Light & Engineering
Vol. 27, No. 6, pp. 88–96, 2019
https://doi.org/10.33383/2018-074

DISTINCTIONS OF THE DESIGN OF UHP XENON LAMPS WITH SAPPHIRE ENVELOPE

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ABSTRACT

This article describes the major development results of the first Russian sample of a UHP xenon discharge lamp with sapphire envelope. The article proposes a method of monitoring of thermal fields of semi-transparent materials and studies the thermal distribution of quartz and sapphire envelopes of UHP discharge lamps. Mechanical strength of sapphire tubes depending on the temperature is studied, the thickness of the discharge envelope wall is calculated, and distinctions of the design of a UHP xenon lamp with the sapphire envelope are considered.

Keywords: discharge lamp, UHP discharge, quartz and sapphire envelope, xenon, mechanical strength, thermal distribution, thermal field of a bulb

1. INTRODUCTION

Nowadays, despite the rapid development of the market of various light sources (MHL, fluorescent amalgam lamps, LEDs, etc.), ultra-high pressure xenon lamps in quartz ball bulbs are irreplaceable for spotlights for different applications [1]. Another distinction of these light sources (short-arc lamps) is that after publication of the first works by Kaptsov N.A., Gouhberg D.A., Rokhlin G.N., Rovinsky R.E., et al. [2–4] describing this class of lamps, which became classical ones; the design of these lamps almost has not changed (Fig. 1). UHP lamps still have a ball (elliptic) envelope made of quartz glass with various degree of transparency (doping), current inputs in the form of cylindrical or flat molybdenum foil, etc. Among the disadvantages of the described design are: large dimensions, which determine the size of the spotlight; low mechanical strength caused by strains in the joint of the ball bulb and the electrode unit; spectral range of radiation of the lamp of up to 4.2 μm determined by the transparent region of quartz; complex design and manufacturing technology caused by necessity of precise adjustment of cathode pin to the basic surface of the cap. Therefore, the search for new technical solutions allowing to prevent the said disadvantages is a relevant challenge.

2. BACKGROUND OF DEVELOPMENT OF DISCHARGE LAMPS WITH SAPPHIRE ENVELOPE

Mass production of high-pressure sodium lamps started in the 70-s and search of new materials for their efficiency increasing assisted in the development of the method of tubes directional crystallization made of mono-crystal aluminium oxide (sapphire, corundum) proposed by A.V. Stepanov [5]. This was justified since corundum has unique properties: high optical transparency (up to 96 %) in the spectral region of up to 6 μm, mechanical strength, chemical resistance to vapours of alkali metals, etc. In the beginning, application of sapphire tubes in the design of discharge lamps was economically unviable due to complexity of the crystal-growing process, the high power consumption of the process, low quality of sapphire processing (lapping, polishing), lack of high-purity raw materials and methods of their treatment. At the beginning of the 90-s, the listed problems were practically solved, the sapphire tubes were serially grown by means of group method, which made these products cheaper, and, at the same time, intensive development of discharge lamps with plasma supporting media based on alkali metals have begun [6]. Therefore, the established situation and obtained results of successful application of sapphire preconditioned necessity of development of UHP lamps in corundum envelope.

The material of envelope of any discharge lamp should meet the following requirements: optical transparency in a broad spectral range, resistance to operating temperatures and filling pressure, lack of gas releases, chemical resistance to components of the plasma supporting medium, mechanical strength, etc. [2, 4]. Such a wide range of limitation is caused by energy deposition on the envelope from both sides. From the plasma side, it comprises emitted radiation and the energy caused by thermal conductivity, charged particles, impact waves, from the outside, it comprises the returned radiation from the light-forming optical system or from other lamps (in case of multi-lamp systems), external factors (X-radiation, neutron radiation, etc.), chemical interaction with the environment, etc. In case of UHP discharge lamps, the bulb should additionally provide mechanical strength with the impact of internal filling pressure of up to 50 atm at operational temperatures of the lamp. Therefore, three relevant challenges arise for designing of the envelope of UHP DL with sapphire envelope:

1. Development of the method and measurement of thermal distribution of the quartz bulb (T_{en}) of the xenon lamp at various specific electrical loads for forecasting of the thermal fields of light sources with sapphire envelope;
2. Studying of the dependence of mechanical strength of sapphire tubes on structural perfection of crystals and temperature;
3. Evaluation of the size of the sapphire bulb and development of the UHP lamp with sapphire envelope manufacturing technology.

Fig. 1. Design of UHP xenon lamps with quartz ball envelope and cylindrical sapphire envelope

3. STUDIES OF LONGITUDINAL THERMAL DISTRIBUTION OF A QUARTZ BALL BULB OF AN UHP XENON DISCHARGE LAMP

3.1. Study Methodology

Due to simplicity and wide range of the measured temperatures in the course of studies of the thermal condition of discharge lamp bulbs, the thermocouple method has become the most widely used [4, 7]. However, in this case, the measurement of T_{en} has a number of significant aspects, which should be taken into account when selecting the design of a thermocouple and evaluating the measurement error of temperature. First, the surface temperatures of thin-wall envelopes are usually measured, with conductivity coefficient χ nearly a hundredfold lower than χ of the thermal electrodes material. Second, the envelopes on the surface of which the temperature is measured are transparent, and the thermocouple is affected by the radiant flux of the discharge.

The methods of pyrometry (thermography) [8] allow eliminating the said disadvantages. Due to volume nature of radiation of semi-transparent quartz and sapphire crystals, the standard thermography methods are not applicable to them. Therefore, for measurement of temperature, special partial radiation pyrometers operating beyond the bandwidth of a studied object are developed [8, 9]. With the growth of temperature from room values to operational ones, the non-transparency interval of the envelope material within the range of wavelength $\Delta\lambda$, which can be used for pyrometry, is being changed. For instance, with the heating of sapphire its $\Delta\lambda$ insignificantly shifts to the short-wave region of the spectrum of infrared bandwidth [9].

Short-wave absorption (UV region) of quartz or corundum where the value of absorption coefficient reaches (10^3–10^4) cm^{-1} is the result of the interaction of the electromagnetic wave with the electrons of the crystalline grid. The position of the long-wavelength side of this absorption is defined by impurities in the material structure [8, 9]. Therefore, the absorption coefficient may significantly vary in case of insufficient variation of flaw concentration and is not of interest for pyrometry due to this.

The most interesting is the short-wavelength border of the first vibrational absorption band of quartz

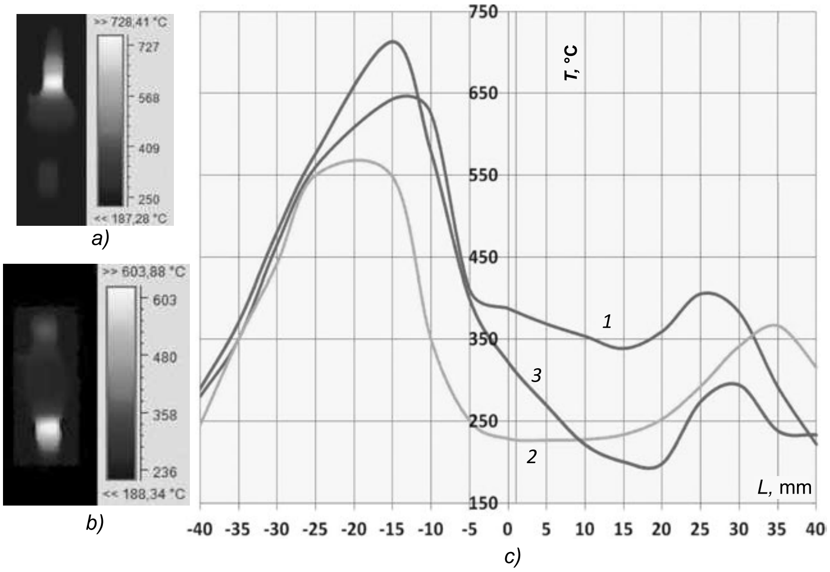


Fig. 2. Photos of thermal fields of the xenon lamp DKsSH-150 with vertical operating position of anode (a) and cathode (b) in the upper part and lateral thermal distribution (c) in the course of operation of the lamp in a horizontal (1) and vertical (2) positions with cathode (2) and anode (3) in the upper part

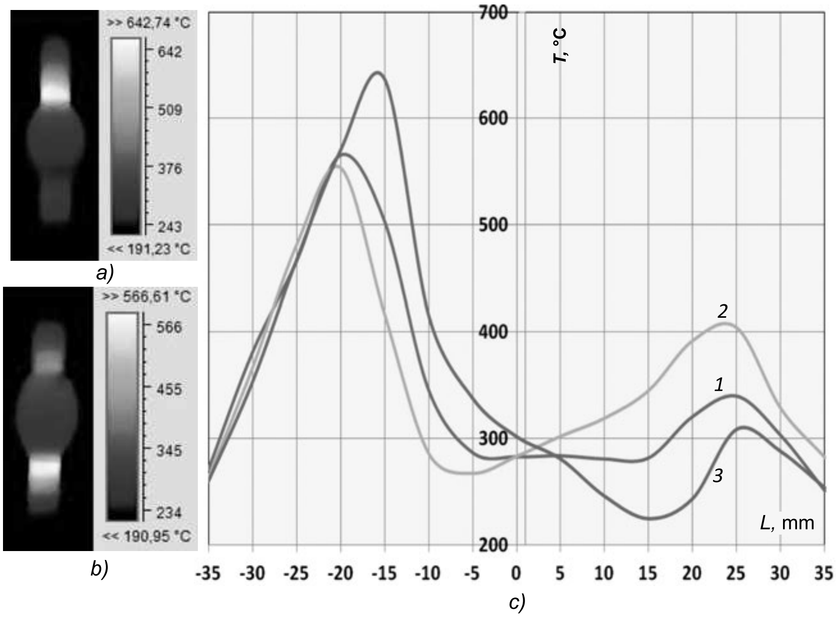


Fig. 3. Photos of thermal fields of the xenon lamp DKsSH-500 with vertical operating position of anode (a) and cathode (b) in the upper part and lateral thermal distribution (c) in the course of operation of the lamp in a horizontal (1) and vertical (2) positions with cathode (2) and anode (3) in the upper part

and corundum. In this region, k_λ of semi-transparent materials may reach $k_\lambda = (10^2–10^3)$ cm^{-1}, and emissivity approximates one. For instance, according to [8] for corundum at temperature of 2000 K within the spectral region of (6–10) μm, 95 % of energy is radiated by the near-surface layer with thickness of just 0.65 mm, which allows to consider the surface temperature of the discharge tube given the conventional thicknesses of discharge lamp envelopes (1.5–3.5) mm. Due to the low value of reflectance k_r in this region, its effect on the measurement results is insignificant. Therefore, if the receiver receives radiation from this non-transparency region of sapphire, the signal of the receiver will be definitely related to the temperature of the surface of the envelope made of this material.

3.2. Experimental Study of Thermal Distribution of the Surface of UHP Discharge Lamp Ball Bulb

For our experiments in the determination of thermal fields of sapphire envelopes, we used the SDS HotFind-LXT thermal vision system based on multi-element radiation receivers, i.e. matrices, the number of elements of which allows forming a TV image with good spatial resolution. The operational spectral range of this pyrometer is (7.5–14) μm, which allows measuring temperature within the range from –20 °C to +1500 °C.

The studies of thermal fields of UHP xenon lamps with quartz ball bulb were conducted with design and electrical characteristics listed in Table 1.

Table 1. Design and Electrical Characteristics of the DKsSH-150 and DKsSH-500 Lamps

Lamp type	Design parameters				Electrical characteristics				
	d_1^*, mm	d_2^*, mm	$l_{b.e.}$, mm	p_{Xe}, MPa	P_l, W	U_l, W	I_l, A	$j_{an.}$, A/cm^2	$P_{sp.}$, W/cm^2
DKsSH-150	20	14	2.5	2.0	154	18.8	8.4	60.0	25.0
DKsSH-500	30	26	1.3	1.2	514	13.6	38	54.3	24.2

* – *d_1 and d_2 are outer and inner diameters of the ball bulb respectively*

The bulb temperature was measured in 10 minutes after reaching the nominal electric power of the lamp. As a result of such heating, thermal distribution along the envelope was stabilised and took the form shown in Figs. 2, 3. For clarity of the obtained thermal profiles of the quartz ball bulb, the photos from the thermal camera display are shown in the said figures. During measurements, for the curves shown in Fig. 2, 3, the location of the cathode spot was taken as a zero point for calculation of distance along the bulb.

The obtained data shows that the courses of thermal curves of the studied lamps are similar. There is a deviation of T_{en} of two lamps in a plane crossing the cathode spot perpendicularly to the lamp axis. This effect is related to differences in the distance between electrodes $l_{b.e.}$, which provides higher losses of discharge by radiation on the bulb in case of DKsSH-150. An important distinction of the obtained results is the availability of high lateral temperature gradients of the lamp caused by high losses of power by xenon thermal conductivity and effect of the heated anode radiation on the closely adjacent part of the ball bulb [2–4].

As it is seen from Table 1, the specific electric power per unit of the inner surface of the ball bulb is the same and the values of anode current density j_{an} are commensurable, therefore, the temperatures of the bulb surface in the anode area of both lamps are close to each other and do not exceed 700 °C. The minimal temperature of the ball envelope can be seen at distance of (15–20) mm from the cathode pin and is within the range of (180–350) °C depending on the type of lamp and its operating position. The said temperature range is related to convection of xenon after changing the lamp position.

Therefore, in the course of designing of a UHP xenon lamp with a sapphire bulb and with the power of up to 500W, it is necessary to take into account the lamp envelope should provide mechanical strength in conditions of a pressure of up to 50 atm at operational temperatures of up to 700 °C.

4. DEVELOPMENT OF XENON DISCHARGE LAMPS WITH SAPPHIRE ENVELOPE

Using of sapphire as an envelope of a discharge lamp is a new problem, therefore, for its solving, it is necessary to study the relation between strength properties of this material and structural perfection of a mono-crystal and operational conditions of an instrument, primarily, its operational temperature.

4.1. Studies of Mechanical Strength of Sapphire Tubes

Mechanical strength of tubes made of monocrystal colourless corundum grown using the Stepanov method depends on the structural perfection of a crystal [4, 9, 10]. Detailed analysis of the flaws of sapphire tubes is described in the article [10]. In this publication, the author proved that the

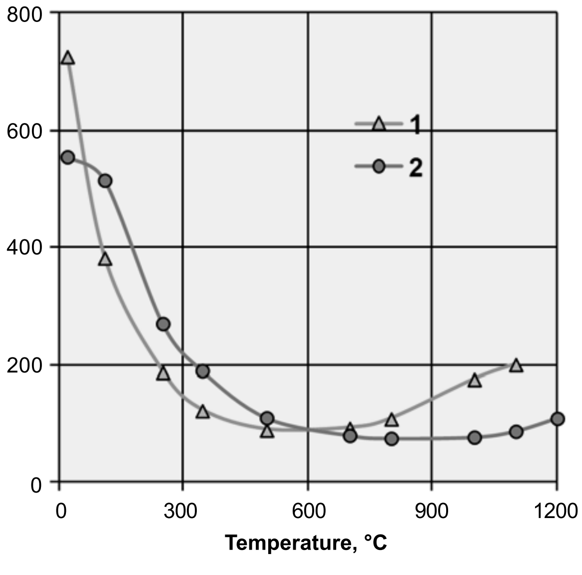
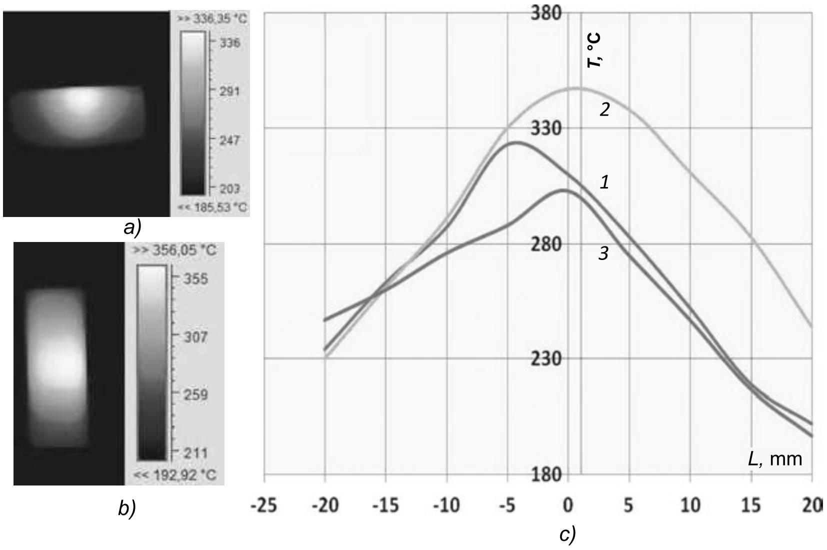


Fig. 4. Thermal dependence of ultimate strength of corundum tubes grown with crystallographic orientations: 1 – [0001]; 2 – [1012.]



a)

b)

c)

Fig. 5. Photos of thermal fields of the xenon lamp SPKs-500 with horizontal (a) and vertical (b) operating position of anode in the upper part and lateral thermal distribution (c) in the course of operation of the lamp in a horizontal (1) and vertical (2) positions with cathode (2) and anode (3) in the upper part

main factor determining mechanical strength is the availability of a large amount of disordered crystalline regions with macroscopic size (crystallites). The borders of crystallites are strains concentrators, and the values of these strains are determined by macro-region boundary angle and temperature condition of a crystal. Part of strains is removed by means of uniform annealing of the grown corundum. However, the high-temperature gradient in the wall of the lamp sapphire envelope will inevitably leads to increase of internal strains and destruction of a mono-crystal. It is clear that the more the number of crystallites is and the higher the temperature gradient is, the less is the mechanical strength of the sapphire tube [4, 10].

The corundum strength, like that of other brittle materials, depends on many factors: testing speed, temperature, quality of sample surface, environment, different orientation of a crystal in relation to the applied load. The operating principle of the instrument for the destruction of tube samples proposed in [10] is based on the application of a yielded composed medium allowing to reliably and simply seal a particular volume of a sample thus providing uniform and all-round loading of inner walls of the sapphire tube. Since the load is applied to the inner surface of the tube uniformly in the radial direction in the medium part of 1/3 of the sample length during testing of samples using this instrument, boundary disturbance is negligible. The butts of the tested tubes were sanded only for ensuring straightness.

The value of strength, i.e. tangential fracture strain of the walls of a tube sample σ_f, was calculated using the formula [10]:

$$\sigma_{\mathrm{f}} = \frac{F}{\pi \times R_1^2} \times \frac{(R_2^2 + R_1^2)}{(R_2^2 - R_1^2)}, \qquad (1)$$

where F is the force; R_1 is the inner diameter; R_2 is the outer diameter. Measurement accuracy provided by the method is about 5 kg/mm^2.

In Fig. 4, the experimentally obtained temperature dependence of mechanical strength of crystallite-less tubes with a wall thickness of 1.4 mm grown using the Stepanov method with the crystallographic orientation of [000$\bar{1}$] (curve 1) and [1012] (curve 2) within the temperature range from 200 to 1100 °C is shown. The temperature was increased with a step of 10 degrees per minute and controlled by a thermocouple. The samples were loaded for (5–10) seconds. After the destruction, critical strains were calculated using formula (1) and averaged.

Mismatch of the minimum values of strength on the curves is caused by the fact that destruction was conducted in different crystallographic planes. Despite some differences in mechanical strength values, the courses of the curves are identical. Fig. 4 shows that there is an obvious minimum of strength at the temperature range of (400–700) °C. Reduction of fracture strain caused by temperature is natural for many brittle materials and is caused by availability of overloaded sections in the latter characterised by the coefficient $n = \sigma_{\mathrm{e}} / \sigma_{\mathrm{av}}$, where $\sigma_{\mathrm{av}} = P / S$ (P is the force, S is the cross-section of the sample) are local overstrains distributed over the volume, which depend on the microscopic structure of the sample.

The anomalous dependence of strength on temperature is explained by superposition of the processes of deformation and destruction. In the low-temperature region, the deformation processes are slowed down, the overstrain coefficient is high and almost constant. Increasing of temperature up to 800 °C accelerates deformation, local strains reduce during the test and after increasing of temperature, the coefficient n dramatically decreases, therefore, σ_f also increases after increasing of temperature. Therefore, the coefficient of local overstrains affects, primarily, the temperature-strength dependence of the sapphire tube in the first instance. The influence of disorientation of crystallites with an angle of up to 25° and strains of up to 16 kg/mm^2 are not discovered.

The above-listed results relate only to the mechanical strength of sapphire tubes. Meanwhile, a designer of high-intensive radiation discharge sources for different applications will take additional requirements obtained by the authors in [5, 9–12] into account. In terms of crystallographic properties, the geometrical axis of sapphire tubes should not deviate from the $[000\bar{1}]$ crystallographic orientation more than by 10 °, should not contain more than 5 crystallites in the wall volume cross-section with the disorder of adjacent crystallites exceeding 10 °. The transmittance of corundum tubes should be of at least 90 % within the spectral range from 0.3 to 5 µm, the tubes should not include second phase impurities, clouds, non-transparent flaws, blisters, and growth shifts and should sustain growth of temperature up to 1950 °C without losing optical transparency. In terms of dimensions for tubes with an inner diameter from 5 to 11 mm, deviation of ±0.3 mm is acceptable, maximum deflection is 0.2 mm with the length of 150 mm, surface waviness should be within the size tolerance. The concentration of blisters is standardised on the basis of categories and classes of optical materials.

5. DESIGN DISTINCTIONS OF UHP DISCHARGE LAMP

Some distinctions of operation of quartz xenon short-arc lamps [2, 3], which may significantly affect the operation of similar light sources with sapphire envelope, should be taken into account. The bulbs of high-intensity lamps should be designed so that the mechanical strains appearing inside the sapphire tube do not cause its destruction. The strains are caused by high pressure of filling gas and thermal strains due to temperature gradients in the walls of the envelope and in joints of sapphire and metal. Destruction of the sapphire bulb occurs in cases when the maximum tensile loads reach tensile strength rupture limit.

If the internal pressure is higher than the external pressure, the bulb will suffer breaking strains. Axial strain σ_a, which appears in the cylindrical bulb, in this case, is equal to [11]:

$$\sigma_a = \frac{pd}{2h}, \qquad (2)$$

where d is the inner diameter of the discharge bulb, h is the sapphire tube wall thickness, p is the pressure of filling gas.

This expression is correct if the wall thickness h is a non-significant part of the inner diameter of the bulb d. The long experience of operation and tests of ultra-high pressure quartz lamps with natural cooling has shown that strength reserve of about 10 is sufficient for most of the lamps [11]. Therefore, it is necessary to calculate the wall thickness in the centre of the bulb for a case, when the maximum value of overall breaking strains does not exceed the acceptable value $\sigma_a/10$. According to Fig. 2c, the temperature of the bulb in the area of the anode is T_{en} = 700 °C. Given the higher thermal conductivity of sapphire, it is possible to expect T_{en} of up to 800 °C in this area. As it follows from the data shown in Fig. 4, the ultimate strength of a crystallite less sapphire tube at such temperature is 10^7 Pa. Then, according to formula (1) for UHP xenon lamp with the inner diameter of the bulb 115 mm and filling pressure of xenon of 1.5 MPa, the thickness of the wall of a sapphire tube should be equal to at least h = 1.65 mm.

It is necessary to note that the given calculated values are obtained for pressure of filling gas at room temperature. Increase of temperature of the filling gas will lead to increase of gas pressure by several times, but the foreseen strength reserve allows keeping the calculated values of the wall thickness in the course of design of UHP xenon lamps with sapphire envelope.

6. THERMAL PROFILE OF THE CYLINDRICAL SAPPHIRE BULB OF AN UHP XENON LAMP

The ball form is used for the quartz-glass bulb due to the necessity to provide uniform distance between the inner surface of the envelope and the high-temperature cathode spot. Given that ther-

Table 2. Design and Electrical Characteristics of the SPKs-500 Lamp

Design parameters				**Electrical characteristics**				
d_1^*, **mm**	d_2^*, **mm**	$l_{b.e.}$, **mm**	p_{Xe}, **MPa**	P_l, **W**	U_l, **W**	I_l, **A**	$j_{an.}$, **A/cm^2**	$P_{sp.}$, **W/cm^2**
20	15.5	1.3	1.2	514	13.6	38	30.4	26.5

* – *d_1 and d_2 are outer and inner diameters of the cylindrical sapphire bulb respectively*

mal distribution of the envelope depends not only on specific electric power but also on operation position of a lamp (Figs. 2, 3), it can be expected that replacement of the bulb form with sapphire cylinder will inevitably lead to the transformation of the thermal field of the lamp. This is related to the high thermal conductivity of sapphire and the difference between convection currents in the considered lamps. In its turn, due to anisotropic properties of the thermal expansion coefficient of corundum, appearing of high-temperature gradients in the wall of a sapphire tube may lead to the destruction of the envelope.

The thermal field studies based on the above-described method were conducted using a SPKs-500-type UHP lamp with a sapphire envelope, the design of which is given in Fig. 1 and the main technical specifications are listed in Table 2.

The results of the study of the lateral thermal distribution of the cylindrical sapphire envelope of an UHP xenon lamp with average electric power of 350 W are shown in Fig. 5. The highest temperature of the bulb is seen in the plane crossing the cathode spot perpendicularly to the lamp axis. It is related to heating of the sapphire envelope by radiation. Smooth temperature gradient to the area of cathode and anode equal to about 5°/mm is related to several design distinctions of the lamp:

1. There is a significant gap between the electrodes and the inner surface of the sapphire tube (3.5 mm for the anode and 6 mm for the cathode) along the whole length of the electrodes;
2. The electrodes are fixed to metal current inputs with high thermal conductivity, which provides reliable removal of heat from their operating surface (Fig. 6);
3. Thermal conductivity of sapphire is fifteen times higher than that of quartz (30 W/(m ∙°C) as compared to 1.7 W/(m ∙°C)) at a temperature of 100 °C and is three times higher at a temperature of 1000 °C [12].

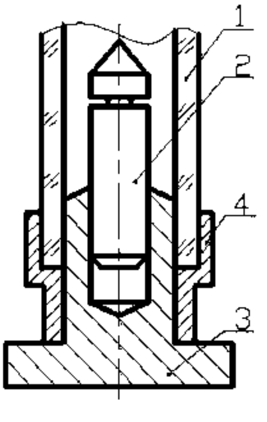


Fig. 6. Design of the cathode unit of the SPKs-500 lamp.
1 – discharge tube; 2 – cathode; 3 – holder (cap);
4 – cover cap

It is worth noting that using of forced cooling through conical confusor by means of a directed airflow from the anode allows keeping thermal distribution along the surface of the bulb in the form similar to that shown in Fig. 5. The temperature gradient practically remains the same in case of increase of electric power of the designed lamp up to 500 W. Another position of the lamp, e.g. at an angle of 45° to the horizontal plane, insignificantly shifts the maximum temperature of the heated envelope surface to the electrode located above. In this case, the temperatures of the envelope surface are located between the curves 1 and 2 in Fig. 5.

An important distinction of the considered design is its high manufacturability. It is known that the cathode spot of a UHP discharge lamp should be located in the focus of the reflector of the spotlight system. It is reached by fixation of the cathode pin in relation to the base surface of the lamp cap. In the case of UHP xenon lamps with quartz ball bulbs, adjustment of the cathode is conducted during the final operation of the cap connection by means of complex devices and sealing compounds. In the proposed design (Fig. 6), installation of the electrode pin in relation to the butt (base) part of the cap is conducted during assembling of the cathode 2 with holder 3. Then the assembled electrode unit is hermetically connected to the sapphire envelope 1, which was soldered with kovar caps 4 in advance.

In the proposed design, for sealing of the connection of the cap 4 with the sapphire 1, the soldering technology with copper solder on the titanium coating applied by means of vacuum-arc method is used. For detail information of this technology, see [13].

The lifetime of the designed lamp was more than 200 hours. The quality criterion of the lamp was the decrease of luminous flux intensity by 30 %. During the whole testing period, the lamp provided stable operation, and reduction of its light parameters is related to electrode sputtering. Depositing of a film of the cathode material on the inner surface of the envelope insignificantly increases the bulb temperature in conditions of forced cooling of its surface.

7. CONCLUSION

This article describes the major results of the development of the first Russian sample of a UHP xenon discharge lamp with sapphire envelope. The article describes the method of designing of such class of discharge lamps including subsequent solving of the following problems:

1. Studying method development of thermal fields of semi-transparent materials and studying of the thermal profile of mass-manufactured UHP lamps in order to determine the requirements to sapphire envelope;
2. Studying of mechanical strength of sapphire tubes depending on temperature and calculation of the wall thickness of the discharge envelope;
3. Studying of the temperature condition of the sapphire bulb and development of the design of a UHP xenon lamp with a sapphire envelope.

The proposed methods of research aiming at designing of UHP discharge lamps with sapphire envelope will be useful for developers of discharge equipment with the use of new prospective materials, e.g. different types of transparent oxide ceramics [14]. After studying mechanical strength of ceramics depending on temperature, issues of optical transparency increasing, and obtainment of reliable connections with the metal current input, new materials of envelopes may be successfully used instead of sapphire in discharge lamps.

The author expresses gratitude to the colleagues Loginov V.V., Puchnina S.V., and Kondratiev A.N. for assistance provided in the course of the study, development of the design, and technology of manufacturing of a new class of Russian UHP discharge lamps.

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