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WAVE PHENOMENA IN THE PLASMA OF A MOLECULAR GAS DISCHARGE[1])

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A simple hydrodynamic model of wave phenomena observed in the plasma of the low pressure glow discharge in molecular gases is given. The dispersion relation of the wave modes has revealed two branches of the acoustic wave and the ionization-thermal-diffusion wave.

ВОЛНОВЫЕ ЭФФЕКТЫ В ПЛАЗМЕННОМ РАЗРЯДЕ МОЛЕКУЛЯРНОГО ГАЗА

В работе описана простая гидродинамическая модель волнового эффекта, который наблюдался в плазме тлеющего разряда при низком давлении в молекулярных газах. В дисперсионном соотношении этого типа волн обнаружены две ветви волн: акустической волны и волны ионизационно-термодиффузные.

I. INTRODUCTION

The low pressure glow discharge in molecular gases (especially in laser mixtures) is characterized by a high longitudinal electric field and an intensive release of heat compared to a discharge in atomic gases. The electric field accelerates the electrons, whose energy is fed predominantly in the vibrational degrees of freedom. The vibrational energy either escapes to the tube walls (via the vibrational — vibrational transitions), but in molecular lasers the most important process is usually the vibrational — translational relaxation, by which the neutral gas is strongly heated and, consequently, a strong electric field is needed to maintain the energy balance. The heating and the electric field may profoundly influence the wave processes commonly observed in the plasma.

The heating of the neutral gas gives rise to the acoustic wave. The amplification of the wave can be explained in terms of the enhanced collisional rate and thus the

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enhanced heating if the neutral gas density is increased locally, leading to a further increase in the pressure.

The typical wave phenomena in the low pressure glow discharge in molecular gases (e.g. N_2, H_2, CO_2, CO, etc.) is the forward wave (both v_f and v_{gr} anode directed). This type of wave originates due to the ion motion in the perturbed electric field, where the essential part of the perturbation is the electron thermal diffusion. As the ion drift in the quasi-neutral plasma is proportional to the square of the longitudinal field intensity, this type of wave appears only at stronger electric fields, which occur in molecular gas discharges. The theoretical description was performed on the basis of usual hydrodynamic conservation equations for both the electrons and the neutral gas, where the vibrational energy balance was accounted for separately. The linearized system was solved on a computer, yielding the dispersion of both wave modes.

II. THE WAVE DISPERSION

To describe a molecular gas plasma the simplest possible model is considered. Thus it is assumed that the plasma is one-dimensional with no free atoms present (the dissociation degree is zero) and that there are positive ions only. The translational and vibrational energy balance of the neutral molecules are considered separately, as the vibrational — translational relaxation time is fairly long. We get the following set of equations for the neutral component:

$$\partial_t n_g + \partial_z(n_g v_{gz}) = 0$$

$$m_g \partial_t v_{gz} = -(1/n_g)\partial_z(n_g T_g)$$

$$c_p \partial_t T_g + T_g \partial_z v_{gz} = (1/n_g)\partial_z(\varkappa_g \partial_z T_g) + (T_v - T_g)/\tau_{vT} - T_g/\tau_T$$

$$\partial_t(n_g c_v T_v) + \partial_z(n_g c_v T_v v_{gz}) = \partial_z(\varkappa_v \partial_z T_v) + n_g(nH_v - (T_v - T_g)/\tau_{vT} - T_v/\tau_{vw}),$$

where n_g, T_g, m_g, v_{gz}, c_p, $\varkappa_g$ ... are concentration, temperature (volt equivalent), molecular mass, acoustic velocity, specific heat per molecule and thermal conductivity of neutral particles, respectively; T_v, $\varkappa_v$, c_v, ... are vibrational temperature, vibrational conductivity and specific vibrational heat per molecule; τ_{vT} is the vibrational-translational time, τ_T is heat conduction time (to the wall), τ_{vw} is vibrational energy wall loss time and $\partial_t = \partial/\partial t$, $\partial_z = \partial/\partial_z$. This set has to be supplemented by the balance equations of the electron plasma component. The usual set of the local electron hydrodynamics includes the electron continuity equation, the inertialess equation of motion, the energy balance equation and the ion continuity equation:

$$\partial_z(n v_{ez}) = 0$$

$$v_{ez} = -(b_{e0}/n_g)\,(E_z + \alpha(U_e/n)\partial_z n + \gamma \partial_z U_e)$$

$$\partial_z(nU_e\zeta v_{ez} - (b_{e0}/n_g)\,U_e(\xi U_e \partial_z n + n\delta\partial_z U_e)) = -n(v_{ez}E_z + n_g H)$$

$$\partial_t n + \partial_z(n(v_{gz} + (b_{i0}/n_g)\,E_z)) = n(n_g S - 1/\tau_{w0} n_g),$$

where $n(=n_i=n_e)$ is electron (ion) density; v_{ez}, U_e, are drift velocity and temperature (volt equivalent) of electrons, E_z is the longitudinal electric field intensity; b_{e0}, b_{i0} are electron and ion mobilities; $H(U_e, T_v)$ is the average electron energy loss function; $H_v(U_e, T_v)$ is the average vibrational electron energy loss function; α the Einstein coefficient, (diffusion to mobility ratio), γ, ζ, ξ, δ coefficient of the thermal diffusion, of the heat convection, of the energy transport along the density gradient, of the heat conduction of electrons; τ_{w0} is the life time of the charged particles (wall recombination assumed), $S(U_e, T_v)$ is the coefficient of direct ionization by electrons. If linearized, this system of equations yields a rather complex dispersion relation for five modes in the plasma. Two of them are not interesting. These are both the translational and the vibrational energy propagation modes (heat wave), which are slow and heavily damped. Of the three remaining waves two pertain to the sound propagation and the last represents the ionization-thermal-diffusion wave. The computer solution of the dispersion relation shown in Fig. 1 renders a sound dispersion dominated by translational degrees of freedom only. The vibrational-translational relaxation is clearly at low pressure not fast enough to ensure the energy equipartition between the translational and vibrational degrees of freedom. This result is essentially in agreement with [1].

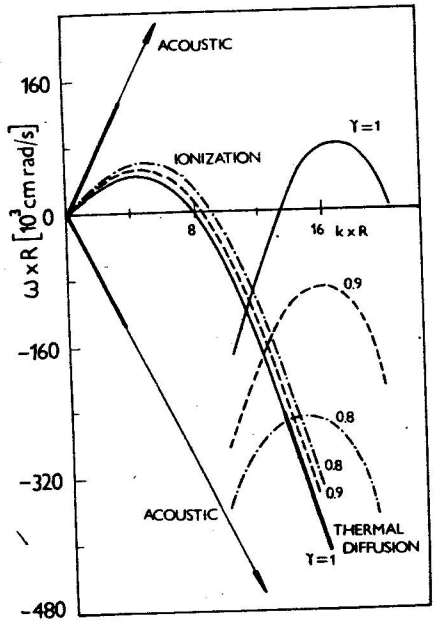

Fig. 1. Dispersion curve (k-dependence of the wave frequency ω) of the acoustic mode and of the ionization-thermal-diffusion mode (thicker lines); R ... tube radius. The amplification curves of the latter mode are given (weak lines) for three values of the coefficient of the electron thermal diffusion $\gamma = 1$, 0.9 and 0.8. At $\gamma = 1$ the lower part of the dispersion curve (i.e. the forward wave) is amplified (the amplification curve reaches positive values). The positive amplification of this part and that of the sound wave are marked out by the thickest line. The calculation was performed for nitrogen; necessary kinetic coefficients were computed on the basis of [5], T_g being 450 K. The sound velocity $v_a = \pm\sqrt{\frac{7}{5}\frac{T_g}{m_{N_2}}} \sim 390$ m/s.

More interesting is the ionization-thermal-diffusion mode. Its long-wave part (small wavenumbers k) resembles the usual dispersion known for the case of atomic gases (ionization wave [2]) but its short-wavelength part intersects the k-axis (standing striations) continuing below the axis as a (almost) straight line (forward, anode directed wave). A more detailed analysis [3] reveals that this wave with the negative phase velocity originates due to the ion drift in the perturbed electric field. The perturbation of the field is displaced from the point of the original ion disturbance (or phase-shifted) by the electron thermal diffusion effect. Without the electron thermal diffusion the ion motion in the perturbed field would lead just to a decay of the original ion perturbation by the axial ambipolar diffusion. The thermal diffusion creates an additional phase-shift between the perturbed field and the ion density perturbation which enables the wave (which normally would be cathode directed if only the ionization effects are taken into account) to reverse the phase velocity and become a forward, anode directed wave, typical of molecular gases. A critical dependence of the wave amplification on the value of the thermal diffusion coefficient is demonstrated in Fig. 1.

III. CONCLUSION AND DISCUSSION

A very simple model provides a correct description of the wave observed in the molecular gas plasma. It is interesting that the difference between the atomic and molecular gas plasma is essentially but a quantitative one given by the high value of the longitudinal electric field intensity characteristic of a molecular gas discharge. The strong electric field enhances the ion drift, which may lead to the phase velocity reversal of the ionization wave. At the same time, however, in the presence of a strong longitudinal field doubt is cast on the validity of the strictly local hydrodynamics equations used in our model. Similarly as in [4] it is possible that all the transport coefficients (including the thermal diffusion coefficient) will acquire a tensorial character due to the non-locality effects, which would introduce qualitative changes in the theory. In fact, the curves in Fig. 1 were calculated with the longitudinal diffusion coefficient taken from [4], and it is hoped that, in particular, the thermal diffusion coefficient will also be changed in the direction favourable for the wave amplification.

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