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Optical radiation of high-pressure xenon discharge plasma: spectral, integral and energy characteristics

© N.A. Timofeev[1], V.S. Sukhomlinov[1], G. Zissis[2], I.Yu. Mukharaeva[3], V.S. Borodina[1], Yu.E. Skoblo[1]

[1] St. Petersburg State University,
199034 St. Petersburg, Russia
[2] Université de Toulouse, LAPLACE UMR 5213 CNRS-INPT-UT3,
31062 Toulouse cedex 9, France
[3] St. Petersburg Mining University,
199106 St. Petersburg, Russia
e-mail: niktimof@yandex.ru

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A short-arc xenon discharge of high (ultrahigh) pressure with a thoriated tungsten cathode, which is the reason for the presence of thorium atoms in the discharge gap, is investigated. A one dimensional problem is considered; a discharge between two infinite planes. Based on the previously developed model, the volume-integral optical radiation of plasma is calculated, to which both processes associated with xenon atoms and ions and those associated with thorium atoms and ions contribute. Radiation distributions along the discharge axis, including spectral distributions, are obtained over a wide range of discharge conditions, as well as the efficiency of optical radiation generation in different spectral ranges. It is shown that the presence of thorium atoms in the plasma strongly affects the optical characteristics of the plasma, including the distribution of thorium and xenon radiation along the discharge axis. At the same time, its total value and distribution along the discharge axis varies relatively little, which is largely due to the geometry of the problem and the high efficiency of converting electrical energy into optical radiation of the high-pressure xenon arc discharge in question.

Keywords: short-arc xenon discharge, high pressure, thorium, integral optics characteristics, efficiency of radiation.

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Introduction

A high-pressure short-arc xenon discharge, which is widely used as a source of powerful optical radiation in a wide spectral range from UV to IR [5,6], has been studied in [1–4]. This discharge is characterized by a high efficiency of conversion of electrical energy into optical radiation, reaching $(85-88)\%$ at high xenon pressures $\geq 10\,\mathrm{atm}$ [7]. The authors of experimental and theoretical studies of plasma in [1–4] are the first to report on the emission of thorium atoms into the discharge plasma and their influence on the properties of the discharge [1], construct a model of plasma in planar (one-dimensional) [2] and real-world geometries [3], and examine the influence of the electrode shape on the optical characteristics of plasma [4].

The results of [1–4] show that the emission of thorium atoms into the discharge plasma fundamentally changes its characteristics. Thorium atoms have about half the ionization energy ($\sim 6\,\mathrm{eV}$) of xenon atoms ($\sim 12\,\mathrm{eV}$), so their presence in the near-cathode region strongly affects the ionization processes and ion composition. As a result, the plasma temperature near the cathode decreases markedly and thorium ions dominate over xenon ions (at the anode the picture is reversed). Naturally, this should strongly influence the processes of optical radiation generation. It is known that in high-pressure arc discharges in rare gases, recombination-bremsstrahlung processes are the main mechanism of radiation generation [7]. This can be supplemented by the emission of spectral lines of rare gas atoms, which for xenon lie mainly in the IR region, $\sim(800-1100)\,\mathrm{nm}$ [5,6]. The recombination-bremsstrahlung emission of xenon and thorium produces a continuous emission spectrum in the visible region as close as possible to that of the Sun, which ensures the exclusive use of xenon discharge when the best color rendering is required. However, without thorium, a high-pressure xenon discharge could hardly have optical characteristics close to the solar spectrum: as was shown in [1–4], thorium atoms reduce the plasma temperature from $\sim 10000\,\mathrm{K}$, which is characteristic of a discharge in pure xenon [8], to $\sim 6000\,\mathrm{K}$ (solar surface temperature). It can also be added that IR radiation from the xenon discharge under study is extremely important, as it is widely used in night vision searchlight technology and in technological processes involved in thermal treatment of materials.

Such characteristics as the total emission in a particular region of the spectrum, the efficiency of radiation generation, and the ability to influence the optical characteristics of the discharge are important for practical applications. The influence of thorium emission in the studied plasma on its optical properties is obvious, but has remained virtually unexamined; therefore, the purpose of this work is to study the role of an easily ionizable additive (thorium atoms)

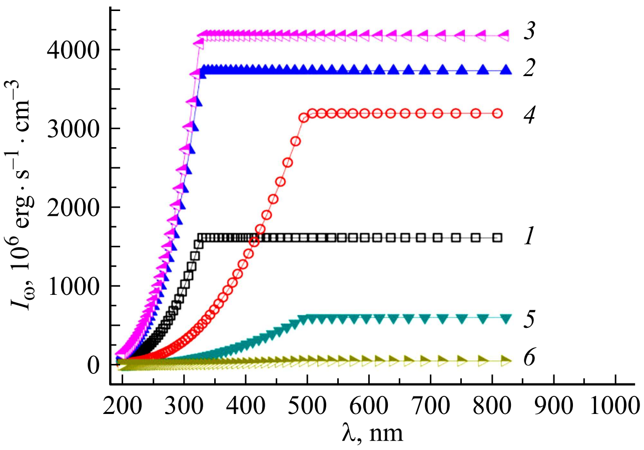

Figure 1. Continuum emission spectrum of I_ω^{Xe} (*1–3*) and I_ω^{Th} (*4–6*) at three points (near the cathode, in the middle of the discharge, and at the anode) with coordinates of 0.05 (*1, 4*), 0.15 (*2,5*), and 0.25 cm (*3, 6*) on the discharge axis.

on spectroscopic, integral optical, and energy (radiation generation efficiency) characteristics of plasma of a short-arc high-pressure xenon discharge. As in [2], the problem is solved for the case when the discharge is between two planes with their linear dimensions being much larger than the distance between them. In this case, the problem can be considered one-dimensional, which significantly simplifies the calculations without losing the possibility of making general conclusions about the influence of thorium atoms on the processes and characteristics of the plasma under study.

Calculation results and discussion

A discharge between two planes whose linear dimensions are much larger than the distance between them is considered. In this case, the problem can be considered one-dimensional. We will consider the discharge conditions to be close to those of a short-arc ultrahigh-pressure xenon lamp with a power of 250 W [1–4] for which experimental data are available. The discharge conditions are as follows: the initial pressure of xenon (cold lamp) is ~ 20 atm, the current density at the cathode surface is $\sim 2 \cdot 10^3$ A/cm^2, and the distance between electrodes is 0.3 cm. We will assume that the cathode surface temperature (~ 3600 K) provides concentration N_{Th}^0 of thorium atoms of $\sim (10^{17}-10^{18})$ cm^{-3} on its surface. These values are quite realistic, taking into account the data from [9–12]. We will also assume that plasma of a high-pressure xenon arc discharge is in conditions of local thermodynamic equilibrium [5–7,9].

The total emission in the continuous spectrum (recombination-bremsstrahlung continuum) and its spectrum were calculated using the relations given in [7]. It was assumed that the main contribution comes from recombination radiation, which for a high-pressure discharge in rare gases in the UV and visible regions of the spectrum prevails over bremsstrahlung [7]. The intensity of xenon spectral lines was calculated using data on the strongest xenon lines and their emission probabilities in the (800–1100) nm region [12–14].

Modelling of the plasma of a high-pressure xenon arc discharge in a planar geometry [2] clearly demonstrated the influence of thorium atoms on the electrokinetic characteristics of plasma. A marked decrease in the plasma temperature near the cathode and a cardinal change in the spatial distribution of the ionic composition of plasma (prevalence of thorium ions at the cathode and xenon ions at the anode) were noted. Obviously, these changes in the electrokinetic characteristics of plasma will affect the optical characteristics.

Figure 1 shows the results of calculations of the optical emission spectrum of plasma produced by xenon atoms and ions I_ω^{Xe} and thorium atoms and ions I_ω^{Th} in the 200–800 nm region at three points $x = 0.05$, 0.15, 0.25 cm on the discharge axis (near the cathode, in the middle of the discharge, and at the anode). The relations for calculation were taken from [7]. The spectra present a somewhat idealized (simplified) view and consist of two parts: an exponential decline in the region of small wavelengths and a spectrum that changes only slightly as wavelength λ increases. The boundary wavelength (the kink at the boundary between two parts) is determined by the lower excited atomic state to which recombination proceeds. For a xenon atom, this state is $5p^5 6s$. For a thorium atom, it is not possible to define one such level because the structure of terms of a thorium atom is very complex. Therefore, we assumed that the main recombination flux goes to the „crowding“ of levels, which is located about 2 eV below the ionization threshold. The drop in emission is determined by the decrease in the number of recombining electrons as their energy increases. With a Maxwellian velocity distribution of electrons, this decline will be exponential on the energy scale. The nearly constant emission spectrum above the boundary wavelength is the result of integration over a large number of atomic levels to which recombination proceeds and the additional contribution of bremsstrahlung radiation, which becomes apparent with the increase of λ [7].

It can be seen from Fig. 1 that the main contribution to the emission spectrum near the cathode at $x = 0.05$ cm is made by thorium atoms and ions, and the „temperature“ of the spectrum is noticeably lower than the corresponding „temperature“ of xenon and that observed at a distance from the cathode. This result is in good qualitative agreement with that obtained in [1]. With distance from the cathode, the radiation associated with thorium atoms and ions decreases, and, starting almost from the middle of the discharge gap, optical radiation of xenon atoms and ions becomes predominant.

Figure 2 shows the spectrally integral longitudinal (along the discharge) distributions of continuum radiation density associated with xenon atoms and ions $I_{\mathrm{Xe}}^{\mathrm{c}}$ and with thorium atoms and ions $I_{\mathrm{Th}}^{\mathrm{c}}$, spectral line emission of xenon atoms

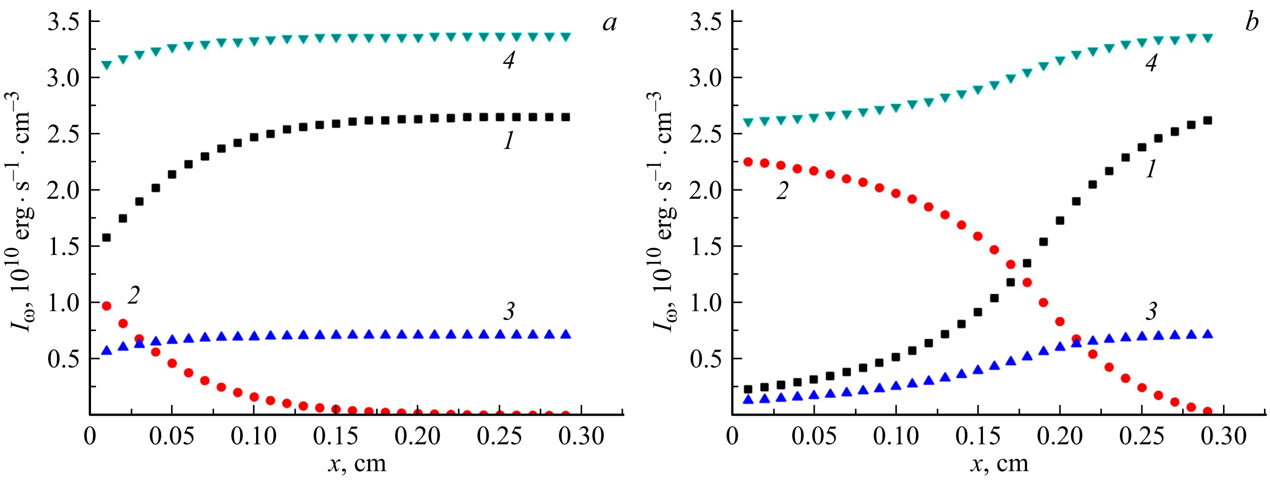

Figure 2. Spectrally integral longitudinal (along the discharge) distributions of continuum emission associated with xenon atoms and ions I^c_{Xe} (*1*) and thorium atoms and ions I^c_{Th} (*2*), spectral line emission of xenon atoms I^{IR}_{Xe} (*3*), and total plasma emission I_{sum} (*4*) at xenon atom concentration $N^0_{\mathrm{Th}} = 2 \cdot 10^{17}\,\mathrm{cm}^{-3}$ (*a*) and $10^{18}\,\mathrm{cm}^{-3}$ (*b*). Discharge current $i = 10\,\mathrm{A}$ and xenon atom concentration $N_{\mathrm{Xe}} = 3 \cdot 10^{19}\,\mathrm{cm}^{-3}$.

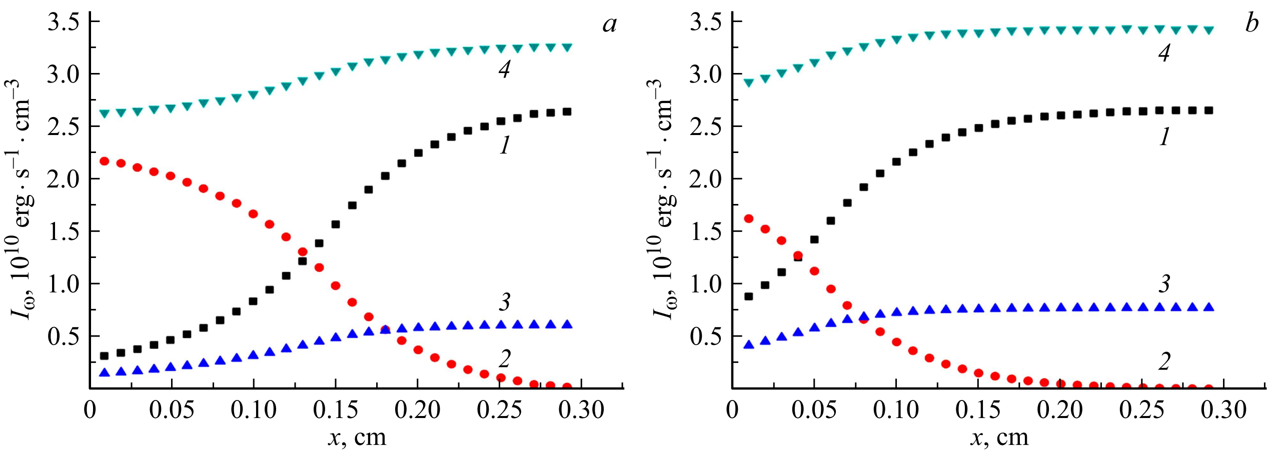

Figure 3. Spectrally integral longitudinal (along the discharge) distributions of continuum emission associated with xenon atoms and ions I^c_{Xe} (*1*) and thorium atoms and ions I^c_{Th} (*2*), spectral line emission of xenon atoms I^{IR}_{Xe} (*3*), and total plasma emission I_{sum} (*4*) at xenon atom concentration $N_{\mathrm{Xe}} = 10^{19}\,\mathrm{cm}^{(-3)}$ (*a*) and $5 \cdot 10^{19}\,\mathrm{cm}^{-3}$ (*b*). Discharge current $i = 10\,\mathrm{A}$ and thorium atom concentration $N^0_{\mathrm{Th}} = 5 \cdot 10^{17}\,\mathrm{cm}^{-3}$.

I^{IR}_{Xe}, and total plasma radiation I_{sum}. It can be seen from Fig. 2, *a* that the total radiation intensity depends rather weakly on the longitudinal coordinate. This is due to the planar discharge geometry and to the fact that more than 85% of the power of the xenon discharge under study is due to optical radiation, i.e., practically everything that is introduced into plasma is emitted as radiation. A slight decrease in the total intensity is observed at the cathode, which is mainly due to the lower plasma temperature in this region [2]. It can also be seen from Fig. 2, *a* that when the concentration of thorium atoms on the cathode surface is relatively low at $N^0_{\mathrm{Th}} = 2 \cdot 10^{17}\,\mathrm{cm}^{-3}$, radiation I^c_{Th}, which is determined by thorium atoms and ions, is relatively weak, reaching its maximum at the cathode and decreasing practically to zero at the anode. The low intensity of radiation generated with the participation of thorium atoms and ions is explained by a rather high plasma temperature under these conditions [2] and the predominant excitation and ionization of xenon atoms. Radiation I^c_{Xe} associated with xenon atoms and ions is quite intense at the cathode and increases towards the anode, being predominant in the entire discharge volume. Xenon spectral line emission I^{IR}_{Xe} is of an appreciable magnitude; at the anode, it is about four times weaker than the xenon continuum emission.

An increase in thorium pressure leads to an expected increase in the intensity of emission associated with thorium atoms and ions and a decrease in emission associated with xenon atoms and ions. Figure 2, *b*, which shows the results for thorium atom concentration $N^0_{\mathrm{Th}} = 10^{18}\,\mathrm{cm}^{-3}$, supports this conclusion. In this case, total plasma emission I_{sum} is noticeably weaker at the cathode than in the previous case and reaches the levels of Fig. 2, *a* only at the anode, where

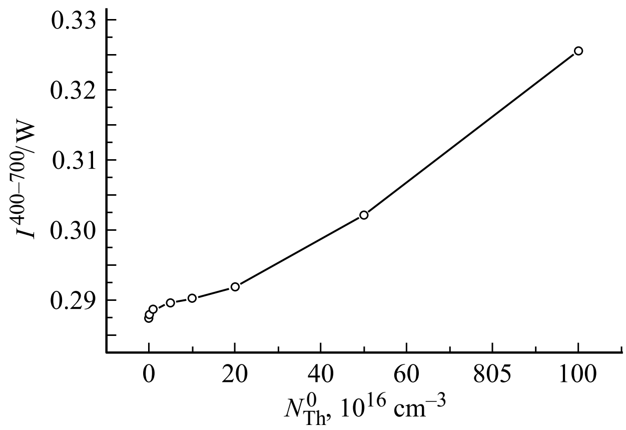

Figure 4. Radiation generation efficiency in the optical spectral region (400–700) nm as a function of thorium atom concentration N^0_{Th}. $i = 10$ A, $N_{\text{Xe}} = 3 \cdot 10^{19}$ cm^{-3}.

Efficiency of generation of the radiation continuum, which is associated with xenon atoms and ions J^c_{Xe} and thorium atoms and ions J^c_{Th}, and emission of spectral lines of xenon atoms J^{IR}_{Xe}

Discharge conditions	N^0_{Th}	J^c_{Xe}/W	J^c_{Th}/W	J^{IR}_{Xe}/W
$i = 10$ A,	$2 \cdot 10^{17}$ cm^{-3}	0.609	0.047	0.173
$N_{\text{Xe}} = 3 \cdot 10^{19}$ cm^{-3}	$5 \cdot 10^{17}$ cm^{-3}	0.514	0.145	0.157
	10^{18} cm^{-3}	0.318	0.351	0.112

the plasma properties are determined by xenon. The reason for this is a stronger decrease in the plasma temperature at the cathode due to a higher concentration of thorium atoms. The thorium emission continuum at the cathode exceeds the xenon emission, which becomes dominant only at $x > 0.17$ cm.

The dependence on xenon pressure is fairly obvious. The increase in the number of xenon atoms levels out the effect of thorium on the plasma characteristics. Figure 3 shows the emission intensities of the studied discharge for xenon atom concentrations $N_{\text{Xe}} = 1 \cdot 10^{19}$ cm^{-3} (a) and $5 \cdot 10^{19}$ cm^{-3} (b). As can be seen from the figures, for the given discharge conditions, an increase in xenon pressure leads to an approximately twofold reduction in the thorium emission intensity and makes xenon emission predominant in the entire plasma volume. Total discharge emission I_{sum} is, as expected, more constant along the discharge length at a higher xenon pressure.

The table shows the efficiency of generation of radiation associated with xenon atoms and ions J^c_{Xe}/W, with thorium atoms and ions J^c_{Th}/W, and IR line emission of xenon atoms J^{IR}_{Xe}/W under various concentrations of thorium atoms. Here, intensities J^c_{Xe}, J^c_{Th} of plasma and J^{IR}_{Xe} are the corresponding powers of radiation emitted by a volume representing a „column" with a unit-area base on the cathode and a length equal to the length of the discharge gap. Power W is the electrical power dissipated in the same volume. At the lower one of the presented concentrations of thorium atoms, the efficiency of generation of thorium continuum (J^c_{Th}/W) is very low and does not exceed 5%. The main contribution to the efficiency comes from the continuum radiation of xenon atoms. When the concentration of thorium atoms increases by a factor of 5, J^c_{Xe}/W decreases by a factor of about 2, while J^c_{Th}/W increases more than seven times. The decrease of J^{IR}_{Xe}/W in this case is somewhat smaller than for the xenon continuum, which is due to the smaller role of thorium ions in producing the IR emission of xenon atoms. The total radiation in the continuum remains approximately constant.

The efficiency of radiation generation in the 400–700 nm optical spectral region $(I^{400-700}/W)$ is shown in Fig. 4. The thorium atom concentration in the plot varies by two orders of magnitude: from 10^{16} to 10^{18} cm^{-3}. It can be seen that the emission generation efficiency in the visible region increases by (12–13)% with increasing thorium content. This increase is associated with an increase in the recombination-bremsstrahlung emission intensity of thorium atoms and ions that is stronger than the drop in the corresponding intensity associated with xenon atoms and ions. A certain contribution to the growth of $I^{400-700}/W$ is also given by the calculated decrease in the electric power supplied to the discharge at constant current, which is (2–3)% and is associated with a decrease in the electric field strength near the cathode [3,4].

Conclusion

The emission of thorium atoms into a short-arc high-pressure xenon discharge strongly affects both the electrokinetic and optical characteristics of plasma. The decrease in plasma temperature near the cathode changes the ion balance and affects the processes of optical radiation generation. In this case, the plasma temperature decreases to about 6000 K, which is close to the temperature of the solar corona.

At an appreciable concentration of thorium atoms, the continuum of optical emission near the cathode is produced mainly by recombination of thorium atoms and ions. The role of xenon atoms and ions becomes predominant in the region adjacent to the anode. Calculations show that the influence of thorium emission becomes noticeable, but not determinant, at $N^0_{\text{Th}} > 10^{16}$ cm^{-3}, while at lower concentrations the plasma characteristics are close to those of a discharge in pure xenon. Despite the simplicity of the problem (one-dimensional case), the emission spectra are in good qualitative agreement with the experimental data [1]. The presence of thorium atoms in plasma does not strongly affect the total integrated emission: it remains approximately constant along the discharge length regardless of concentration N^0_{Th}. Apparently, this was one of the reasons why the possible emission of thorium into plasma was disregarded. The efficiency of generation of optical radiation associated with xenon and thorium atoms and ions naturally depends strongly on the concentration of thorium atoms in the discharge. At the same time, the efficiency of radiation generation in the visible region is relatively weakly affected by the presence of thorium: as the concentration of thorium atoms increases, it increases by (12−13)%, which is due to the overall effect of recombination of both xenon atoms and ions and thorium atoms and ions.

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Conflict of interest

The authors have no conflict of interest.

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