# CONDITIONS OF THE CURRENTS SMALLNESS IN COMBUSTION PLASMAS

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The spatial distribution of the floating potential of an isolated probe between electrodes in combustion plasma at passing a current is experimentally investigated. It is found out that the spatial distribution of the bulk plasma potential is a linear function of a coordinate at small currents. The linearity is broken with increase in the current. The theoretical analysis of the passage of a current in thermal plasma is carried out. The conditions for a violation of the Ohm's law are established. It is shown that equilibrium is maintained if there are enough the charge carriers formed as a result of both the ionization by collisions in plasma and the exchange processes on the interface to maintain the necessary intensity of a current. Otherwise, there occurs the additional ionization of plasma atoms, and the equilibrium functions are not applicable.

## Introduction

A combustion plasma contains a gas at atmospheric pressure with the admixture of an alkaline metal and, in some cases, the particles of combustion products. The collision ionization of the admixture happens at the gas temperature of about 2000—3000 K, and the equilibrium electron and ion densities are established. The ionization rate in such a system exceeds the diffusion rate of charge carriers. Therefore, the equilibrium distribution functions [1],

$$n_e = \nu_e \exp\frac{\mu_e + e\phi}{kT}; \quad n_i = \nu_i \exp\frac{\mu_i - e\phi}{kT}, \tag{1}$$

can be used, where $\nu_e = 2(m_e kT/2\pi\hbar^2)^{3/2}$ is the effective density of electron states, $\nu_i = g_i(m_i kT/2\pi\hbar^2)^{3/2}$ is the effective density of ion states, $\mu_e and \mu_i$ are, respectively, the chemical potentials of electrons and ions, $\phi$ is the electric potential with respect to the bulk plasma potential $\varphi_{\rm pl}$ [2].

The sum $\varphi = \varphi_{\rm pl} + \phi$ is the measurable potential. For example, the floating potential of a probe in the plasma is $\varphi_f = \varphi_{\rm pl} + \phi_b$, where $\phi_b$ is the potential barrier on the "plasma—probe" boundary.

In the present paper, we elucidate, in the case of a combustion plasma, whether the equilibrium distribution functions are valid if the plasma is perturbed by an electric current.

## Experiment

The experimental study was carried out with the use of a three-slot burner supplemented by the system of electrodes and a device providing the motion of a probe. The burner is supplied with other device injecting fluid hallmarks, which has allowed us to inlet the admixture, potassium, as a water solution of potash in the beforehand mixed propyl hydride — air flame. The potential difference was supplied to electrodes (Fig. 1), and the current in the circuit was measured (the left electrode is grounded). The probe signal was filed by a high-resistance ($R_{\rm in} = 10^{10}\Omega$) compensative recorder.

Electrodes were steel plates of 10×4 cm in size and 0.5 cm in thickness. The distance between the electrodes $L = 10$ cm. The electrodes were supplied with thermoelectric couples for the check of temperature. The temperature of electrodes was changed with the parameters of a flame in the range 1000—1050 K (0.006—0.09 eV), which is approximately by 1.2 times less than the mean temperature of the flame which was equal to 1200 K (~0.1 eV). The electric probe was a steel strand of 0.2 mm in diameter and 3 mm in length. The probe was made of steel, so that the work function of electrons was identical for all electrodes. Prior to the measurement, the probe was heated up to a steady-state temperature, and only after that the recording of probe's floating potential was started by the high-resistance recorder.

The results of measurements of the floating potential of the probe $\varphi_f$ in a gap between electrodes are submitted in Fig. 2. It is seen that, outside the layer of space charge near the electrode, $\varphi_f$ is a linear function of the coordinate at small currents, and $d\varphi_f/dr$ linearly depends on the current intensity. With increase in the current, the function $\varphi_f(r)$ ceases to be linear.

The floating probe potential $\varphi_f = \varphi_{\rm pl} + \phi_b$, and, if the potential barrier $\phi_b$ is constant, the distribution shown in Fig. 2 corresponds to the spatial distribution of the bulk plasma potential $\varphi_{\rm pl}$.

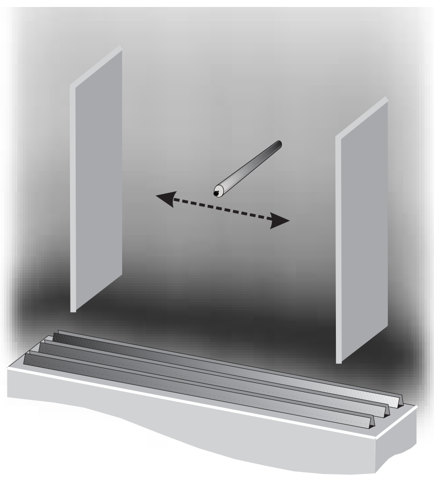

Fig. 1. Arrangement of electrodes in a flame

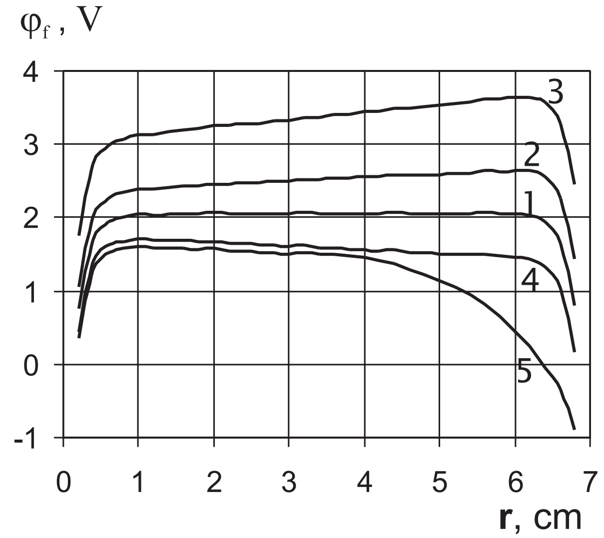


Fig. 2. Spatial distribution of the probe's floating potential between electrodes, $\varphi_{\rm left} = 0$ V: *1* — $\varphi_{\rm right} = 0$ V, $I = 0.01\,\mu$A; *2* — $\varphi_{\rm right} = 1$ V, $I = 0.85\,\mu$A; *3* — $\varphi_{\rm right} = 10$ V, $I = 1.70\,\mu$A; *4* — $\varphi_{\rm right} = -1$ V, $I = -0.62\,\mu$A; *5* — $\varphi_{\rm right} = -10$ V, $I = -0.91\,\mu$A.

**Theoretical Analysis**

Two mechanisms of charge transfer in a plasma in the absence of a magnetic field are regarded: diffusion and drift in an electric field,

$$j_e = b_e\left(kT\nabla n_e - en_e\nabla\varphi\right), \qquad (2)$$

$$j_i = -b_i\left(kT\nabla n_i + en_i\nabla\varphi\right), \qquad (3)$$

where $b_e$ and $b_i$ are, respectively, the electron and ion mobilities.

Taking into account the electron and ion densities given by Eq. (1), Eqs. (2) and (3) yield

$$j_e = b_e[n_e\nabla(\mu_e + e\phi) - en_e\nabla\left(\varphi_{\rm pl} + \phi\right)] =$$

$$= b_e n_e\nabla(\mu_e - e\varphi_{\rm pl}), \qquad (4)$$

$$j_i = -b_i[n_i\nabla(\mu_i - e\phi) + en_i\nabla\left(\varphi_{\rm pl} + \phi\right)] =$$

$$= -b_i n_i\nabla(\mu_i + e\varphi_{\rm pl}). \qquad (5)$$

Since the electrochemical potential or Fermi level of the plasma is $F_{\rm pl} = \mu_e - e\varphi_{\rm pl}$, and the sum of the chemical potentials of components $\mu_e + \mu_i - \mu_a = \psi$, Eqs. (4) and (5) take the form

$$j_e = b_e n_e\nabla F_{\rm pl}, \qquad (6)$$

$$j_i = b_i n_i\nabla F_{\rm pl} - b_i n_i\nabla(\mu_a + \psi), \qquad (7)$$

where $\psi$ is the non-equilibrium parameter. We note that $\psi = -e\varphi_{\rm pl}$ [2].

This yields that the total current

$$j_c = j_e + j_i = (1/e)\sigma\nabla F_{\rm pl} - b_i n_i\nabla\left(\mu_a - e\varphi_{\rm pl}\right), \qquad (8)$$

where $\sigma = e(b_e n_e + b_i n_i)$ is the electric conductivity of the plasma.

It follows from Eq. (8) that the Ohm's law is satisfied for the plasma provided that

$$\nabla\left(\mu_a - e\varphi_{\rm pl}\right) = 0. \qquad (9)$$

When this condition is not satisfied, the Ohm's law ceases to be true, and there is no equilibrium in the plasma. Thus, Eq. (9) is a condition for currents to be small. It follows from Eq. (9) that this condition corresponds to the relation

$$e\nabla\varphi_{\rm pl} = kT\frac{1}{n_a}\nabla n_a.$$

Since $n_i + n_a = N_A$ is constant, we get

$$e\nabla\varphi_{\rm pl} = -kT\frac{1}{n_a}\nabla n_i. \qquad (10)$$

As seen from Fig. 2, $\nabla\varphi_{\rm pl} = $ const for small currents. Therefore, $n_i$ is a linear function, and

$$\nabla n_i = \frac{n_{is} - n_{io}}{L}, \qquad (11)$$

where $L$ =10 cm is the distance between electrodes, $n_{is}$ is the ion density near the right-hand electrode, and $n_{io}$ is the ion density near the left-hand electrode.

The surface ion density is defined by the Saha—Langmuir equation [3]

$$\frac{n_{is}}{n_{as}} = \frac{g_i}{g_a} \exp \frac{W - I}{kT}, \tag{12}$$

where $W$ is the electrode work function and $I$ is the ionization potential of admixture atoms.

The ion density near the grounded left-hand electrode can be approximated by the unperturbed density $n_0$ which is defined by the Saha equation

$$\frac{{n_0}^2}{n_{a0}} = 2\frac{g_i}{g_a}\ \nu_e \exp \frac{-I}{kT} = K_S. \tag{13}$$

Thus, Eqs. (10)—(13) yield that the maximum value of the gradient $\varphi_{\mathrm{pl}}$ near the right-hand electrode is

$$|\nabla\varphi_{\mathrm{pl}}|^{\max} = \frac{kT}{eL}\left[\frac{g_i}{g_a} \exp \frac{W - I}{kT} - \left(\frac{K_S}{N_A}\right)^{1/2}\right], \tag{14}$$

where we took into account that $n_a \sim N_A$ in the combustion plasma at a temperature of 1200 K and the admixture density $N_A \sim 10^{15}$ cm$^{-3}$. For these parameters, the ionization potential $I = 4.3$ eV, and the work function $W = 4.6$ eV, we have

$$\frac{g_i}{g_a} \exp \frac{W - I}{kT} = 9,$$

$$\left(\frac{K_S}{N_A}\right)^{1/2} = 3 \times 10^{-7},$$

$$|\nabla\varphi_{\mathrm{pl}}|^{\max} = 0.09\ \mathrm{V/cm}. \tag{15}$$

If one requires that the gradient be greater than the value given by (15), the existing density of charge carriers cannot provide it. In this case, there occurs the additional ionization of the plasma, and the equilibrium distribution functions are not applicable, what is seen in Fig. 2 (curve *5*).

## Conclusion

It follows from the performed analysis that if the equilibrium distribution functions of electrons and ions are applicable to the plasma, they also remain applicable upon the passage of a current through the plasma if the densities of charge carriers are sufficient. The equilibrium current is restricted by the ion density generated as a result of the ionization by collisions in the plasma and the surface ionization at the interface. If the amount of the ions generated by both processes is sufficient for the passage of a current, the equilibrium is maintained. Otherwise, the additional ionization of the admixture atoms is necessary to provide the passage of a current, and the equilibrium distribution functions are not applicable.

1. *Kittel Ch.* Thermal Physics. — New York: Wiley, 1969.
2. *Vishnyakov V.I., Dragan G.S.* // Ukr. J. Phys. — 2004. — **49**. — P. 132—137.
3. *Vishnyakov V.I., Dragan G.S.* // Ibid. — 2004. — **49**. — P. 229—235.

УМОВА МАЛИЗНИ СТРУМІВ У ПЛАЗМІ ПРОДУКТІВ ЗГОРЯННЯ

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Р е з ю м е

Експериментально досліджено просторовий розподіл плаваючого потенціалу ізольованого зонда між електродами в плазмі продуктів згоряння в умовах протікання струму. Виявлено, що для малих струмів розподіл плазмового потенціалу є лінійною функцією координати. Зі збільшенням струму лінійність порушується. Проведено теоретичний аналіз протікання струму в термічній плазмі. Визначено умови порушення закону Ома. Показано, що рівновага зберігається, якщо носіїв заряду, які утворюються внаслідок ударної іонізації в плазмі та за рахунок обмінних процесів на межі поділу фаз, є у достатній кількості, щоб забезпечити необхідну величину струму. У супротивному випадку відбувається додаткова іонізація атомів плазми і рівноважні функції не застосовні.