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Deionisation of the afterglow plasma due to accelerated ambipolar diffusion

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***Abstract*. The accelerated ambipolar particle diffusion is simulated in the afterglow of discharges in He – Cu and Ne – Cu mixtures. The calculations showed that a heating field $E \approx 0.3 - 1.3$ V cm^{-1} imposed on the afterglow discharge at a buffer gas pressure of 8 – 10 Torr and a tube diameter of 4 – 10 mm reduced the electron density by a factor of $10^2 - 10^4$ for ~ 100 µs. The effect was shown to be most pronounced in helium. According to the calculations, the application of accelerated ambipolar diffusion during the interpulse period will increase the pulse repetition rate of copper vapour lasers with low-diameter tubes (4 – 6 mm) and low buffer-gas pressures (6 – 8 Torr) by 20 % – 50 %. The production of excessive prepulse density of the metastable states of copper can be prevented by interrupting the plasma heating 3 – 6 µs before the onset of the next excitation pulse.**

Keywords: *ambipolar diffusion, plasma deionisation, copper vapour laser*.

1. Introduction

The acceleration of ambipolar diffusion (AAD) of ions upon a moderate heating of the afterglow plasma of a repetitively pulsed discharge is caused by the dependence of the ambipolar diffusion coefficient D_a on the electron temperature T_e described by the expression

$$D_a = D\left(1 + \frac{T_e}{T}\right), \tag{1}$$

where T is the gas temperature and D is the ion diffusion coefficient. It follows from (1) that the rate of diffusion escape of charged particles to the tube walls increases with T_e.

The first experimental observation of AAD was reported in Ref. [1]. The experiments of Ref. [1] involved the heating of the electron gas in the afterglow of He – Cd and He – Zn ion laser discharges. The heating was produced by short ($\sim 0.5 - 1$ µs) or long (~ 6 µs) low-amplitude current pulses, and the effect of the current on cadmium and zinc ion level populations was studied. It was found, in particular, that the intensity of Cd II and Zn II ion lines arising from charge exchange with He^+ ions and of recombination radiation of He I, Zn I, and Cd I lines did not recover after a long pulse, but vanished almost completely (Fig. 1), unlike the case when the heating was produced by short pulses. The latter effect was explained in Ref. [1] by the fact that, due to the AAD according to (1), the charged particles during the long pulse manage to escape to the tube walls almost completely and recombine there.

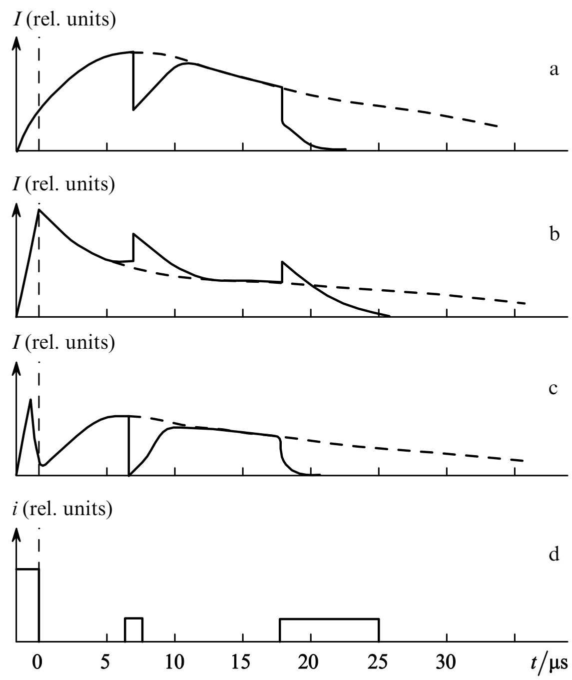

Figure 1. Experimental time dependences of afterglow line intensities for Cd II, $\lambda = 537.8$ nm and Zn II, $\lambda = 492.4$ nm (a), Zn II, $\lambda = 775.8$ nm (b) and He I, Cd I, and Zn I (c) upon applying heating current pulses for $d = 8$ mm, $p_{He} = 2$ Torr, and $p_{Cd}(p_{Zn}) = 5 \times 10^{-2}$ Torr [1] (the heating is absent where dashed lines show), and also the positions of current pulses in time (d).

Since then, this effect has not been studied in more detail. The interest in this effect was rekindled in connection with the search for the ways to raise the pulse repetition rate of metal vapour lasers, including the most efficient of them – a copper vapour laser (see papers [3, 9 – 11] and references therein).

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In this paper, we used the mathematical simulation to verify the explanation for the line afterglow suppression by the long heating pulses proposed in Ref. [1] and to explore the prospects for applying AAD for deionising the plasmas of repetitively pulsed gas discharges.

2. Description of the model

We constructed a simple afterglow model for discharges in He – Cu and Ne – Cu mixtures to describe AAD. In this model, the kinetic equations describing the temporal evolution of plasma characteristics in the afterglow include the equations for the concentrations of buffer-gas and copper ions and the equation for the electron temperature:

$$\frac{dN_{b^+}}{dt} = \alpha_b N_b N_e - \beta N_{b^+} N_e^2 - \gamma^a_{b^+} N_{b^+},$$

$$\frac{dN_{Cu^+}}{dt} = \alpha_{Cu} N_{Cu} N_e - \beta N_{Cu^+} N_e^2 - \gamma^a_{Cu^+} N_{Cu^+},$$

$$\frac{dT_e}{dt} = -\left[\left(\frac{2m_e}{M_b}\right)\nu_{eb} + \left(\frac{2m_e}{M_{b^+}}\right)\nu_{eb^+} + \left(\frac{2m_e}{M_{Cu^+}}\right)\nu_{eCu^+}\right] \quad (2)$$

$$\times (T_e - T) + \frac{2E^2\sigma}{3eN_e} - \frac{2}{3}(I_b N_b \alpha_b + I_{Cu} N_{Cu} \alpha_{Cu})$$

$$+ \frac{2}{3} N_e \beta (I_b N_{b^+} + I_{Cu} N_{Cu^+}) - \gamma^a_{Cu^+} T_e - \left(\frac{dN_{b^+}}{dt} + \frac{dN_{Cu^+}}{dt}\right)\frac{T_e}{N_e}.$$

Here, α is the ionisation rate constant; β is the three-body electron – ion recombination rate constant; $\gamma^a = 6D_a/R^2$ is the ambipolar ion diffusion frequency; ν is the frequency of elastic collisions of electrons with atoms and ions of heavy particles (see Table 1); I is the ionisation potential; σ is the plasma conductivity; m_e and M are the masses of electrons and heavy particles, respectively; and the subscript b corresponds to buffer gas parameters (helium or neon). It is assumed in the model that $N_b = \text{const}$ and $N_e = N_{b^+} + N_{Cu^+}$. The concentration of copper atoms in the ground state is $N_{Cu} = N_{Cu}^{(0)} - N_{Cu^+}$, where $N_{Cu}^{(0)}$ is the total concentration of copper vapour. The equation for T_e includes a term which takes into account the heating of the electron gas in the electric field E. The population of the metastable level of copper atoms was calculated assuming that it is related to the ground-state population by the Boltzmann distribution [3, 11].

The system of equations (2) was numerically solved. The conditions typical for a copper vapour laser were commonly used as the initial afterglow conditions: $N_{Cu^+} = 2 \times 10^{14}$ cm^{-3}, $N_{b^+} = 10^{14}$ cm^{-3}, $T_e = 0.8$ eV, $N_{Cu}^{(0)} = 10^{15}$ cm^{-3} [9].

3. Results of numerical simulation

First, we made an attempt to simulate numerically the effects observed in Ref. [1]. We performed calculations for the conditions close to those of Ref. [1]: $T = 500$ K, $p_{He} = 2$ Torr, $d = 8$ mm. The obtained results are presented in Fig. 2 and illustrate the essence of the effect under study. One can see that the imposition of a short (1 μs) field pulse on the afterglow discharge causes an ordinary dip in the recombination pumping rate due to plasma heating, because $\beta \sim T_e^{-4.5}$. However, the electron concentration does not manage to change significantly in a short period of time, and therefore the recombination pumping rate is almost completely restored after the short pulse (Fig. 2a). Upon imposition of a long (10 μs) field pulse, the recombination pumping rate drastically decreases not only during the pulse, but also after its termination, remaining low. This takes place because the concentration

Table 1.

Process	Rates of processes*	References**
Three-body recombination of singly charged ions	$\beta = 3.206 \times 10^{-27} T_e^{-4.5}$	[2]
Single ionisation of atoms		
helium	$\alpha_{He} = 1.623 \times 10^{-9} T_e^{0.81231} \exp(-24.56/T_e)$	[2]
neon	$\alpha_{Ne} = 4.91 \times 10^{-11} T_e^{0.5} \exp(-16.6/T_e)$	[3]
copper	$\alpha_{Cu} = 5.13 \times 10^{-8} T_e^{0.5} \exp(-3.8/T_e)$	[3]
Diffusion of		
helium ions in helium	$D_{He^+} = 8.4214 \times 10^4 T^{1.62623}/p_{He}$	[4]
neon ions in neon	$D_{Ne^+} = 4.0413 \times 10^4 T^{1.65329}/p_{Ne}$	[4]
copper ions in helium	$D_{Cu^+} = 2.73193 \times 10^5 T^{1.7622}/p_{He}$	[5]
copper ions in neon	$D_{Cu^+} = 6.0874 \times 10^4 T^{1.5}/p_{Ne}$	[6]
Elastic electron collisions with		
helium atoms	$\nu_{e\,He} = 3.55 \times 10^{-8} N_{He}\sqrt{T_e}$	[2]
neon atoms	$\nu_{e\,Ne} = 10^{-8} N_{Ne}\sqrt{T_e}$	[7]
helium ions	$\nu_{e\,He^+} = 8.6 \times 10^{-6} N_{He^+} T_e^{-1.5}$	[2]
neon ions	$\nu_{e\,Ne^+} = 2.89 \times 10^{-6} N_{Ne^+} T_e^{-1.5}[23.4 - 0.5\ln(N_e/T_e^3)]$	[8]
copper ions	$\nu_{e\,Cu^+} = 2.89 \times 10^{-6} N_{Cu^+} T_e^{-1.5}[23.4 - 0.5\ln(N_e/T_e^3)]$	[8]

*Here, β is in cm^6 s^{-1}, α is in cm^3 s^{-1}, D is in cm^2 s^{-1}, ν is in s^{-1}, N is in cm^{-3}, p is in Torr, and T_e and T are in eV.

**We give references to the papers whose data or calculation techniques were used to derive the analytical formulas conveniently employed to evaluate the rate constants presented in the Table.

of charged particles (He^+, Cu^+, and electrons) in the discharge drastically decreases due to the AAD during the long pulse (Fig. 2b), resulting in the disappearance of emission lines related to the charge exchange, for which the pumping rate $W_{ce} \sim N_{b^+}$, and to recombination, because $W_{rec} \sim N_e^3$ (Fig. 2b). This effect was experimentally observed in Ref. [1] for the charge-exchange lines of Zn II and Cd II (Figs 1a and 1b) and the recombination lines of He I, Cd I, and Zn I (Fig. 1c).

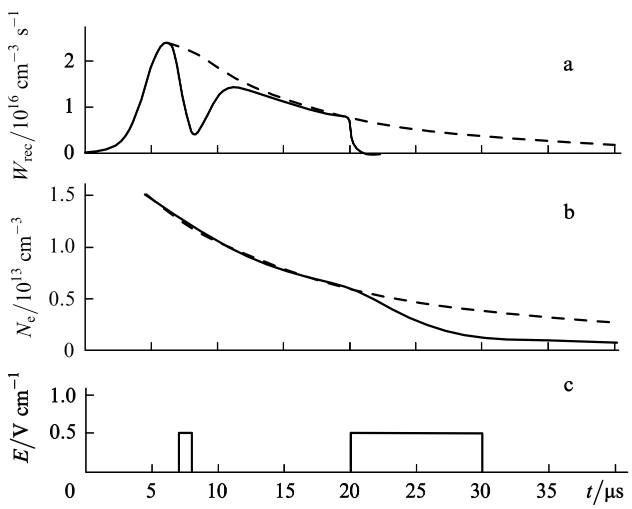

Figure 2. Time dependence of the recombination pumping rate W_{rec} of the levels of neutral atoms (a) and the electron concentration N_e (b) upon applying short and long heating pulses of the field E (c); the heating is absent where dashed lines show.

To analyse the prospects of using the AAD to deionise the afterglow plasma, we performed a series of numerical experiments by varying the mixture pressure, the diameter of the gas-discharge tube, and the intensity of the heating electric field in broad ranges. The duration of the heating pulse was rather large, approximately equal to the typical pulse separation ($\sim$ 100 μs). The gas temperature T at the walls was assumed to be 1500 °C. The average gas temperature inside the tube was assumed, as in Ref. [3], to be 1.5 times higher: $T_{av} = 2387\,°C = 0.229$ eV; this value was used in the calculations. The results of some calculations are presented in Fig. 3, which shows the dependences of the residual electron concentration N_{e0} on the heating field E for He – Cu and Ne – Cu mixtures at the instant of the afterglow $t = 100$ μs (say, before the onset of the next pulse). One can see that for certain values of p and d, it is possible to select the heating field at which the electron concentration will decrease by 3 – 4 orders of magnitude by the onset of the next pulse.

The AAD can also be used to increase the pulse repetition rate in metal vapour lasers. This is particularly significant for copper vapour lasers: because it was pointed out in several papers that in many cases it is the high prepulse electron concentration that prevents the production of inversion in this laser at high repetition rates (see papers [3, 9, 10] and references therein). By using the expression

$$f_{max} = 300/d, \qquad (3)$$

which was proposed in Ref. [10] for estimating the maximum pulse repetition rate (in kilohertz) of a copper vapour laser, where the tube diameter d is in milimeters, we can find the critical electron density $N_{e\,cr}$, i.e., the electron density at the instant of the afterglow $t = 1/f_{max}$. Knowing $N_{e\,cr}$, we can estimate the factor by which the AAD upon heating will reduce the time period after the beginning of the afterglow required to decrease N_e to $N_{e\,cr}$.

However, one should keep in mind that heating the plasma increases the population of the metastable states of copper atoms, which are the lower laser levels. Therefore, we must terminate the heating pulse on time to permit the

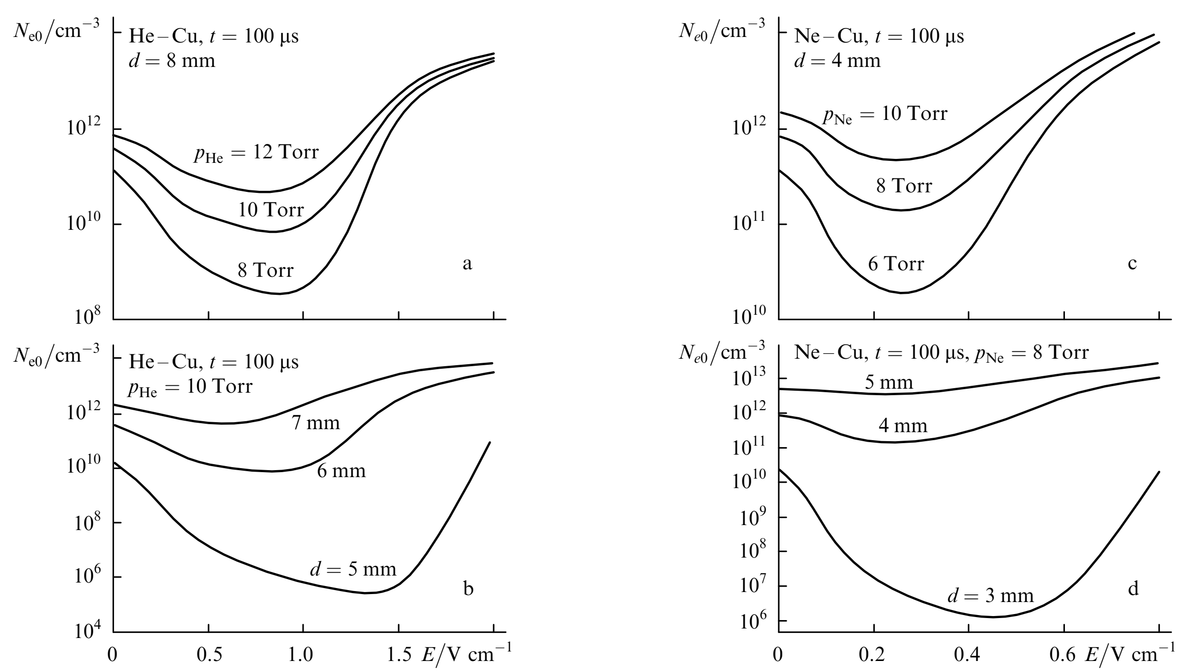

Figure 3. Dependences of the electron concentration on the heating field in He – Cu (a, b) and Ne – Cu (c, d) mixtures for different d, p_{He}, and p_{Ne}.

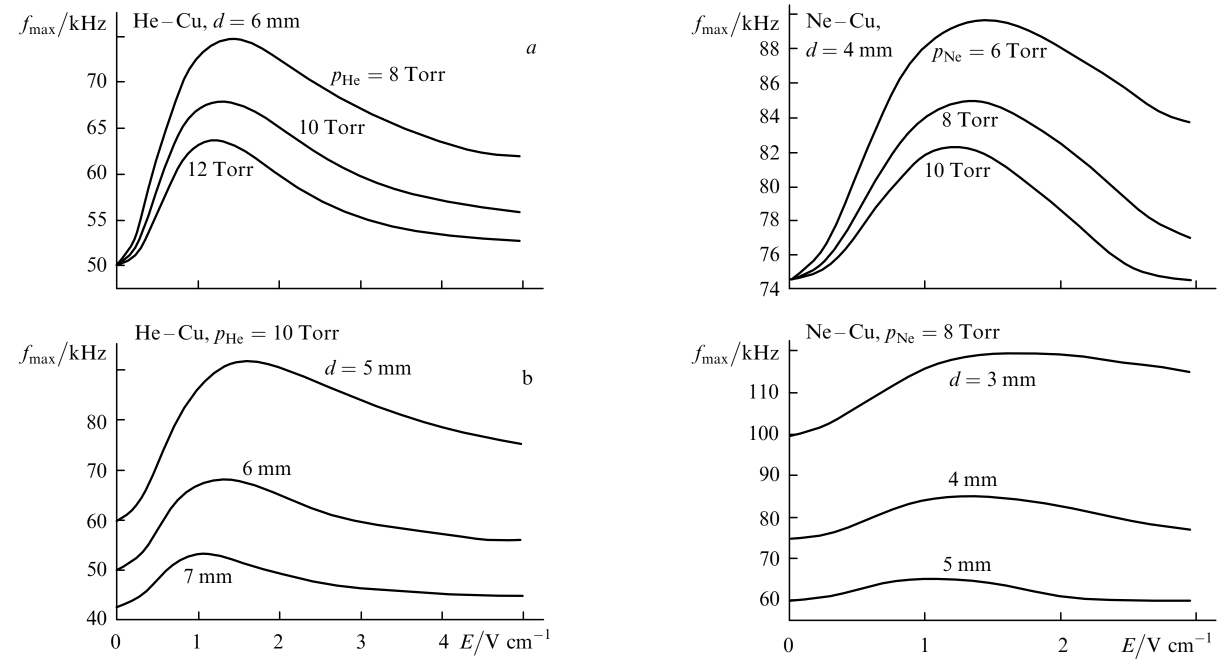

Figure 4. Dependences of the maximum pulse repetition rate on the heating field in He – Cu (a, b) and Ne – Cu (c, d) mixtures for different d, p_{He}, and p_{Ne}.

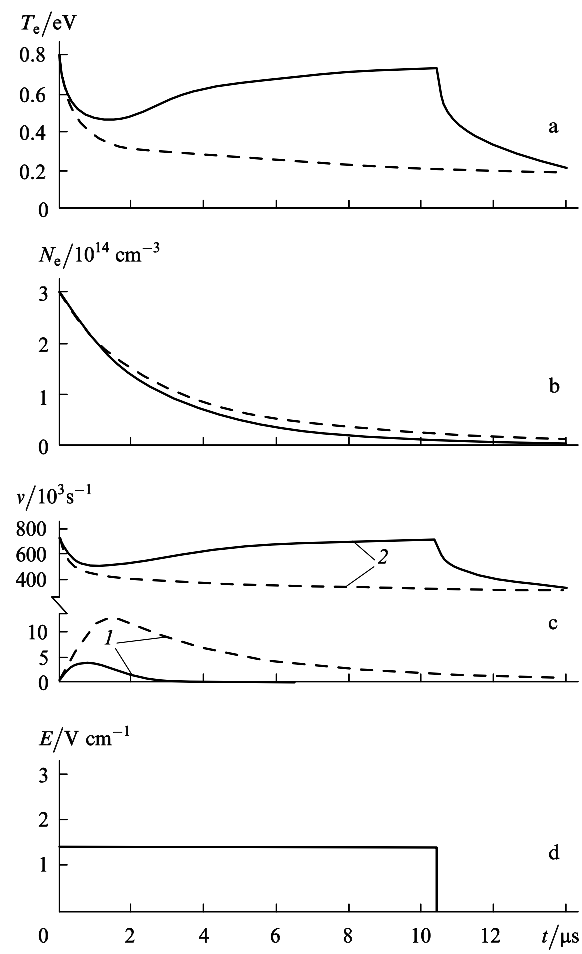

Figure 5. Time evolution of the electron temperature (a), the electron concentration (b), and the recombination (1) and ambipolar diffusion (2) frequencies (c) upon applying the heating field pulse (d) (solid lines) and without the field (dashed lines) in the He – Cu mixture for $d = 6$ mm and $p_{He} = 8$ Torr.

electron temperature (and hence the metastable levels of copper atoms related to the ground state by the Boltzmann distribution) to relax to the level realised without heating. The results of calculations are presented in Fig. 4 in the form of the dependences of f_{max} on the heating field E for He – Cu (Figs 4a and 4b) and Ne – Cu (Figs 4c and 4d) mixtures. In these calculations, the heating was terminated several microseconds (3 – 6 μs) before the onset of the next excitation pulse. The instant of the field switching off was selected to provide the fulfilment of the above condition that the electron temperature should return to its value in the absence of heating. One can see from Fig. 4 that with thin tubes and for low buffer gas pressures (these conditions are closest to the optimal ones for a copper laser with a helium buffer gas [10]) the expected increase in the limiting pulse repetition rate can be 20 % – 50 %.

The results of calculations showed (see Fig. 4) that the deionisation is more pronounced in the He – Cu mixture than in the Ne – Cu mixture, because the diffusion coefficient of copper ions in helium is significantly higher than in neon.

Figs 5 and 6 show the time dependences of the electron temperature, the electron concentration, and the recombination and ambipolar diffusion frequencies in the afterglow for He – Cu and Ne – Cu mixtures in two cases: when the heating is absent (dashed lines) and when the heating pulse (Figs 5d and 6d) acts for a certain period of time and then is switched off to allow the electron temperature to drop to the temperature corresponding to the first case (Figs 5a and 6a) (solid lines). One can see from Figs 5c and 6c that the volume recombination mechanism of plasma deionisation is of secondary importance compared to ambipolar diffusion under the conditions involved, and therefore the suppression of this mechanism upon plasma heating does not exert a significant effect on the plasma deionisation rate.

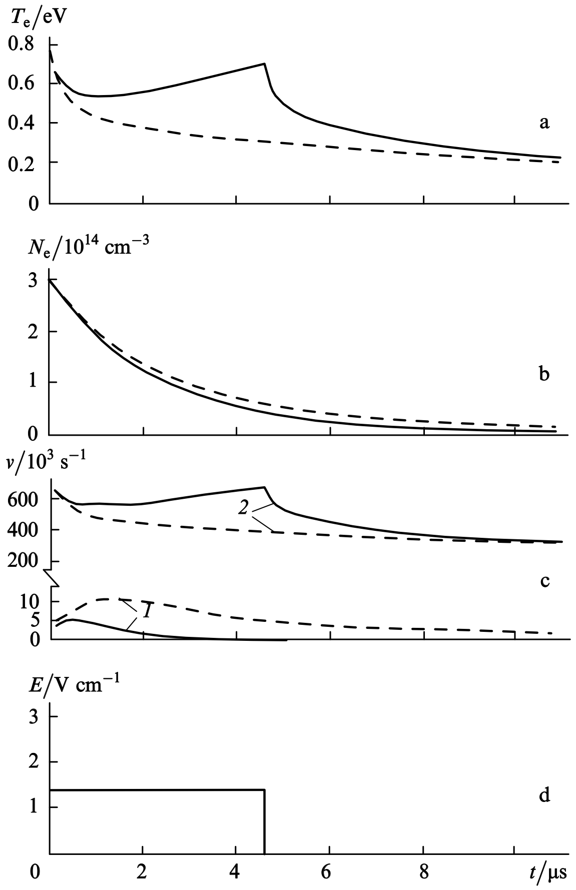

Figure 6. The same as in Fig. 5 for the Ne – Cu mixture for $d = 4$ mm and $p_{Ne} = 6$ Torr.

4. Conclusions

Our numerical simulation of plasma deionisation in the afterglow of a repetitively pulsed discharge due to accelerated ambipolar diffusion upon plasma heating by an electric field in Ne – Cu and He – Cu mixtures confirmed the interpretation [1] of the line afterglow suppression after a long heating pulse as a consequence of AAD. The obtained results show that the prepulse electron concentration can be decreased by 2 – 4 orders of magnitude due to AAD for a pulse separation of ~ 100 μs at relatively low pressures and small tube diameters. The calculations also give grounds to hope for a 20 % – 50 % increase in the limiting pulse repetition rate in small copper vapour lasers. Moreover, the accelerated plasma deionisation caused by AAD may be useful in gas-discharge switches with controllable triggering.

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