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Modulation of Pressure, Density and Temperature in Acoustoplasma Discharge

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Abstract. For the plasma with an acoustic perturbation, the temperature and density changes due to acoustic perturbation were calculated from the experimentally measured acoustic pressure values. Acoustic modulation of temperature, density and pressure is not more than 0.1% of the average values. The vibrational velocity of molecules is hundreds of times less than the root-mean-square velocity, but because of the collective effect of a big quantity of molecules and the selected direction of vibrations, it is the vibrational velocity that determines the creation of acoustic superlattices in the plasma. Thus, in acoustoplasma, acoustic superlattices of particle velocities and momenta are created, rather than pressure and density ones.

Keywords: gas discharge, acoustics, acoustoplasma, modulation of temperature, density and pressure

1. Introduction

Modulation of the discharge current leads to the appearance of acoustic oscillations in the plasma. These oscillations interact with the plasma, as a result the plasma passes into a new acoustoplasma state [1, 2]. In this state, at certain modulation frequencies, acoustic superlattices, formed by standing acoustic waves, appears in the plasma [1, 2]. The parameters of the acoustoplasma can differ significantly from the parameters of the plasma without acoustic perturbation [2-4]. For the first time, a one-dimensional lattice consisting of point particles was used in the calculation of the speed of sound by I. Newton [5]. L. Brillouin [6] introduced the concept of "superlattice" when considering waves in periodic structures, i.e. lattice with a period that can be much longer than the period of the lattice of solids.

Standing acoustic waves create exactly such acoustic superlattices in the medium. The spatial variation of each of the parameters of the medium can be represented in the form of such superlattices. As it is mentioned in [1], these superlattices are formed by the change of density and pressure.

It is well known that acoustic waves in gases and liquids are longitudinal and satisfy the adiabatic conditions [7]. An exception is the surface waves at the interface between two media. The adiabatic condition is satisfied if the energy exchange, between the compression and rarefaction regions, does not occur during the passage of a sound wave in a gas or liquid.

For acoustic oscillations in the gas without discharge the adiabatic condition [8] is $\lambda \cdot k \ll 1$ and hence is valid from the hundredths of *Hz* to the *GHz* frequency range and above, i.e. the length of the sound wave is much greater than the mean free path of the gas particles $\lambda; k = \omega/c$ is the wave vector, ω is the frequency and c is the phase velocity of an acoustic wave.

Due to the Coulomb interaction, the behavior of the acoustoplasma differs in its properties from the behavior of purely acoustic oscillations, which are due only to the elastic forces. For plasma oscillations propagating in a weakly ionized plasma, adiabatic conditions are satisfied even for the case when the length of the sound wave is comparable with the particle mean free path $\lambda \cdot k \leq 1$ and the adiabaticity criterion in a weakly ionized low-temperature plasma can be written [6] as: $\lambda r_d k^2 \ll 1$, where r_d is Debye radius. For ions, the adiabaticity criterion is satisfied up to frequencies less than

10^8-$10^9 Hz$. For the electron gas, the adiabaticity criterion: $v_e \lambda k^2 / \omega \ll 1$ is satisfied up to frequencies less than 10^6-$10^7 Hz$, where v_e is the electron velocity.

One of the main expressions used in acoustics is the dispersion relation. For longitudinal sound waves propagating in a stationary gas, without the plasma, the dispersion relation is given by the expression:

$$\omega^2 = k^2 \left(\gamma \cdot T / M \right), \tag{1}$$

where γ is the adiabatic index; T is the temperature of the gas; M is the mass of an ion or a neutral atom.

If in the plasma the wavelength of ion sound (at the absence of external fields) much more than the Debye radius, the dispersion relation is given by the expression [8]:

$$\omega^2 = k^2 \left(T_e / M \right), \tag{2}$$

where T_e is the temperature of electrons.

The comparison of (1) and (2) shows, that the expressions are similar. However, it should be noted that electrons, having high velocities and mobility, adapt adiabatically to ion displacements and affect their motion and field distribution, so the frequency and velocity of ion sound and the speed of its propagation depend on the parameters of the electronic component of the plasma.

In order to stay in the region of linear acoustics, we assume that the amplitude of the acoustic oscillations is so small, that the deviation of the density $\tilde{\rho} = \rho - \rho_0$ and pressure $\tilde{p} = p - p_0$ from their equilibrium values is also small. The average vibrational velocity of neutral particles and ions is also small.

It is known (see, for example, [9]) the expression for the so-called acoustic Ohm's law:

$$\tilde{\rho} / u = \rho_0 c, \tag{3}$$

where $\rho_0 c$ is called the wave impedance and u is the vibrational velocity.

For acoustic perturbation of density and vibrational velocity:

$$\tilde{\rho} / \rho_0 = u / c \tag{4}$$

$$\tilde{p} / \rho_0 = c^2 \tag{5}$$

Using (3) - (5) and measuring the acoustic pressure $\tilde{p}$ in the experiment, we will further define all the parameters.

2. Experimental

The experimental setup is discussed in detail in [10]. The difference is that inside the discharge tube behind the electrode, outside the discharge, there is a special small-sized (Φ <3 mm) condenser microphone measuring the acoustic pressure. The methods of measuring and calibrating the microphone are described in detail in [11].

On a similar installation [11-13], sound generation by modulation of the discharge current in a plasma was experimentally studied and a table of values of the coefficient was obtained for determining the acoustic pressure in the acoustoplasma discharge, i.e., the dependence of the sound pressure $\tilde{p}$, on the type of gas, the amplitude of the variable component of the discharge current and gas pressure p_0 (Table 1).

In Table 1 and in further discussions, two systems of units are used to denote the pressure. Such a recording system strictly delineates the acoustic pressure ($\tilde{p}$ in Pa) from the gas pressure in the discharge tube (p_0 in torr).

Table 1. Dependence of the generation coefficient K_{sp} (p_0, I~) (specific generated acoustic pressure) on the variable component of the discharge current, the type and pressure of the gas, [Pa / A torr].

P_0 torr	He	N_2	CO_2	$CO_2:N_2$ 1:1	CO_2:He 1:1	N_2:He 1:1
0,1	83	166	166	-	-	-
6	6,5	5,5	22	-	-	-
12	5,5	4,2	14	-	-	-
25	4	3,3	12	23	16	6,7
50	3,7	3	6	-	-	-
100	2,4	2,5	3,6	-	-	-

3. Results and discussions

It should be noted that Table 1 is already compiled for the acoustoplasma mode. We believe that in a purely acoustic regime in a gas (without plasma), we could create exactly the same pressure. We define the values for the variable components $\tilde{p}$, $\tilde{\rho}$ and $\tilde{T}$, where $\tilde{T}$ is the temperature modulation due to acoustic oscillations, i.e. the deviation of the temperature from its equilibrium value T_0.

According to [9], the temperature change in an acoustic wave is given by the expression:

$$\tilde{T} = T_0 \frac{\gamma - 1}{\gamma} \left(\frac{\tilde{p}}{p_0} \right) \tag{6}$$

From Table 1 it follows that with a variable component of the discharge current of the order of 5-10 *mA* and a pressure of the order of 12*torr*, the amplitude of the acoustic pressure will be of the order of 0.8-1.7 *Pa* (i.e. 0.006-0.013*torr*) for carbon dioxide, and for pure nitrogen – 3 times less.

For simplicity, we will assume the acoustic pressure $\tilde{p} = 2\,Pa$ for both CO_2 and N_2; $p_0 = 12torr = 1600Pa$; $c \sim 350\,m/s$ (more precisely, the velocities for different gases and the parameters of the discharge of pressures are given in [11, 13]); $\rho_0 \approx (0.2 - 0.3) \times 10^{-2}\,kg/m^3$ (values of 0.2 for N_2 and 0.3 for CO_2). For gas without a discharge $T_0 \approx 300K$; for acoustoplasma $T_0 \approx 1500K$. The temperature value on the discharge axis is taken from [14].

In this case, direct measurements [11-13] give a value of $\tilde{p}/p_0 \approx 0.001$; from (5) follows that $\tilde{\rho}/\rho_0 \approx (5.3-8)*10^{-4}$. As it follows from (6), the acoustic temperature modulation is $\tilde{T} \sim 0.09K$ (for gas) and $\left(\tilde{T}/T_0\right) \approx 0.0003$.

For acoustoplasma mode the values $\tilde{\rho}/\rho_0 \approx (5.3-8)*10^{-4}$ and $\left(\tilde{T}/T_0\right) \approx 0.0003$ are also the same, but $\tilde{T} \sim 0.45K$.

In [1], from the experimental data, the intensity of acoustic oscillations in the discharge tube was estimated at 80-90*dB*. Acoustic pressure $\tilde{p}$ expressed by the level of intensity *J* in logarithmic units is given in [8] $J = 20\lg\frac{\tilde{p}}{p_0}$, where $p_0 = 2\times10^{-5}\,Pa$ is the zero level of the sound pressure. Then, an intensity of 80 *dB* corresponds to an acoustic pressure of 0.2*Pa*. For the acoustic intensity levels given in [1], the modulation of pressure, density, and temperature will be 10 times smaller than those obtained in our experiments.

From the kinetic theory of gases, the root-mean-square (rms) velocity of the molecules for the conditions given above $v_{msq} = \sqrt{3\hat{k}T/M}$, where $\hat{k}$ is the Boltzmann constant; *M* is the mass of the molecule, for example (for $M(N_2) = 4.7\times10^{-26}\,kg; M(CO_2) = 7.3\times10^{-26}\,kg$), $v_{msq} \sim 594\,m/s$, which is higher than the sound velocity in nitrogen plasma $(\sim 350\,m/s)$ and carbon dioxide $(\sim 450\,m/s)$ [11, 13].

From (4), the acoustic vibration velocity of the molecule: $u(CO_2) = 3.7\,m/s; u(N_2) = 6.1\,m/s$.

Thus, for the above-described discharge parameters, the ratio of the vibrational velocity to the speed of sound in the medium; $\mu = u/c; \mu_{CO_2} = 0.008; \mu_{N_2} = 0.017$. Small Mach numbers confirm that we are in the field of linear acoustics. We note that the ratio of the vibrational velocity to the rms velocity of the particles is of the order of 0.01, which is much larger than the acoustic modulation of pressure and temperature in the acoustoplasma discharge.

If we take into account that the vibrational velocity for a longitudinal acoustic wave has a clearly expressed direction, and the rms velocity is distributed over all possible directions, and the fact that the oscillatory process is collective, in which a big quantity of molecules participate simultaneously, it becomes clear that at standing wave in the acoustoplasma it's the acoustic lattice of vibrational velocities and momenta that plays an important role, and not the pressure lattice, as was assumed in [1]. It should be noted that in the works of other authors devoted to acoustic waves in plasma, the main attention is paid precisely to the influence of acoustic pressure [15-18].

4. Conclusion

Thus, in a low-temperature gas-discharge acoustoplasma obtained by the discharge current modulation due to acoustics, changes in pressure, density, and temperature not more than 0.1% of the mean values and standing waves of pressure and density cannot directly create acoustic superlattices in the plasma. The vibrational velocity of molecules is hundreds of times less than the root-mean-square velocity, but because of the collective effect and the selected direction of vibrations of a big quantity of molecules, it is the vibrational velocity that determines the creation of acoustoplasma acoustic lattices. Thus, in an acoustoplasma, acoustic superlattices of particle velocities and momenta are created, rather than pressure gratings.

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