated plasmas are being used for material processing, such as etching, deposition and surface treatment [14]. Recently, electron beam generated plasmas has been used and successfully implemented in industry for flue gas treatment of power plants. The technology is called electron beam flue gas treatment (EBFGT) [44, 45].

Despite the fact that presented various types of plasma sources (i.e. DBD, corona, RF plasmas etc.) can be adjusted for a wide range of applications, both industrial and laboratory scale, the major purpose of this report is to emphasize and compare mentioned technologies which could be easily applied to a narrow field of applications, such as pollution removal, with economic estimations where possible. This part of report deals with the following plasma devices:

- Barrier discharge devices;
• Corona devices;
• Microwave discharges;
• Fused Hollow Cathodes;
• Electron beam flue gas treatment (EBFGT);
• Ozone injection methods.

2. Application of plasma devices for pollution removal

2.1 Barrier discharge devices

2.1.1 Ozonation

The most typical application of DBD reactors is generation of ozone (O₃). Ozone can be generated from oxygen, air or from other N₂/O₂ mixtures [14]. Ozone is known as one of the strongest oxidants. It is characterized by potent germicide properties. In many applications it can replace chlorine thus causing less environment impact and side effects. The traditional application of ozone is used for water treatment. For industrial purposes ozone is generated in large installations using direct barrier discharges [5]. Most technical ozone generators are made of cylindrical discharge tubes of about 20-50 mm in diameter and 1-2 m length. Large generators of several hundred tubes can produce up to 100 kg ozone per hour. With technologically advanced ozone generator, ozone can be produced at a price less than 2 US$/kg with a power consumption of several megawatts. [46, 14].

The major advantages of the ozonation process over conventional chlorination processes for water treatment are listed below [47]:

• There is no need to store and handle toxic chemicals.
• By-products of ozonation do not have any known adverse effects on health or the environment.
• Ozone is a stronger and faster-acting oxidizer.
• Ozone can safely destroy a broader range of organic contaminants.
• Ozone helps in removal of colour, odour and suspended solid materials.
• Ozone is far more efficient in killing bacteria, viruses, spores and cysts.

On the other hand, there are some disadvantages handling the ozone generation for water treatment or other disinfection areas. There are strict requirements for ozone monitoring and recording. The leakage of ozone can be dangerous or even deadly for human health. Second, it is not as effective as other disinfection methods for inactivation of some viruses, spores, cysts at low dosages used for coliform organisms; very toxic and corrosive; oxidizes organic and inorganic materials (iron, magnesium); energy intensive and relatively expensive than chlorine [48].

Despite some disadvantages, the production of ozone in assistance of direct barrier discharges renders this technology rather attractive for implementation for industrial scale applications.

2.1.2 Treatment of air pollutants

The emissions of SO$_x$, NO$_x$ and VOC$_x$ by industrial and agricultural processes cause a series of problems on human’s health and the environment in general. In the variety of dozens of technologies, a direct barrier discharge technology may be one of the effective solutions for treatment of the emissions and neutralization of odours. Frequently, the DBD modules for treatment of air pollutants are combined with other techniques such as filters. With special configuration of the reactors it is possible to treat not only gaseous pollutants but aerosols and particles also [49]. In Fig. 12 DBD type reactor is showed. The reactor consists of two electrodes (one electrode is in the form of metal pipe, and the other electrode is a metal wire that runs down the middle of the pipe) separated by a void space that is lined with dielectric material and is filled with glass beads [50].
Emissions flow inside of the pipe. A phenomenon occurs when the voltage through the beads exceeds the insulating effect of the beads and millions of micro-discharges occur. The duration of these discharges is in range of nano-seconds. In this environment, atoms are being separated from their molecules to become free radicals. Since free radicals are highly reactive, they quickly recombine with other atoms and/or molecules to form new compounds. For example, oxygen radicals react with carbon monoxide (CO) to form carbon dioxide (CO$_2$), sulfur dioxide (SO$_2$) to form sulfur trioxide (SO$_3$), and nitrogen oxide (NO$_x$) to form nitric acid (HNO$_3$) in the presence of moisture. Ozone will also react with small (2.5 micron) carbon particles (soot) to form carbon dioxide, and reacts with elemental mercury (Hg) to form mercury oxide (HgO). Thus, flue gas is being treated removing pollutants. The removal efficiency of treated flue gas in modified pilot FirstEnergy power plant containing a DBD reactor is presented in Table 2 [50].
Table 2. Removal efficiency of pollutants from modified pilot FirstEnergy power plant

<table>
<thead>
<tr>
<th>POLLUTANT</th>
<th>REMOVAL EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur dioxide, SO\textsubscript{2}</td>
<td>98 %</td>
</tr>
<tr>
<td>Nitrogen oxides, NO\textsubscript{x}</td>
<td>90 %</td>
</tr>
<tr>
<td>Total particulate, TPM</td>
<td>99.9 %</td>
</tr>
<tr>
<td>Fine particulate, PM\textsubscript{2.5}</td>
<td>95 %</td>
</tr>
<tr>
<td>Mercury, Hg</td>
<td>80-90 %</td>
</tr>
</tbody>
</table>

2.1.3 Economics

No cost effectiveness numbers were found in the public records for the FirstEnergy power plant process. Despite the fact of lack of information, in reference [51] investment and running cost comparison of waste air purification processes of 50000 Nm\textsuperscript{3}/h for removal of volatile organic compounds of flavour processing industry. Investment cost of non-thermal plasma technique are showed in Fig. 13.

![Fig. 13. Investment cost of non-thermal plasma technique [51]](image-url)
The given numbers in Fig. 13 may be a good guideline for approximate evaluation of investment cost of non-thermal plasma devices being installed for industrial scale removal of air pollutants.

2.2 Corona devices

2.1.1 Pulsed corona

The electrical discharge process, especially the pulsed plasma discharge process can be applied to the removal of pollutant gases from industrial plants such as power generation plants and incinerators. Pulsed corona discharge, where electric discharge can be generated in treated water or above (Fig. 14 a,b). Its principle is that high energy electrons are created during the propagation phase of the streamer. These electrons dissociate molecules and create radicals such as O, OH, N₂ and indirectly HO₂, O₃ and others. All these radicals start chemical reactions which cause, mainly, oxidation of impurities present in the gas or water. This makes it possible to convert NO and/or SO₂ into acids and hydrocarbons into CO₂ and H₂O [52].

In table 3 the basic working parameters are presented independently on the phase of pulsed corona discharge. According to [53, 54] the removal efficiency of SO₂ and NOₓ from industrial flue gases exceed 80 % and 70 %, respectively, at power consumption of 6 kW, total gas flow rate of 2000 Nm³/h, temperature of gas 70 °C and 2400 ppm concentrations of SO₂ and 450 ppm of NOₓ. However, in [55] is reported that removal efficiency of SO₂ was 99 % while the removal of NOₓ 70 % at gas flows of 42000 Nm³/h at 170 °C, concentrations of SO₂ and NOₓ 120 ppm and 75 ppm, respectively.

Table 3. Basic working parameters of pulsed corona discharge

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pulsed corona</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>$10^2$-$10^3$ Hz</td>
</tr>
<tr>
<td>Voltage pulse</td>
<td>$10$-$10^5$ kV</td>
</tr>
<tr>
<td>Current phase</td>
<td>$10$-$10^5$ A</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Voltage pulse rise time</td>
<td>$10^{-7}$-$10^{-9}$ s</td>
</tr>
<tr>
<td>Gap</td>
<td>of cm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>$\approx 1$ J</td>
</tr>
<tr>
<td>Electrical field at electrode</td>
<td>100-10000 kV/cm</td>
</tr>
<tr>
<td>Current transfer</td>
<td>Ions</td>
</tr>
<tr>
<td>Plasma nature</td>
<td>Non-thermal</td>
</tr>
<tr>
<td>Shockwave</td>
<td>Week-moderate</td>
</tr>
<tr>
<td>UV</td>
<td>Week-moderate (conductivity dependence)</td>
</tr>
<tr>
<td>Heat production</td>
<td>Week</td>
</tr>
<tr>
<td>Conductivity influence</td>
<td>Strong</td>
</tr>
<tr>
<td>Electrode erosion</td>
<td>Week</td>
</tr>
</tbody>
</table>

Fig. 14. Schematic diagram of liquid phase pulsed corona discharge reactor (a), and gas-liquid phase discharge reactor (b): a) 1 – point discharge electrode, 2 – ground electrode, 3 – tube, 4 – cylindrical glass vessel reactor, 5 – magnetic stirring bar; HV – pulse power supply; b) 1 – gas phase, 2 – electrode, 3 – gas phase discharge, 4 – ground electrode, 5 – aqueous solution, 6 – liquid phase point, 7 – liquid phase discharge, 8 – reactor chamber, 9 – insulator; HV – pulse power supply [52, 56]
Despite the fact, that pulsed corona discharge is used for flue gas treatment of power plants it could be successfully implemented for relatively new approach such as treatment of water, both ground and waste [12].

2.3 Microwave discharges

Atmospheric pressure microwave discharge methods and devices producing non-thermal plasma could be used for control of gaseous pollutants. One of the device is microwave torch discharge (MTD) used for gaseous pollutants (SO$_x$, NO$_x$, VOCs) removal. According to [57] MTD is mainly used for decomposition of highly concentrated volatile organic compounds (up to tens of per cent).

Microwave plasmas operating at atmospheric pressure can be induced by microwave resonator cavities, microwave surfatrons with surface-wave-sustained discharges and microwave torch discharges. The first and the second induction methods have some limitations when large power densities are deposited into the plasma, resulting in deterioration of the tube due to plasma-tube interactions. Microwave plasma can be induced in ‘open’ air at the tip of an MTD applicator. Due to the absence of an enveloping tube, no limitation to the power density is imposed by the induced plasma [57].

There are developed two types of microwave torch discharges: coaxial-line-based and waveguide-based coaxial-line MTDs (Fig. 15). The power fed to the both reactors is 2.45 GHz.
The gas flow rate and microwave power delivered to the discharge were in the range of 1-3 l/min and 100-400 W, respectively. The concentrations of the processed gaseous pollutants were from several to several tens of per cent. MTD plasmas fully decomposed (efficiency 100 %) the VOCs at a relatively low energy cost [57]. This suggests that microwave torch discharge plasmas can be useful tools for decomposition of gaseous pollutants.

2.4 Fused Hollow Cathodes

2.4.1 Technology

Atmospheric pressure plasma sources based on hollow cathodes exhibit a high activation degree of species. Thus, allowing for successful surface treatment, activation and cleaning as well as conversion of pollutant gases.

The FHC cold atmospheric plasma source is based on simultaneous generation of multiple RF-HCDs in an integrated open structure with flowing gas [58]. Fig. 16 shows a schematic diagram of the system. The operational stability of the FHC system is excellent; the discharges are homogeneous and do not exhibit streams. The power consumption for noble gases is of the order of 0.1 W/cm² of the active electrode area. The RF powers to ignite and sustain the discharge are comparable for the FHC and single hollow cathode at atmospheric pressure. The FHC system allows generation of cold plasma in both monoatomic and molecular gases [59].

The fused hollow cathode discharge (FHC) concept, with aerodynamic stabilization, was successfully applied for the gas conversion. 100 % conversion of NOx in nitrogen was achieved using both the RF and pulsed DC generations, for gas flows as high as 20 l/min [59].
In [60] the effect of the electrode material on the atmospheric plasma conversion of NO\textsubscript{x} in air mixtures has been investigated. The experiments were carried out at the oxygen content of 5 %. The NO\textsubscript{x} content in the mixture was 150 sccm NO and 5 sccm of NO\textsubscript{2}. It was found that a 100 % conversion of NO and NO\textsubscript{2} was achieved with a graphite electrode, without using any auxiliary gas and catalyst.

Fig. 16. Schematic sketch of the FHC with integrated open structure and flowing gas

2.4.2 Economics

No available data on fused hollow cathode technology installation for industrial applications. Moreover, there is no economical evaluation.

2.5 Electron beam flue gas treatment (EBFGT)

2.5.1 Technology evaluation

The electron beam flue gas treatment system provides dry-process treatment of flue gas produced in the combustion of fossil fuels. It simultaneously performs desulfurization and denitrification, preventing atmosphere-polluting emissions of NO\textsubscript{x} and SO\textsubscript{x} from flue gas of coal/oil combustion process. Also, EBFGT enables the removal of other pollutants, such as HCl, HF, VOC, dioxins, mercury etc [61, 62]. Three industrial installations have already been
Flue gas treatment using electron beams is a technology in which desulfurization and denitrating of flue gas is carried out by combining it with ammonia gas and then irradiating it with electron beams. When the flue gas is irradiated with electron beams, highly chemically reactive free radicals are generated within the emissions. The sulfur oxides (SO$_x$) and nitrogen oxides (NO$_x$) present in the flue gas react with these radicals and are thereby converted first into sulfuric acid and nitric acid and subsequently into aerosols, (fine powdered matter) of ammonium sulfate and ammonium nitrate.
According to [44] main operational data of the latter power plant is:

- Flue gas flow rate: 100 000 – 270 000 Nm³/h;
- Pollutants removal efficiency: 90 % SO₂
  70 % NOₓ
- Total accelerators power: 1.04 MW;
- Inlet flue gas parameters:
  - Temperature 130 – 150 °C
  - SO₂ concentration 1500 – 2200 mg/Nm³
  - NOₓ concentration 400 – 600 mg/Nm³
- Ammonia water consumption: 150 – 300 kg/h;
- By-product yield: 200 – 300 kg/h.

Electron beam flue gas treatment technology may be applied for treatment of:

- Flue gas from heavy oil fuel.
- Flue gas from high-sulfur coal.
- Flue gas from low-sulfur coal.
- Flue gas from iron/steel sintering.

Advantages and disadvantages of EBFGT are given below:

**Advantages**

- High removal efficiency;
- There is no need for treatment of waste water;
- No expensive catalysts;
- Wasteless process, useable by-products as fertilizers;
- Dry process;
• Simple facility construction;
• Economical competiveness.

Disadvantages
• Needs of ammonia.

2.5.2 Economic feasibility

Total investment cost of EBFGT installation planned at a selected oil refinery was evaluated for 13,800,000 USD in the case than flue gas flow rate 65,000 Nm³/h and 19,200,000 USD in the second case, than flue gas flow rate 130,000 Nm³/h. The elements of investment cost are presented in Table 4 [65].

Table 4. Investment cost of EBFGT installation at a selected oil refinery

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Cost [1000 USD]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Option 1 (65 000 Nm³/h)</td>
</tr>
<tr>
<td>1</td>
<td>Site engineering and design</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>Heat exchanger</td>
<td>530</td>
</tr>
<tr>
<td>3</td>
<td>Gas conditioning unit</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>Ammonia storage and dosing</td>
<td>510</td>
</tr>
<tr>
<td>5</td>
<td>Accelerators</td>
<td>1600</td>
</tr>
<tr>
<td>6</td>
<td>Reactor with radiation shielding</td>
<td>800</td>
</tr>
<tr>
<td>7</td>
<td>By-product ESP</td>
<td>2600</td>
</tr>
<tr>
<td>8</td>
<td>By-product handling and storage</td>
<td>610</td>
</tr>
<tr>
<td>9</td>
<td>Auxiliary fan</td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>Ducts and piping</td>
<td>480</td>
</tr>
<tr>
<td>11</td>
<td>Electric power supply system</td>
<td>400</td>
</tr>
<tr>
<td>12</td>
<td>Control and monitoring system</td>
<td>1100</td>
</tr>
<tr>
<td>13</td>
<td>Structural elements</td>
<td>450</td>
</tr>
</tbody>
</table>
14 Land development 590 890
15 Supervision, training, start-up 1500 1500
16 Reserve (10 %), spare parts 1250 1750

**TOTAL** 13 800 19 200

The design criteria determined minimum availability of electron beam flue gas treatment installation in a selected oil refinery for 8000 hours/year. Calculations of annual operation cost of the installation were performed assuming 95 % availability which gives 8320 hours/year for continuous of oil refinery [65].

The expenses will be partly compensated by the sale of obtained by-product for agricultural purposes. Usually income from sale of by-products shall cover expenses of raw materials. By-product yield was calculated to be 460 kg/h and 920 kg/h depending on the option of installation. The income depends on the price negotiated with the by-product buyer. Assuming mean market price of ammonium sulfate 135 USD/ton, the income will be reach 516 000 USD/year for option 1 and 1033 000 USD/year for option 2 [65].

Total annual operation cost of proposed EBFGT installation will reach 558 000 USD/year for option 1 and 681 000 USD/year for option 2. The costs shown above are direct annual expenditures connected with operation of EBFGT installation and don’t cover any non cash expenditures as amortization or bank credit costs.

### 2.6 Ozone injection methods

#### 2.6.1 Technological aspects

Ozone injection methods can be used for the reduction of contaminants of flue gas of industrial power plants. The NO\textsubscript{x} reduction of flue gas by plasma generated ozone is investigated in pilot test experiments at two industrial power plants running on natural gas (Ringsted) and biomass (Haslev) [66].
The flue gas source located in Ringsted is a 2×5.5 MW \textsubscript{el} natural gas fired power plant with a total flow rate of the flue gas of 49000 Nm\textsuperscript{3}/h from which only a portion of 3 % was treated for NO\textsubscript{x} reduction. The flue gas temperature was steady at 60 °C. The main component of NO\textsubscript{x} in the flue gas was NO (over 90 %) and the total NO\textsubscript{x} level was kept by process optimization at around 80 ppm [66]. Fig 18 shows schematic of the experimental setup. Ozone input higher than 75 g/h leads to high NO\textsubscript{x} reduction. Removal efficiency of NO\textsubscript{x} exceeded 95 % than ratio O\textsubscript{3}:NO\textsubscript{x} = 1.56.

![Fig. 18. Scheme of the NO\textsubscript{x} oxidation process using ozone](image)

Ozone was produced by a WEDECO EFFIZON® HP SMO 300 ozone generator based on dielectric barrier discharge plasma source operated in O\textsubscript{2} was injected into the reactor and mixed with flue gas. Maximum ozone capacity was 1,724 kg/h. The ozone generator did not produce pure ozone but a mixture of ozone and oxygen [66].

The experimental details in Haslev power plant running on biomass was significantly different from those performed at Ringsted:
The flue gas temperature was around 115 °C;
- The NOx level in flue gas fluctuated from 100 ppm up to 300 ppm;
- Higher ozone input needs, over 300 g/h for high removal efficiency of NOx.

Only 85 % reduction rate of NOx was achieved compared to 95 % removal of NOx at Ringsted power plant running on natural gas. Higher flue gas temperature and fluctuating NOx content are the main reasons for higher ozone consumptions and lower removal efficiency.

2.6.2 Cost related to ozone production and NOx removal

The costs related to production of ozone are expected to be very sensitive to the electricity price, which has a significant influence on the optimal ozone technology. The main part of the specific cost is related to the production of ozone. At Ringsted CHP approximately 75-85 % of the total cost is bound to oxygen and ozone generation. For Haslev CHP the figure is around 90 % [66].

Furthermore, the annual operation time of operation has a major influence on the specific price, i.e. EUR per kg removed NOx.

Conclusion

In this outlook the guidelines with the characterization and economic estimation (where possible) of different plasma technologies and devices designed for pollution removal is presented. It’s complicated to evaluate plasma technology which suits the best due to lack of information, especially on economic feasibility. However, it may be concluded that most of mentioned plasma devices could be successfully implemented for industrial scale applications removing environmental pollutants.
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