Temperature Distribution Induced by Electron Beam in a Closed Cavity

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ABSTRACT

In order to investigate heat transfer phenomena induced by EB in a closed cavity an experimental arrangement, which allows generating and focusing an electron beam in to closed cavity within 1 mm in diameter and measuring temperature all over any perpendicular section to the EB, is used for this purpose. Experimental data show that the radial distribution of current density and temperature is normal with pressure and location dependent parameters. Moreover, there is two distinguishable regions in the EB: one is central while the other surrounds the first one.

***Key Words:* EB Plasma, Current Density Spatial Distribution, Temperature Radial Distribution**

INTRODUCTION

Electron beam (EB) has a wide field of applications in modern scientific investigations and new technologies. One can mention here, smog radiation cleaning, thin film deposition, etching, laser medium and radicals generation, gas stream diagnostic and surface treatment. In spite of that the optimization of these processes is still demanded because it allows obtaining a greater control over plasma parameters and a higher plasma density and uniformity. Nowadays, there is in use a number of new high-density plasma sources, electron cyclotron resonance(1), inductively coupled plasma(2), helicon reactors(3,4) and large area plasma processing system(5).

Up to date, it is well known that the collision of electron beam with gas's atoms and molecules is of fundamental interest in plasma physics and many researchers pay their attention to study the radial temperature distribution across the EB plasma in order to deeply understand the mechanism of heat transfer from EB to working gas. This mechanism is a very complex self-consistent problem as the propagating of EB in gases involve many physical processes like excitation and ionization, diffusion, generation of electromagnetic waves, heterogeneity of the medium, non-equilibrium state of the EB plasma, ...etc which are in their role strongly dependent on temperature. So, the heat transfer, which is largely influenced by these processes, strongly depends on the temperature also. The theoretical complete solution of the mentioned problem requires powerful computer. Moreover, when injecting an EB in a gas the angular and energy distribution of electrons as well as the properties of the gas will be changed.

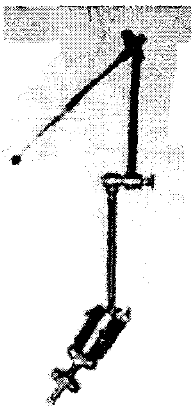
On the other hand, long time ago Shoumakher(6) studied, experimentally, the spatial distribution of EB current density at some EB cross sections according to working air pressure of 30 Torr and electron initial energy of 16.5 keV. Then, he concluded that the distribution is Gaussian all over the cross section. Later on, the researchers cited this result as a non-disputable fact (see, for example, references (7-9)). Moreover, it was supposed(9) that EB current density decreases with distance exponentially and the EB energy converted into heat obtained by a metallic body located at distance z from the injection point is but a simple function of pressure ($1/P^2$). However, EB current density distribution, electron energy distribution and temperature distribution are still subjects of numerous theoretical and experimental investigations (see, for example, references (10-13)).

This work is intended to study experimentally the EB plasma (EBP) temperature and EB current density over two cross sections of the EB, at different pressures, in order to obtain useful information about the radial distribution of these quantities. The temperature in EBP and the heat flux of EB as function of pressure is also studied in the central region of EB located at distance 280 mm far from the injecting aperture.

EXPERIMENTAL ARRANGEMENT

Experiments have been carried out on a setup, which consists of the following basic components: 1) Electron gun, 2) Introductory device ID, 3) Cavity filled with a gas (air in our case) and 4) Vacuum pumps. Experimental setup is described in detail previously[14]. In this arrangement the electron beam of initial radius r_0 enters the so-called working camera (closed cavity), where it can generate EBP. One can watch the EBP through a window, designed for this purpose (see the photo of the beam on Fig.1). Moreover, the equipment allows to regulate the beam current, initial energy and the pressure of gas in the cavity. For measuring the temperature, a copper sphere of small diameter supplied with thermocouple is used (see Fig. 1).

Additionally, we used a simple arrangement for measuring the heat flow from the EB. A schematic construction is shown in Fig. 2.



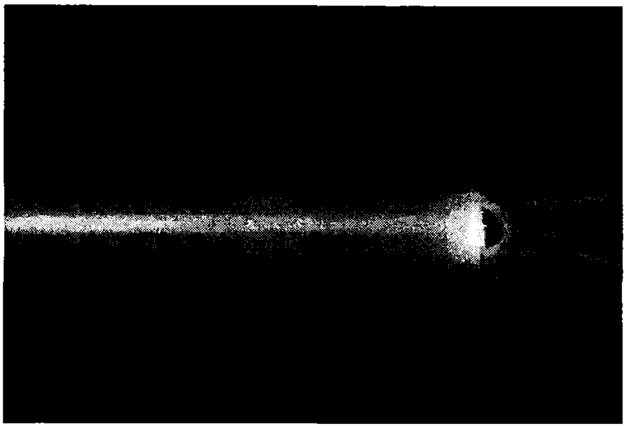


Fig. 1: The photo of EB incident on the copper sphere (on the right) and the arrangement of measuring temperature (on the left).

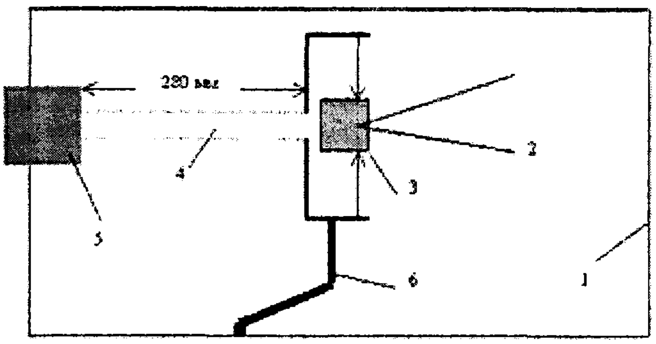


Fig. 2: The experimental arrangement for measuring heat flow. 1 to 6 denote the camera, thermocouple, cylindrical sensor, EB, ID and arm for controlling sensor respectively. Sensor is located 280 mm far from the ID.

RESULTS AND DISCUSSIONS

First of all, we have noticed (see Fig. 1) that the EB, a little far from the places of injection (ID) and incidence (copper sphere), consists of two clearly distiguishable regions: a central one with relatively small dimensions in relation to the surrounding one. The radial dimensions of each of them depend on the gas pressure in the cavity as well as on the location of cross section in relation to the injection point ID. For example, the radius of the central region, at z=210 mm, equals 5.5 mm, 6 mm and 7 mm at pressure value of 0.66 Torr, 1.1 Torr and 2.6 Torr respectively. This division appears clearly when measuring EBP temperature or current EB density radialy and more clearly when analysing these results. Here, it was found that each of the measured EBP temperature and EB current density could be fitted well by normal radial distribution (see Figs (3) and (4)) in each of these regions. These Figures give also measured data of EBP temperature and EB current density at z =210 mm and 130 mm. It is clear from these Figures that, for low pressures, the temperature of the EBP undergoes a sudden change after moving away some mm from the axis of the EB, and this change becomes smooth for higher pressures. The same is observed for EB current density.

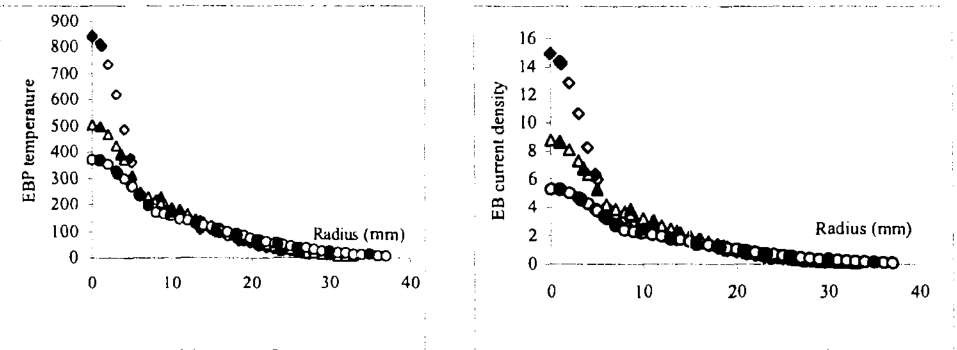


Figure 3: Radial dependence of measured (closed symbols) and fitted (open symbols) EBP temperature ($T - T_a$, T_a ambient temperature) (left in K) and EB current density (right in A/m^2) at z =210mm. Square, triangle and circle denote pressure of 0.66 Torr, 1.1 Torr 2.6 Torr respectively.

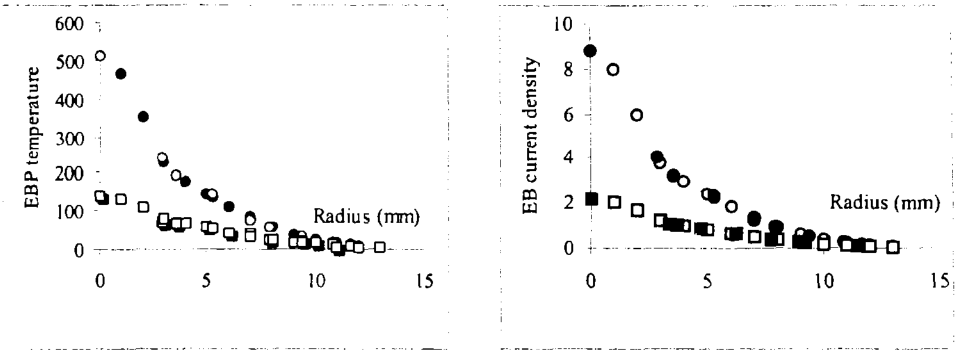


Figure 4: Radial dependence of measured (closed symbols) and fitted (open symbols) EBP temperature (left in K) and EB current density (right in A/m^2) at z =130 mm. Square and circle denote pressure of 8 Torr and 2.6 Torr respectively.

Here, it should be mentioned that we used, in our experiments the aperture radius r_0=0.5 mm, the initial electron energy of 25 keV and the initial EB current intensity of 10 mA. So, the initial EB current density equals 12739 Am^{-2}. This means that our working conditions satisfy the conditions of producing quasi-stationary plasma (namely: the density of the current of beam $10^3 < j_b < 10^6$ A/m^2, and the pressure of the gas $P \sim 1-100$ Torr). So, the space charge is compensational and the density of secondary electrons equals to the density of ions (9). We must also mention that the quasi-stationary state of plasma can be realized by the continuous injection of electron beam, that leads to a balance in formation and annihilation of charged particles by many physical mechanisms (basically by diffusion)[9]. Therefore, the steady distribution of temperature in the cavity could be easily interpreted according to these reasons. Moreover, this result enables us to use steady-state equation for describing the heat transfer.

For the EBP temperature and the heat flux of EB as function of pressure in the central region of EB cross section, located at distance 280 mm far from the injecting aperture, an arrangement shown in Fig. 2 is used. The sensor is a copper cylinder, of 1cm in diameter and 1 cm in height, equipped with a thermocouple, is used. The obtained results are shown in Fig. 5. On the contrary to (9), it was found that the dependence of all quantities shown in Fig. 5 on pressure up to 1.1 Torr could be well approximated by an exponential function. Moreover, the measured radius of enlargement of EB, for pressures more than 1 Torr, differs largely (see Figs 3 and 4) from the proposed theoretical values.

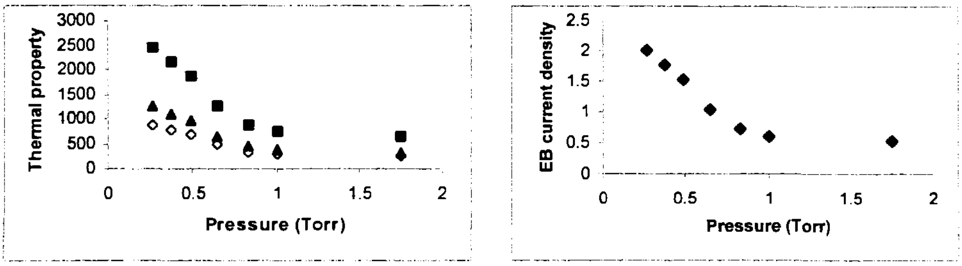


Figure 5: Pressure dependence of (left Fig.) EBP temperature increase (open symbol), EB energy (triangle) in J, heat flow, which is the beam energy flow rate to the metallic stopper, (square) in kWm^{-2} and EB current density (right Fig.) at z =280 mm.

Here it should be mentioned that the EB energy is calculated by:

$$E = 2\pi \int_0^{0.005} N_e(z,r)E_e(z,r)rdr$$

where z is the distance from the ID (see Fig. 2) which equals 280 mm in the case of Fig. 5, $N_e(z,r)$ is the radial distribution of incident electrons at z distance and $E_e(z,r)$ is the radial distribution of the energy of incident electrons. The number 0.005 denotes the radius (in m) of copper cylinder used in experimental arrangement (see Fig. 2).

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