Influence of contraction of a cesium pulse-periodic discharge on its luminous efficacy and spectral properties

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Abstract. The paper presents the results of a study of pulse-periodic discharge cesium lighting lamps with discharge tubes 5 mm in diameter and an interelectrode distance of 55 and 22 mm. The cesium pressure varied from 10 to 750 Torr at a constant triangular current pulse with an amplitude of 80 A. It is shown that the maximum of the luminous efficacy (~ 65 lm/W) corresponds to a pressure of ~ 130 Torr. It was found that a discharge column in the long tube at a pressure of ~ 300 Torr contracted into a bright pinch with a diameter close to that of the electrodes (2 mm). The pinch was localized along the surface of the tube and moves randomly on it. Contraction leads to a repeated increase in the luminous efficacy with pressure up to ~ 70 lm/W. Wall stabilization limits the plasma temperature on the axis of the pinch (it was found from the recombination continuum) to the level of 6000 – 6500 K. The column in short tube is localized along the axis of the tube over the entire power range. The temperature in it quickly rises to 13000 – 14000 K after the maximum of the luminous efficacy.

1. Introduction

In recent years, a cesium high-current high-pressure pulse-periodic discharge (PPD) has been comprehensively investigated as an efficient (already achieved luminous efficacy $\eta = 65$-70 lm/W) and environmentally friendly (mercury-free) source of visible radiation with a very high color rendering index $R_\text{a}$ (up to 95 – 98) [1–6]. Only mercury-free xenon lamps have comparable light quality. They are widely used in television and filming, in studios, etc., where $R_\text{a}$ plays a decisive role. But their light output is almost half that ($\eta = 30$-40 lm/W), and the service life is short (hundreds of hours). Whereas in cesium lamps it is possible to organize a discharge with a thermionic cathode without cathode spots, which should provide a significantly longer service life. Analysis of possible applications of cesium lamps shows that with an increase in luminous efficacy to 90-100 lm/W, they can successfully compete with LEDs where powerful light sources are required - for example, for outdoor lighting. The cost of LED sources grows rapidly with increasing power, and the cost of gas-discharge lamps with power remains almost unchanged, which compensates for the high (110-130 lm/W) luminous efficacy of LEDs. For this reason, a detailed experimental study of cesium PPD is especially important for searching for possible ways to increase its luminous efficacy. Moreover, as a physical object, it turned out to be much more complicated than the theory predicted. This is also important because the nature of the cesium PPD turned out to be more complex than theory predicted.
When investigating such a discharge in a wide range of cesium vapour pressures \( p_{\text{Cs}} = 10 \text{–} 800 \text{ Torr} \), it was found that in the high pressure range (of the order of hundreds of Torr), the positive column contracted in it, significantly changing its characteristics \([5, 6]\). It was suggested that the nature of the contraction depends on the length of the interelectrode gap, and this difference determines the features of the discharge formation and its lighting parameters. The aim of this work was to verify this assumption with the addition of spectral measurements to the luminous efficacy ones.

2. Description of the experiment
The experiments were carried out on lamps with single-crystal sapphire tubes (burners) with an inner diameter of \( 2R = 5 \text{ mm} \). Cesium was introduced into the burner in excess, so that its pressure was set by the temperature of its cold point, which was in one of the electrode leads. To ignite the cold lamp, xenon (30 Torr at room temperature) was also introduced into the burner. The burner was mounted in a quartz tube, which was either evacuated and sealed off, or was under continuous evacuation. The design of the lamp with continuous pumping made it possible to install a thermocouple on the burner to determine the temperature of the cold point and the equilibrium pressure of cesium vapour.

The lamp was powered from a generator of alternating polarity current pulses. The alternating polarity provided the same heating of the electrodes and excluded cataphoresis. The current in the pulses increased linearly, the rate of current increase was 1, 2, or 3 A/\( \mu \text{s} \). The pulse duration \( \tau_p \) could be varied from 10 to 50 \( \mu \text{s} \), the maximum pulse current \( I_m \) was from 10 to 150 A. The pulse repetition rate \( f \) was regulated from 10 Hz to 1.5 kHz. The maximum voltage at the beginning of the pulse was 3 kV and rapidly decreased as the current increased. The voltage and current were recorded with a storage oscilloscope, the data were transmitted to a computer to determine the energy input in the pulse \( q_p \) and the average discharge power \( W = q_p f \). The generator also generated sync pulses for synchronization with the systems for recording the discharge parameters.

The time-average illumination normal to the burner axis was measured with a “TKA-Lux” luxmeter at a sufficiently large distance from the lamp, and the normal luminous flux was calculated from it. The total luminous flux of the lamp \( I \) was determined from this normal luminous flux with an effective solid angle \( \Omega_{\text{eff}} = 11.2 \), experimentally measured for one of the lamps by the zonal solid angle method \([7]\). In addition, a special dynamic luxmeter based on a photodiode made it possible to record the dependence of the luminous flux on time with a resolution of about 1 \( \mu \text{s} \) and determine from it the light energy of an individual pulse \( I_p \) and, accordingly, \( I = f I_p \). An MDR-23 monochromator was used to record the spectral characteristics of the discharge. The gated integration method made it possible to record the discharge spectrum at any time in the current pulse and in the intervals between pulses in the decaying plasma. Time resolution (strobe duration) is 50 ns. It was also possible to record the time dependence of the discharge radiation at any wavelength \( \lambda \).

3. Results and discussion
As the frequency increases, the average discharge power \( W \) increases, the burner temperature rises, and the cesium pressure increases accordingly. With an increase in pressure, the voltage across the discharge increases, this causes an increase in the energy input in the pulse. Due to this, \( W \) and \( p_{\text{Cs}} \) additionally grow. Taking into account this dependence of \( W \) and \( p_{\text{Cs}} \) on frequency, the most convenient method of investigation is to register the dependence of the luminous efficacy \( \eta = I/W = I_p/q_p \) on frequency at a constant current pulse (the amplitude \( I_m \) and duration \( \tau_p \) of the pulse are constant). As a result, the dependence of the luminous efficacy (and other parameters of the discharge) on the average discharge power and pressure for the selected amplitude of the current pulse is obtained. In this case, the pressure \( p_{\text{Cs}}(W) \) dependence is determined by the thermal balance of the burner, which is influenced by the heat removal along the electrodes and the design features of the lamp. Therefore, this dependence is specific for each type of lamp.
The resulting dependence of the discharge parameters on the specific power \( W' = W/L \) \((L – \text{interelectrode distance})\) is shown in figure 1. This power range corresponds to a cesium pressure range of 10 – 750 Torr. At low \( W' \) (low pressures), the plasma is optically transparent for the continuum radiation; therefore, an increase in the power (pressure) and a corresponding increase in the plasma concentration \( n_e \) cause a rapid increase in the light energy in a pulse at the initial portion of the \( i_p(W') \) curve (curves 3, 3'), since in the conditions under consideration the radiation is carried out mainly by the continuum, and its intensity is \( \sim n_e^2 \). Correspondingly, the luminous efficacy also grows rapidly (curves 1, 1'), since the energy input in the pulse increases much more slowly (2, 2'). With an increase in the power and pressure, \( n_e \) increases; however, the optical density of the discharge column also increases. This slows down the growth of the luminous efficacy and forms a maximum when, with an increase in pressure, reabsorption begins to prevail. At the luminous efficacy maximum for a long burner (curve 1), the cesium pressure is 130 Torr (there was a thermocouple on this lamp at the cold point). A similar pressure value at the maximum luminous efficacy should also be for a short burner, which did not have a thermocouple (curve 1'). The difference in the power at which this pressure is achieved is explained by the fact that, the lamp with a short burner had very little heat removal through the electrode leads.

As can be seen from the figure, a decrease in the luminous efficacy is replaced by its repeated increase (above the initial maximum) for a lamp with a long burner. It was natural to associate this increase with the visually observed contraction of the discharge at this moment, as a result of which the glow contracts into a pinch with a diameter of about 2 mm (equal to the diameter of the electrodes) adjacent to the burner wall. The glowing pinch jumped from one place on the wall to another with a period of several seconds. With a further increase in the power (pressure), such an unstable regime quickly stabilized, the hopping frequency increased, so that soon the eye ceased to distinguish them, and the glow visibly filled the entire discharge tube. In modes with a jumping pinch, the error in measuring the illumination was 10 – 15% (instead of the usual 5 – 7%).

Figure 1. The cesium PPD parameters dependence on the mean discharge power \( W' \). 1, 1' – the luminous efficacy \( \eta \), 2, 2' – the energy input in the pulse \( q_p \), 3, 3' – the light energy of the pulse \( i_p \), 4 – the temperature on the discharge axis. (1 – 4) for the burner with the interelectrode distance \( L = 55 \) mm, (1' – 3') – for \( L = 22 \) mm. The current pulse \( I_m = 80 \) A, \( \tau_p = 40 \mu \text{s} \).
On lamps with \( L = 22 \text{ mm} \), a repeated increase in the luminous efficacy was not observed up to powers that were \( \sim 5 \) times higher than the power at the maximum (curve 1'). Under the investigated conditions, the discharge channel does not touch the burner walls, although it is not always localized strictly along the tube axis. This shows that the main reason for the increase in the luminous efficacy in a long burner lies not in the contraction itself, but in the near-wall arrangement of the pinch, i.e. in reducing the distance from the center of the pinch to the wall.

Localization at the wall includes two oppositely acting factors. On the one hand, the transfer of energy by plasma particles from the discharge to the wall increases, which reduces the light output. This manifests itself in an increase in the rate of growth of the energy input in the pulse \( q_p \) from the power (curve 2). On the other hand, the size of the absorption region of the continuum decreases, in which the concentration of excited atoms at the 6P and 5D levels is high, this facilitates the emission of radiation. Therefore, the light energy in a pulse \( i_0 \) (Figure 1, curve 3), which has practically reached saturation after the maximum of the luminous efficacy begins to grow rapidly again after the minimum. On a short burner, the light energy in the pulse also slows down after the maximum of the luminous efficacy (curve 3'), but then drops sharply at \( W' \sim 100 \text{ W/cm} \), when contraction on the axis is observed. The \( q_p(W') \) dependence also undergoes a kink with a sharp decrease in the growth rate, and it is this decrease that slows down the decline in the luminous efficacy (curve 3').

An increase in the luminous efficacy upon contraction of the discharge on the burner wall means that cesium PPD is especially sensitive to the length of the absorbing layer. This confirms the important result obtained in the study of such lamps in [8]. It turned out that their luminous efficacy increases with a decrease in the diameter of the discharge tube from 6 mm to 2.7 mm. For other arc lamps (sodium, mercury), the luminous efficacy increases with an increase in the diameter of the burner [9]. For them, the relative decrease in heat removal to the wall (the volume of the emitting plasma increases as \( R^2 \), and the burner surface area as \( R \) prevails over the increase in reabsorption.

The reason for this difference is associated with the fact that in sodium and mercury lamps the main output of radiation occurs in the lines, and in cesium – in the recombination continuum. In the first case, the re-emission mechanism works [9], while for cesium the absorption of a quantum means practically its loss. Of course, the formed ion and electron can recombine in the near-wall layer and make up for the loss of the primary quantum. But because of the lower \( T \) and \( n_e \) in the absorbing layer and the quadratic dependence of the recombination rate on the concentration \( n_e \), the probability of this will be much less than the probability of the initial recombination, so that most of the absorbed radiation is spent on heating the peripheral plasma. This implies the high sensitivity of the cesium discharge to the size of the absorption region.

The above considerations were confirmed by spectroscopic measurements. It was shown in [10] that the temperature \( T \) and plasma concentration \( n_e \) on the discharge axis can be determined with sufficient accuracy from the integral spectra of the continuum. The results of such temperature measurements for several power modes are shown in figure 1, curve 4. Before the contraction of the discharge, the temperature increases slowly with an increase in \( W' \), since the concentration of cesium atoms, which must be excited and ionized, increases with power. During the transition to the contracted mode, a sharp decrease in temperature is observed, and then the temperature begins to rise again. These changes are small, so that the temperature remains relatively low (6000 – 7000 K) over the entire range of \( W' \) in the discharge. Accordingly, plasma is formed mainly due to the excitation and ionization of cesium atoms up to the highest investigated powers (pressures), where all intense cesium lines are reabsorbed (not only resonance lines) (figure 2, curve b, it is shifted 400 units up). At low \( W' \) to the left of the maximum of the \( \eta(W') \) curve, a purely cesium spectrum is also observed, but practically without reabsorption [2]. A similar spectrum with a temperature of 6600 K is observed in this pressure range on a short burner (figure 2, curve a). All spectra in figure 2 were recorded at the end of the pulse at the maximum current value.
Figure 2. Emission spectra of cesium PPD for the current pulse $I_m = 80$ A, $\tau_p = 40$ μs.

a – $L = 22$ mm, $W' = 15$ W/cm, $T = 6600$ K, b – $L = 55$ mm, $W' = 210$ W/cm, $T = 6300$ K,
c – $L = 22$ mm, $W' = 50$ W/cm, $T = 14000$ K.

A completely different picture turned out on a short burner with an increase in power. With an increase in $W'$ by only 20 W/cm on a short burner, the temperature immediately rises to 13000 K. An increase in $W'$ by another 15 W/cm (up to 50 W/cm) leads to an increase in temperature only up to 14000 K. As a consequence, in the spectra at such temperatures, there is a significant shift of the emission maximum to shorter wavelengths (from 650 nm to 400 nm) and many CsII and XeII lines appear (figure 2, curve c, is shifted 800 units up).

Such an uneven increase in temperature and a corresponding change in the spectrum on a short burner is due to the lower energy removal from the discharge during its localization on the axis and to the peculiarities of the plasma of the Cs+Xe mixture. Estimates show that at $p_{Cs} \sim 100$ Torr, already at $T = 5000 – 6000$ K, cesium is almost completely ionized. At the same time, the degree of ionization of xenon is still quite insignificant (~10⁻³), as well as the energy consumption for the excitation of its levels. This is due to the fact that the ionization potential of cesium (3.89 eV) is three times lower than the ionization potential of the Xe atom (12.1 eV) and two times lower than the energy of its first excited level (8.3 eV). The difference with the ionization potentials of Cs⁺ (23.2 eV) and Xe⁺ (20.97 eV) is even greater.

Temperatures of 5000 – 6000 K on the ascending branch of the luminous efficacy curve $\eta(W')$ mean that cesium in the discharge channel is close to full ionization. An increase in $W'$ here leads to an increase in radiation, as well as to ionization of an additional number of cesium atoms, caused by an increase in pressure. Therefore, the temperature on the ascending branch rises relatively slowly. But after the maximum, an increase in the supplied power no longer causes a relative increase, but a relative decrease in radiation (per unit power), so that an increasing part of the additional energy must be spent on heating the plasma. With the complete ionization of cesium, energy can only be invested...
in the translational degrees of freedom of the plasma components; therefore, heating must occur very quickly, which is observed on a short burner (figure 2). (On a long burner, the localization of the discharge on the wall completely changes the situation). But as soon as the temperature rises so much that it becomes possible to pump additional energy into the bound states of Xe$^+$ ions and, especially, Cs$^+$ ions, the rate of temperature rise decreases sharply again.

4. Conclusions
It is shown that in all investigated burners with an inner diameter of $2R = 5$ mm and an electrode diameter of $\sim 2$ mm, contraction of the positive discharge column is observed in the region of relatively high pressures. With an interelectrode distance $L = 22$ mm (or less), the discharge channel (area of bright glow) is localized along the tube axis and tied to the electrodes; at $L > 55$ mm, the channel is localized on the wall. It was found that contraction with localization along the axis forces an increase in the plasma temperature with an increase in the energy input in the pulse, while localization near the wall decreases the temperature and sharply slows down its subsequent growth with an increase in the input energy. It was found that contraction at the wall increases the luminous efficacy, and contraction along the axis decreases it. It is shown that the reabsorption of the continuum radiation affects the luminous efficacy of cesium PPD lamps much more strongly than the reabsorption of resonant radiation of sodium and mercury arc lamps affects the luminous efficacy of such lamps.

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