Plasma processes in new technologies of water and air cleaning

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Resume

Paper presents chosen plasma processes and its application in technologies of water and air cleaning. The features of the non-thermal plasma and reactors for plasma generation are presented. Non-thermal plasma reactors, depending on the discharges used for plasma generation, have special designing and construction. The schematic construction of the plasma reactors with dielectric barrier discharges, corona discharges, arc and quasi-arc discharges are presented and their application in technologies of water and air cleaning are specified. Non-equilibrium plasma processes seem to be very promising for reducing the emission of the most dangerous air pollutants, as they initiate chemical reaction with low energy requirement at low gas temperature of atmospheric pressure.

1. Introduction

In recent years new methods of water and air cleaning by means of low temperature non-equilibrium plasma, named “cold” plasma, have been investigated and introduced to industry. In the cold plasma the electron mean energies are much higher than those of the component of the ambient gas, therefore their energy is directed to the dissociation and ionization of the polluted gas to produce radicals, which next decompose the toxic molecules. So, in contrast with conventional chemical methods, the cold plasma processes are energetically more efficient, as the whole treated gas does not have to be heated in order to remove its pollutants. Moreover, the plasma induced chemical reaction can be carried out under atmospheric pressure and in big volume of treated gas.

Different kinds of electrical discharges, depending on the geometry of reactor’s electrodes and form of supply electrical energy, can be applied as the source of cold plasma for industrial application. Relatively new and promising plasma technique is based on the gliding arc discharge energized by AC sine voltage.

Plasma reactors, in which the plasma is produced by electrical discharges, are technological devices because plasma cannot be stored or transported and has to be produced at the place where it is directly applied in the technological process. Moreover, the plasma reactors are very uncommon electrical energy receivers of relatively large power that operate at high voltage power supply of mains or increased frequency. Therefore, the power supply, which is the inseparable part of the plasma generation system, requires special methods of designing and construction.

In the paper the chosen non-thermal plasma generation systems are presented and discussed from the point of view of their application in water and air cleaning technologies. The special attention is paid to the plasma reactor, in which the gliding arc produces the low temperature non-equilibrium plasma at reasonable energy consumption.

2. Non-thermal plasma reactors

Non-thermal plasma reactors represent emerging technology of air pollution control that allows processing of large volumes of gas containing dilute concentrations of pollutants.

The main features of cold plasma are:
- cold plasma does not heat the whole polluted gas but is the source of energetic species that, in turn, decompose toxic molecules
- plasma induced chemical processes are carried out directly in polluted gas of big volume at the atmospheric pressure
- cold plasma permits simultaneous removing a number of air pollutants
- energy selectivity and capability to remove the wide variety of gaseous pollutants
- methods based on non-thermal plasma do not result in dangerous for environment by-products.
Above presented features make the non-thermal plasmas very promising to solve many environmental problems.

The potential of non-thermal plasma for the destruction of pollutants and toxic molecules has already been demonstrated in many contexts, such as nitrogen oxides NO\textsubscript{x} and sulfur dioxide SO\textsubscript{2} in flue gases, heavy metals and volatile organic compounds (VOCs) in industrial effluents.

In industry „cold plasma” is usually produced by two methods:
- electron beam irradiation,
- electrical discharges, silent, corona, glow or arc in plasma generators, called plasmotrons.

Electron-beam pollution control systems are replaced by alternate plasma-based technologies utilizing electrical discharges mainly because of high capital cost of electron accelerators and X-ray hazard.

There are many types of non-thermal plasma devices based on electrical discharges that have been developed for environmental application. Table 1 presents plasma reactors with different type of discharges, their main application in environment processes and their power supply.

### Table 1. Plasma reactors and their application

<table>
<thead>
<tr>
<th>Type of reactor</th>
<th>Application</th>
<th>Power Supply</th>
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<tbody>
<tr>
<td>Dielectric barrier-discharge reactor</td>
<td>Ozone synthesis, conversion of methane, removal of NO\textsubscript{x}, SO\textsubscript{2} and CO\textsubscript{2}</td>
<td>AC high voltage of mains or increased frequency</td>
</tr>
<tr>
<td>Ferroelectric bed reactor</td>
<td>SO\textsubscript{2} and NO\textsubscript{x} decomposition VOCs conversion</td>
<td></td>
</tr>
<tr>
<td>Pulsed corona and glow discharge reactors</td>
<td>As above</td>
<td>DC voltage, pulse voltage</td>
</tr>
<tr>
<td>Surface discharge reactors</td>
<td>NO\textsubscript{x} and VOCs removal</td>
<td>High frequency AC high voltage</td>
</tr>
<tr>
<td>Flow stabilized arc reactors (plasmotrons)</td>
<td>Chemical synthesis, melting and welding, surface treatment</td>
<td>DC or AC mains frequency voltage</td>
</tr>
<tr>
<td>Radio-frequency and microwave plasma reactors</td>
<td>CO\textsubscript{2} dissociation, chemical synthesis</td>
<td></td>
</tr>
<tr>
<td>Quasi-arc reactors with fast gas flow</td>
<td>H\textsubscript{2}S valorization and destruction, SO\textsubscript{2} and NO removal, N\textsubscript{2}, CO, CH\textsubscript{4}, SO\textsubscript{2}, N\textsubscript{2}O, CO\textsubscript{2}, freons and other gases and their mixture processing</td>
<td>DC, pulse or AC sine voltage</td>
</tr>
</tbody>
</table>

Dielectric-barrier discharge technology is the most mature and reactors based on the silent discharges have been applied commonly for over hundred years to produce large quantities of ozone for applications such as water improvement and bleaching of the textile and pulp [5]. One or two electrodes of the dielectric barrier discharge reactor are covered with the glass dielectric layer and connected to the AC high voltage. The schematic drawing of a silent discharge plasma reactor is presented in Fig.1. Environmental applications of dielectric barrier-discharges are connected with removal of NO\textsubscript{x}, CO\textsubscript{2}, and SO\textsubscript{2} from exhaust gases of diesel engine [7]. Barrier-discharge reactors can also be applied to decompose many types of VOCs and to treat H\textsubscript{2}S.

Among corona reactors [1], the ferroelectric bed reactors which construction is presented in Fig.2 seem to be very promising for environment applications. The dielectric constant pellets. The pellets are held within the tube arrangement by two metal mesh electrodes. There is an intense electric field formed around each pellet contact point and many pulsed discharges take place, the energy of which can be controlled changing the dielectric constant of the pellet and by the supply voltage value, form and frequency [5]. There were laboratory trials of ferroelectric bed reactors in the process of decomposition of CH\textsubscript{4}, CO\textsubscript{2} and of hazardous organic compounds, like toluene and methylene chloride [6].

Classical arc plasma reactors, in which the arc discharge is stabilized by fast gas flow, besides their application in metallurgy can be used in processes of cleaning air, especially including mixtures of very toxic pollutants or to incinerate solid wastes. In such case, arc reactor is used for
thermal incineration the complete wastes, usually together with container. The arc plasma reactor can operate at DC or AC power supply and its schematic construction is presented in Fig.3.

The fast gas flow can also be used in corona reactors and in quasi-arc reactor to stabilize discharges and to produce non-thermal plasma. This technique using tapered gaps, called a gliding discharge (Glidarc), in which the stationary glow discharge is replaced by a moving arc was invented in France, Orleans and its idea is presented in the Fig.4 [2]. The construction of the gliding arc reactor is simple. At least two diverging electrodes are placed in the fast gas flow and in the flow direction. The discharges occur between electrodes and across them. The displacement of the discharge roots prevents their corrosion.

**Fig.1.** Schematic view of the dielectric - barrier discharge reactor

**Fig.2.** View of the ferroelectric bed-packed reactor

**Fig.3.** Schematic construction of the classic arc plasma reactor (A-water cooled anode, K- cathode, B- anode cooling medium, G -gas inlet, Z-supply system)

**Fig.4.** Electrode arrangement in the plasma reactor with gliding arc (B-electrodes, C-ignition electrode, A-discharge chamber, Z-supply system)

The electrical energy in the gliding arc reactor is directly and totally transferred to the treated gas. All gas or vapour like argon, nitrogen, oxygen, carbon oxide and dioxide, sulfur dioxide, chloroform, freons, steam, air, and some other mixtures can be directly processed at any inlet temperature and 0,1-5 atm pressures. Dusty and misty fluids are also accepted [2].

Plasma produced in gliding arc plasma reactor is out of equilibrium with relatively low energy density. It is difficult to define the nature of such discharges when the electric energy is put across the fast and turbulent gas flow and when the discharge roots move rapidly along electrodes, but its transient characteristic is similar to the glow discharge characteristic.

The discharge starts at the shortest distance between electrodes and within a very short time there is formation of low resistance plasma (Fig. 4). The quite small plasma volume at this stage is then drew by the fast gas flow at speed more than 10 m/s, and both the length and voltage of discharge column increase together with growing distance between electrodes. In the first stage plasma is closed to the thermodynamic equilibrium because electrical power delivered to the reactor is sufficient to compensate energy losses by thermal conduction. In the second stage a transition to a step-wise ionization occurs that is linked to a sudden increase in discharge length. The electrical energy in this stage is directly used to produce non-equilibrium and very reactive plasma allowing efficient gases processing. The main innovative aspect of the plasma process with gliding arc is the way in which the chemical reaction is activated by powerful electrical discharges under atmospheric pressures. Up to now, quite a lot of applications were tested in laboratory and close to industrial scale [3]:

- air cleaning from volatile hazardous compounds
- combustion of very lean methane-air mixtures
- flue gas SO₂ reduction to elementary sulfur
- processing of CO₂
- oxidation of chloroform vapours
- flame overheating (electro-burner)
- natural gas conversion to the syngas
- steam overheating.

Enumerated applications show that the inexpensive and very simple gliding arc discharges are capable to carry out many chemical reactions that allow cleaning wide range of toxic gases.

3. Conclusion

Numerous studies of the non-equilibrium plasmas for environmental application show that they are particularly favorable for initiation of chemical reactions at reasonable power consumption and at the conditions like polluted gases are emitted to the atmosphere, i.e. at atmospheric pressure and low temperature.

Reactor with gliding arc, due to its simple construction and proven efficiency in many applications presents an alternative to conventional chemical methods technology of air cleaning from toxic pollutants.

References


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