ELECTRON-BEAM PLASMACHEMICAL REACTORS

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1. Advantages of Electron-Beam plasmachemical reactors

The Electron-Beam Plasma (EBP) is generated by injecting an electron beam (EB) into a gas, the typical range of gas pressure being ~ 0,1–10^3 Torr. To generate the EBP a cylindrical, strip and tubular EB with the power ~ 0,1–10 kW are usually used. The energy of the accelerated electrons lies within the range 20-100 keV.

In general the properties of the generated EBP, the plasma composition and the geometry of the plasma bulk are due to:

- the parameters of the EB being injected (electron energy E_b, overall current of the beam I_b and current density j_b),
- the medium properties (chemical and phase composition, pressure P_m and temperature).

The EBP composition is complex: generally it contains molecules, atoms, radicals and ions in stable and excited states, and plasma electrons and injected beam electrons as well. At moderate pressures (P_m < 50 Torr) the EBP is usually strongly non-equilibrium. It means that:

- plasma particles mentioned above are produced in super-equilibrium concentrations,
- the function of the electron energy distribution in the EBP is non-Maxwellian, high energy electrons ($E \sim E_b$), intermediate energy electrons ($E \approx E_b$/2-10 eV) and low energy electrons (E < 10 eV) being available in the EBP.

The EBP generation procedure advantages as compared to the gas discharge plasma result from the following characteristic features:

- The EB can be injected into any gases and gasious or gas-vapor mixtures. A wide spectrum of plasma-chemical tranformations can be realised adjusting conditions of plasma generation.
- Large EBP bulks (at least much larger than the characteristic bulks of the gas discharge plasma generated by conventional means) can be produced. There are no restrictions as to the P_m: the plasma bulk contraction does not occur in a wide range of j_b ($j_b < 10^5$ A/m^2) even at $P_m \sim 10^2$ Torr and higher.
- There are no technical problems with introducing dispersed additives (such as liquid drops or solid powders) into plasmogenerating gases. Compact solid bodies can be placed or liquid jets can be injected into the EBP clouds and flows.
- If the EBP is generated by sufficiently powerful beams ($j_b > 10^4$ A/m^2) the temperature of the heavy plasma particles can be controlled by changing the density of the EB energy liberation. An adequate adjustment of heating and the evaporation of the condensed phase (if it is injected into the plasma bulk) controls the chemical composition, components ratio, gasdynamics and heat exchange in the reaction bulk and thereby affects the plasmochemical processes.
- As to the EB injection into gas streams (both sub- and super-sonic) there are usually no problems with the plasma stability.
- It is possible to inject the EB into gas discharges of various frequencies: from the discharges in electrostatic field to MW-discharges. These lead to generating so called Hybrid Plasma (HP) in which both the EB and the gas discharge are plasma generating agents. The concurrent or the alternating action of the EB and the electro-magnetic field on the substance essentially expands the practical applications of the EBP.

2. Electron-beam plasmachemical reactors: the design in general

The typical Electron-Beam Plasmachemical Reactor (EBPR) consists of three main parts (see fig.1):

- the EBP generator that includes the low-voltage electron accelerator (electron gun), the power source for the electron gun, the injection window (IW) to inject the EB into a reaction chamber;
- the reaction chamber equipped with the temperature control system;
- the reactor feeding system that includes the gas feeder, the evaporator for a vapor production (if it is required) and sprayers if dispersed additives should be introduced into the reaction chamber.

The designs of the electron guns and their power sources are highly developed and described in detail (see for example [1]). Two techniques of the continuous EB injection are usually used for EBP generators: the electron injection through thin foils, separating high-vacuum and working chambers and lock systems. For the thin EB with E_b < 100 keV gas-dynamic windows (that should be considered as a particular type of the lock systems) are very promising [2]. Really to inject the low voltage (E_b < 50 keV) concentrated (j_b > 0,1 A/cm^2) EB only gas-dynamic IW can be used. Even in the most sophisticated designs of the foil windows j_b does not exceed ~ 1 A/cm^2 due to problems with the foil cooling. Two- and three-stage gas-dynamic windows have been developed and are successfully used in MIPT.

The reaction chamber is a vacuum vessel and the chamber walls are or aren't in contact with the EBP. It depends on the relative dimensions of the chamber and the plasma cloud, the EBP cloud shape and sizes being due to both the EB and plasmagenerating medium parameters. In any case the reaction chamber walls are heated due to the EB energy liberation. The heating is extremely high if the fast electrons bombard the chamber walls. The intensive wall bombardment by elastically scattered electrons occurs at high pressures P_m in the reaction chambers of small diameter. To maintain the required temperature of the chamber and reaction bulk the temperature control system (usually cooler) has to be applied.

The gas pressure in the reaction chamber is maintained by the appropriate feeder (see fig. 1) setting. To inject the vapor the heated vessel with a required liquid or a solution rather than the gas balloon 8 is connected to the supply line, the pressure in the reaction chamber being maintained by means of the liquid temperature in the vessel. Sometimes the pipeline needs heating to prevent the vapor condensation inside the pipe.

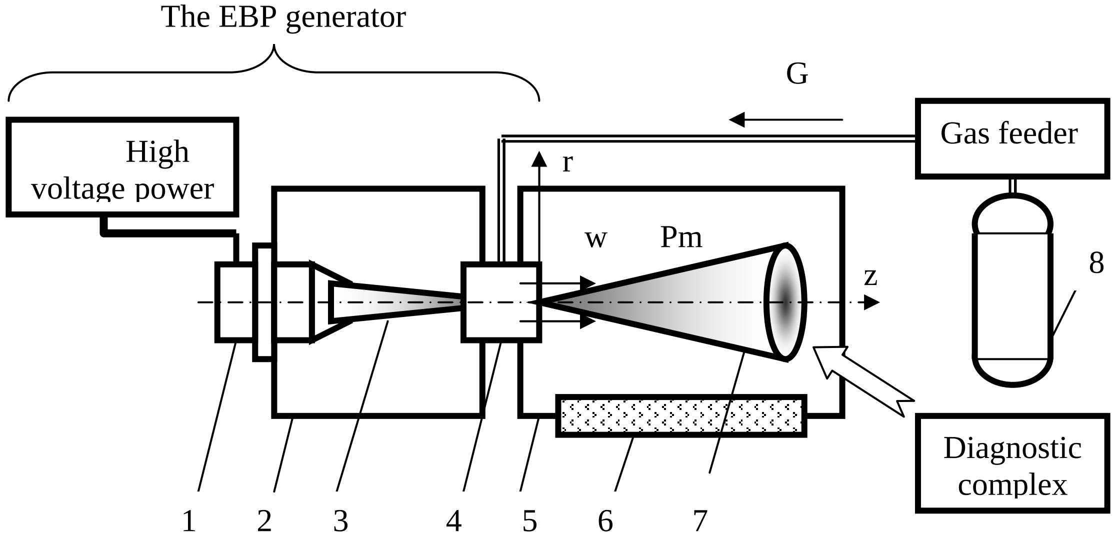

Fig. 1. Experimental electron-beam plasmachemical reactor:
1 – electron gun; 2 – high-vacuum chamber; 3 – electron beam; 4 – injection window combined with the gas nozzle; 5 – reaction chamber; 6 – X-ray protection window; 7 – electron-beam plasma; 8 – gas balloon

Gaseous and gas-vapour mixtures can be supplied to the reaction chamber in the same way either by using premixed media or by an independent injection of the desired components through the individual supply line. In the latter case the chemical composition of the reaction bulk is controlled by partial pressures of the mixture constituents.

The reactoin chambers with the gas circulation seem to be promising, the gas blowing either in the same direction (fig. 2a) or toward the injected EB (is not shown in fig. 2) being possible. The intensive gas (vapour) blowing through the porous wall (fig. 2b) can be used for the chambers with both flowing and still reaction zones.

To introduce the powders into the reaction chamber sprayers of different types are used. The sprayers with impinging jets, rotary liquid sprayers and centrifugal sprayers can be applied for unmoving reaction zones, whereas spraying by means of a high velocity gas stream is promising for the reactors with the gas circulation. The injections of both circular and flat liquid jets into the gas flow were studied to form the heterogeneous EBP. Thin flat liquid films produced by impinging jets and centrifigal sprayers were found to give the best results. Experiments showed the spraying quality to be satisfactory even if the reaction chamber pressure was reduced down to 1 Torr.

The direct liquid injection into the reaction chamber can be used to produce the EBP of vapours or gas-vapour mixtures as well.

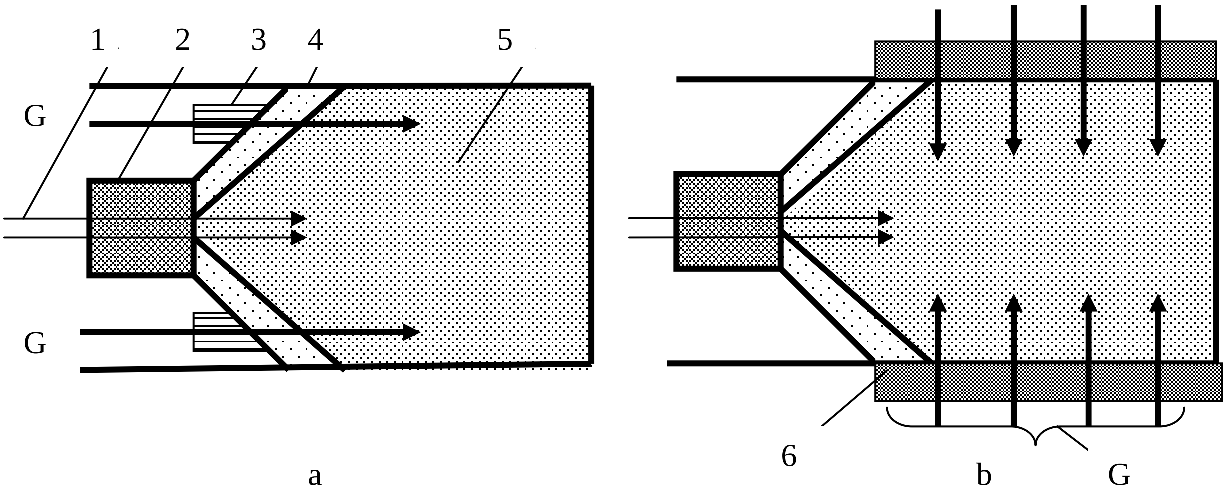

Fig. 2. Reaction chambers of the EBPR:
a – the EB and the gas are injected in same direction; b – the gas is blown through the porous wall; 1 – electron beam, 2 – injection window, 3 – blower, 4 – reaction chamber, 5 – reaction zone, 6 – porous wall

3. Physical problems in the reactors designing

Consider, as the example, one of the simplest statements of the problem for EBPR modeling which is typical for computer simulation. Suppose the EBP composition should be found. The continuos EB is assumed to be injected into a glass cylindrical chamber filled with a still molecular gas. The initial direction of the beam is along the chamber axis. The beam electrons are scattered from the gas molecules elastically and inelastically. The primary electron energy is lost via atom excitation and ionization. Secondary electrons also excite and ionize the gas during their propagation. The electrons reach the chamber wall and penetrate into the wall material or are rebounded from the wall surface. As a result the following phenomena occur:

- plasmachemical reactions between plasma particles;
- gas heating;
- reaction chamber walls heating (see above);
- reaction chamber electrostatic charging.

The analysis of the EBP is difficult as it needs self-consistent solutions of the complicated, even singly, electron- and molecular-kinetic, heat transfer and electrodynamic problems. Gas-dynamic problems should be considered together with those mentioned above if the gas is pumped through the reaction chamber:

- changes of the reaction chamber aerodynamic characteristics (resistance, in particular);
- changes of the drag of compact bodies or aerosol particles if they are inserted into the gas flow.

Theoretical analysis and computer modelling of the EBPR are difficult. Though software to simulate the EB propagation through the gas (usually by means of the Monte Carlo method) and plasmachemical transformations on the basis of complicated models have been developed the calculations are not sufficiently accurate. The experimental studies of the EBPR seem to be more promising.

4. Experimental unit and diagnostic complex

Fig. 1 illustrates the design of the experimental unit. The focussed EB 3 is generated inside the high vacuum chamber 2 by the electron gun 1. The EB is introduced into the working chamber 5 through the IW 4 combined with the nozzle. The nozzle forms the gas flow into which the EB is injected. As a result the EBP flow 7 is produced.

The experimental unit is equipped with a diagnostic complex that carries out the following measurements:

- microwave screening of the EBP to study the spatial distribution of the plasma electron density $n_{ep}(z, r)$;
- study of the electrostatic charging of solid bodies in contact with the EBP (reaction chamber walls in particular);
- measurements of the spatial distribution of the plasma flow brightness in the visible range of spectrum and in X-rays to study the shape of the EBP jet and the EB energy liberation;
- spectral measurements to study the EBP composition and the temperatures of the plasma heavy particles;
- direct measurement of the gas translational temperature and temperatures of channel (nozzle) walls by means of temperature sensors;
- measurement of the bodies drag and the channel hydrodynamic resistance.

Open barrel-shaped resonators mounted inside the working chamber are used for the microwave diagnostics. Optical instruments (spectrometers, photo-sensors, TV and X-ray cameras) are placed outside the working chamber, measurements being carried out through the X-ray protection window 6.

5. Applications of the electron-beam plasmachemical reactors

Thermal, plasmachemical and radiation-chemical processes occurring in EBP and their combinations are used in practice. The following EBPR applications for technologies and scientific researches are studied:

- industrial technologies: substance synthesis and decomposition, material surface modification, plasma-assisted coating [2];
- plasma-dynamic experiments in the field of the aerodynamic characteristic control;
- plasma-assisted combustion in aircraft and rocket engines, magnetohydrodynamic units on aircraft board.

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