Generation And Applications Of Electron-Beam Plasma Flows

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Abstract. Plasma flows generated by continuous or interrupted injection of an electron beam into subsonic or supersonic gaseous streams are considered. Liquid and powder spraying by the electron-beam plasma (EBP) flows is studied as a technique of the aerosol plasma generation. A number of experimental setups generating both free plasma jets and plasma flows in channels are described. Examples of the EBP flows applications for industrial and aerospace technologies are given. The applications are shown to be based on unique properties of the EBP and its stability within very wide ranges of the plasma generation conditions. Some applications of the Hybrid Plasma (HP) generated by combined action of the electron beam (EB) and intermittent gas discharge on flows of gaseous mixtures and aerosols are presented as well.

1. Introduction

The Electron-Beam Plasma (EBP) is generated by injecting an electron beam (EB) into a gaseous medium \cite{1}. To transport the EB from a vacuum chamber, where the EB is originally formed, into a working chamber which is filled with a gas special injection windows (IW) are used. In passing through the gas the EB produces ions and heavy neutral particles in ground and excited states; partially decelerated fast electrons of the original EB and secondary electrons with low and moderate energies are available in the EBP as well. Depending on the EB power $N_b$ and gas pressure $P_m$ plasma temperature $T_m$ varies within a very wide range 300-3000 K. Under typical conditions of the EBP generation ($P_m < 50$ Torr and $N_b \sim 1$ kW) the gas isn’t heated highly ($T_m < 10^3$ K), however plasma particles usually reach very high concentrations, i.e. the EBP is strongly non-equilibrium and can be extremely chemically active even at low temperature.

Among peculiarities inherent in the EBP in general \cite{2} the following features should be mentioned specially:

- The EB can be injected into a gas, vapor or their mixtures of any chemical composition;
- The EBP doesn’t contract even at higher pressures;
- Being strongly non-equilibrium the EBP is chemically active at low temperatures (down to room temperature and lower);
- When the EB is injected into sub- or supersonic gas flows, as well as into the still gas, the plasma bulk usually remains stable;
- Large size bodies of various shapes can be introduced into the plasma bulk; dispersed additives (liquid drops or solid powders) can be sprayed throughout the plasma bulk too;
- The EB is compatible with other ionizers; the EB can be injected into gas discharge in particular.

Combined action of two or more ionizers results in generation of so called Hybrid Plasmas (HP). The combination of these peculiarities is the basis for development of various setups which can be used for numerous industrial and aerospace applications.
2. Techniques of the electron-beam plasma flow generation

Consider free supersonic plasma jet formation in a large-size chamber (see fig. 1) as an example of the EBP flow generation. The focused EB 6 was formed in a high vacuum chamber 8 ($P_m \approx 10^{-5}$ Torr) by an electron gun (the gun is not shown in fig. 1) and then the beam was injected into the working chamber 4 through the IW 1. The IW was placed inside the central body of the plug nozzle 5 which formed supersonic jet 2 of the gas pumped into the prechamber of the nozzle. In passing through the gas the EB excited plasma in zone 1 due to elastic and inelastic processes of the beam-gas interaction. In general, ions and heavy neutral particles in ground and excited states, partially decelerated fast electrons of the original EB and secondary electrons with low and moderate energies are available in the EBP.

The working chamber was filled with a still buffer gas of the same composition as that of the gas being blown or of some other composition. In the latter case the working chamber was equipped with its own gas feeder to maintain the composition of the medium surrounding the jet. The blowing of plasmagenerating and buffer gases was compensated by their evacuation from the working chamber and the value of the gas pressure $P_m$ could be kept constant if the combination of the vacuum pump productivity and total gas discharge was chosen appropriately.

Note that the plug nozzles were used to generate not only supersonic but subsonic plasma jets as well, and the nozzles of other types, e.g. Laval nozzles and non-profiled cylindrical nozzles, turned out to be applicable for the EBP flow generation. All nozzles mentioned above were usually (but not necessarily) combined with injection windows.

3. Generation of the EBP of aerosols

Figure 2a illustrates generation of two-phase EBP flow in free space. The EB was injected through the IW combined with the Laval nozzle, the EB passing along the jet axis through the nozzle throat. As a result, the EBP flow 2 was generated. The liquid was injected into the plasma flow by means of the sprayer 4. We used liquid hydrocarbons and aircraft fuels as the additives to be sprayed. Electrically controlled centrifugal sprayers were used for spraying and pneumatic sprayers could be applied at higher gas flow velocity. The dispersed liquid was mixed with the gas flow and zone 1 of the two-phase EBP was formed. The ratio of the air-liquid mixture components and the shape of the aerosol zone were controlled by the air discharge $G_a$ and by the liquid discharge $G_l$ that can be varied and measured during the experiment.

Plasmas of solid aerosols were generated in a similar way: the mechanical sprayer continuously injected some portions of a powder into the zone of the EBP generation. Powder particles moved together with the plasma flow and then they were caught by a special trap. Though the plasmas of solid aerosols are very

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1 Various IW designs were described in [2] in detail.
promising for applications [3, 7] there is a basic problem in a dusty plasma control since the aerosol particles are able to accumulate ultrahigh electrostatic charge in the EBP [4]. At lower gas pressures ($P_m < 1.5$ Torr depending on the type of the plasmagenerating gas) the Coulomb forces exceed aerodynamic ones and they can cause instabilities of the plasma flow and even destroy the plasma volume.

Fig. 2. Aerodynamic experiments in the EBP:

**a)** generation of the aerosol plasma flows; **b)** complex aerodynamic experiment.

1 – zone of aerosol EBP, 2 – EBP flow, 3 – gas flow, 4 – sprayer, 5 – needle electrode, 6 – high voltage generator, 7 – zone of external combustion, 8 – aerodynamic model

4. Aerodynamic experiments in the EBP

The following experiments were carried out to investigate the EBP influence on:

- ignition and combustion of the aircraft fuels sprayed in free EBP flow;
- ignition and combustion of the aircraft fuels sprayed inside a cylindrical channel;
- external combustion of the air-fuel mixture near the body surface
- drag of bodies of the simplest shape (sphere and cone);
- aerodynamic resistance of long cylindrical channels filled with the flowing EBP.

One of the arrangements of the experiments on plasma-assisted ignition and combustion of air-fuel aerosol is shown in fig. 2a. The aerosol zone 6 was formed inside the EBP flow 2 by pneumatic or centrifugal spraying of the fuel (kerosene) and the air-fuel mixture was ignited by the needle electrode 5 supplied with high voltage from the pulse power source 6. The power source operation frequency was about 100 Hz. Ambient pressure $P_m$, gas velocity, air and fuel discharges, voltage on the needle electrode and its polarity varied. Experiments showed that usually the air-fuel aerosol:

- could be ignited when the EB was injected into the air flow and it could not be ignited when the EB was turned off;
- stable burning was observed only when the EB was turned on and the igniter was operating.

Thus the EBP assisted the ignition of the air-fuel aerosol and supported the aerosol combustion. The similar behavior of the air-fuel mixture was observed if the aerosol flow was formed in a cylindrical channel that can be considered as a model of a combustion chamber.

Measurements of the friction forces between the EBP flow and the wall of the channel didn’t reveal any effects which could be attributed to the plasma processes. Neither plasmachemical modification of the channel surface nor gas ionization and excitation changed the air resistance of the channel. However, the gas heating at higher $N_b$ up to $T_m \sim 10^3$ K resulted in the increase of the channel air resistance that correlated with the temperature function of the gas viscosity. The EB injection into supersonic gas jet was found to be able to change the pressure distribution near the surface of the body placed in the stream. This change may be interpreted as the body’s drag reduction [5].

Scheme 2b illustrates the experimental study of the body aerodynamic characteristics in the presence of the EBP near the body surface. The model 8 was inserted into the EBP flow on the aerodynamic scale that measured integral force of the flow action on the model. The model had thin channels to inject the gaseous or liquid fuel toward the airflow and high voltage pulses were supplied to the model via the model holder if the fuel ignition was required. Under certain conditions (especially adjusted combination of flow velocity and EB parameters) stable combustion of the fuel occurred and zone 7 of the combined
plasma of combustion products was excited around the model surface. The plasma-stimulated external combustion of propane was found to additionally reduce the spherical model down to 20-40% in air flows with Mach number \( \sim 1.5 \) (\( P_m \sim 10 \) Torr).

Note that the described experiments were, in fact, experiments with the HP rather than with conventional EBP since the ignition and combustion of the air-fuel mixtures occurred in the gaseous flows excited by combined action of the EB and intermittent high voltage discharge.

5. Materials treatment in the EBP flows

A number of industrial applications of the EBP jets were studied experimentally. In particular, the flows of oxygen and nitrogen plasmas were successfully used to synthesize oxide and nitride layers on the inner surfaces of the metallic tubes [6] and to treat various powders [1]. The same approach proved to be effective to modify physical, chemical and biological properties of polymers and bio-polymers [7, 8].

Figure 3a illustrates the plasma-assisted synthesis of combined nitride-carbide coatings on the inner surface of the titanium tube. Nitrogen and gaseous hydrocarbon were blown into the tube 2 as two separate vortex gas flows 4 and then the nitrogen-hydrocarbon mixture flew along the tube; the EB 5 was injected along the tube axis too. The plasma flow 3 heated the tube and chemically reacted with the material resulting in the Ti-N-C layer formation on the inner tube surface (see fig. 3b). To prevent heat transfer to the ambient gas and to minimize the power consumption for the sample heating the tube was placed inside the heat-protecting envelope 1.

The samples were processed within the temperature range \( T_s = 350-650 \) °C. The temperature control was carried out by adjusting the EB current \( I_b \) within the range \( 1 < I_b < 50 \) mA at a constant gas mixture pressure that was 10 Torr in the described series of experiments. The optimal treatment time \( \tau \) was found experimentally and varied from 5 to 15 min depending on the required sample temperature. Local temperatures at various points of the tube were measured by sensors 6; one of them was connected to the feedback of the EB controller to automatically keep the sample temperature constant during treatment. After treatment the tube was cut into fragments to measure the synthesized layer thickness and to study the layer chemical composition. The content of the main chemical elements at various depths under the surface is presented in fig. 3c. The figure shows the concentrations of nitrogen and carbon at various depths under the surface. Reaction rates of the surface layer synthesis in the EBP appeared to significantly exceed those in the gas discharge plasma. Typical formation time of the layer of ~10 \( \mu \)m in thickness was about 10 minutes rather than hours as in conventional industrial reactors with DC- or RF-discharges.

The EBP and HP flows are applicable for the treatment of not only bulky bodies but thin films and even nano-materials. In particular, the experiments with graphene deposited as a thin film on a silicon substrate showed that graphene, being treated in low-speed ammonia HP flow (\( P_m \sim 1 \) Torr) during \( \tau \sim 10 \) min, contains about 10% of atomic nitrogen that is a very promising result from the point of view of the graphene functionalization for its further applications.

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**Fig. 3.** Plasma-assisted synthesis of combined nitride-carbide coatings on the inner surface of the titanium tube: a) scheme of the experiment; b) microsection of the tube fragment after the plasmachemical treatment; c) concentrations of nitrogen and carbon at various depths under the surface of treated sample. 1 – heat-protecting envelope, 2 – titanium tube, 3 – EBP flow, 4 – vortex gas flows, 5 – EB, 6 – temperature sensors.
6. Conclusions

A number of pilot plasmachemical reactors and plasmadynamic setups based on the generators of the EBP and HP flows had been designed for advanced aerospace and industrial technologies. The reactors were successfully used for the modification of large items, thin films, and powders made of various non-organic, organic and bioorganic materials.

The EBP and HP of liquid aerosols were proved to be promising for the problems of plasma-assisted ignition and combustion of propellants and plasma control of the aerodynamic characteristics of bodies in sub- and supersonic airflows.

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