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INVESTIGATION OF THE DISCHARGE BREAKDOWN VOLTAGE IN COMPACT ARC TUBES

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Actuality. The high pressure sodium lamps (HPSL) are one of the most effective sources of light, but they have problems with starting. There is a trend to introduce more compact arc tubes in design of the low wattage HPSL. Theoretical and experimental study of the effect of geometry of the arc tube and its fill on the discharge breakdown voltage was the purpose of ours investigations.

Method of calculation of the discharge ignition voltage. A necessary condition for a high intensity lamp to be ignited is breakdown, which resulted in formation of a conductive channel in the discharge gap. The magnitude of the breakdown voltage then constitutes the main portion of the starting voltage. Therefore we assumed the self-sustaining discharge ignition voltage as the breakdown voltage (U_B). Such a definition both determines the location of the breakdown voltage on the volt-amper discharge characteristics, and satisfies the breakdown condition based on the formula of the gas avalanche. The analytical criterion of the existence of the self-sustaining discharge is known [1]:

$$\gamma\left[\exp\left(\int_0^l \alpha dl\right)-1\right]\geq 1, \qquad (1)$$

where α - is the coefficient of volume ionization; γ - is the coefficient of the secondary emission; - is the length of the avalanche trajectory.

In order to estimate the error of ours results, we combined theoretical and experimental methods. At the beginning of study we modeled the pre-breakdown fields (PBF) in the arc tubes of HPSL by Monte Carlo method [2]. First we obtained the arc gaps, which would correspond to the conventional arc tubes of our previous experimental studies [3].

The main goals of our study of the pre-breakdown fields were: 1) to find the zones with the strongest electrical field; 2) to estimate preliminarily a possibility of the breakdown between electrodes; 3) to choose the electrode shape, which would maximize the breakdown probability. The analysis of the found curves of PBF and the distribution of the field strength (E) results in the following conclusions.

The tip extension effect is more important than the effect of the backspace. The difference is more pronounced along the trajectories with the larger radial component of the field strength. The complete electrode model with the tip and the backspace is necessary not only for better accuracy of estimation of the ion amplification, but also for the determination of the breakdown location. The importance of the tip inclusion was indirectly confirmed by the experimental study [3, 4], which demonstrated the appearance of a weak glowing in the tip region right before the ignition.

It is known that during breakdown it is important in what area an initial electron has been formed and along what trajectory an avalanche will propagate. After analyze of PBF we excluded regions with the worst conditions for the avalanche development and chose the zones most favorable for ionization. In order to elucidate the behavior of PBF, the modeling of the potential distribution for the conventional HPSL electrode gaps was conducted [4] for the range of distances between electrodes from 1.8 cm to 9 cm.

For the burners with $l =$ 1.8 cm and $d =$ 6.8 mm all force lines in the electrode rod area are inside the arc gap and do not come to the wall. This confirms the opinion in reference [5] that in the short lamps the breakdown occurs between the electrodes and the effect of the wall can be neglected. With the increase of the distance between electrodes, the region of the trajectories from the rod widens and begins to approach the wall. The breakdown in the burners with $l \geq$ 7 cm occurs only to the wall. In the burners with $1.8 < l < 7$ cm the mechanism is probably mixed: some of the avalanches are developed between electrodes and some come to the wall. As expected, in the arc tubes with smaller diameters the breakdown between electrodes is somewhat difficult. Similar relationships should also be expected in the arc tubes with other electrode dimensions.

The analytical approximations of experimental curves $\alpha/p = f(E/p)$ for Ne, Ar, Kr, Xe, Ne+0.1%Ar and Ne+1%Ar gasesused in our calculations resulted in the maximal relative error of 2 to 12% in the range of E/p values for the given values of the arc gap. For the condition of the self sustaining discharge (1) we used the effective coefficient α', which takes into account the charge attenuation due to diffusion:

$$\alpha' = \alpha - \left(\frac{D_e}{W_e} + \frac{D_i}{W_i}\right)\left(\frac{2.405}{r_o}\right)^2 \qquad (2)$$

where D_e, D_i are the diffusion coefficients for electrons and ions; W_e, W_i are the drift velocities of electrons and ions; r_o is the arc tube radius.

In our calculations we took into account only the lateral diffusion of electrons, since in the considered range of E, p and d values the longitudinal diffusion is at least half that of the lateral one, which depends on the radial component of the field strength, the pressure, and the kind of gas. While calculating the diffusion losses, the radial component of the field strength was determined from the known distribution of $E = f(l)$, then the ratio of D_e/W_e was estimated. We neglected the term D_i/W_i in formula (2), since the ratio D_e/W_e is roughly an order of magnitude larger than the ratio D_i/W_i.

Because of lack of data, we assumed D_e for Xe to be constant for the whole range of E/p. Since the coefficient γ of real electrode is not constant over the surface, we also estimated the response of U_B to the variation of γ in the known range. The influence of the change in γ is the weaker the smaller is the value of the coefficient. Therefore, the accuracy of calculations of U_B in xenon is higher than in argon and neon.

Analysis of results. The comparative analysis of $U_B(l)$ functions for different gases and for the range of diameters show the existence of two sections: corresponding to the functions increasing with l, and almost flat one. This agrees with the known function $U_B(l)$ for xenon at $d = 7.7$ mm [6]. Those two sections are very pronounced in heavy gases Xe and Kr, while the curves are almost linear in Ne and in Penning mixtures. With the decrease of the arc tube diameter, the increasing sections become more flat (the effect of diffusion increases and the probability of breakdown between electrodes decreases).

The curves $U_B = f(l)$ for Ne-Ar mixtures deserve a special attention, since there is an experimental curve for the same range of le value, but with slightly different gas mixture components: Ne+0.7%Ar [3]. Figure 1 shows a good agreement between the calculated and the experimental curves $U_B = f(l)$. The results confirm that our model used to estimate of the breakdown voltage makes sense.

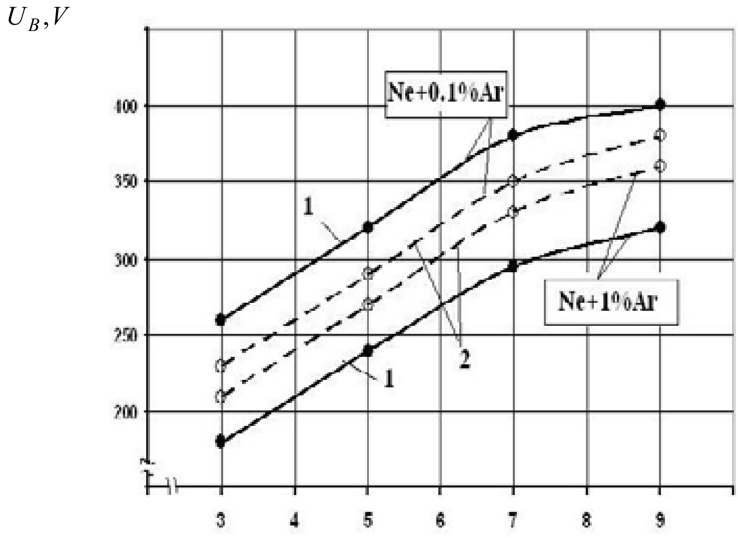

Fig.1. The comparison of calculated (1) and experimental (2) $U_B = f(l)$ for arc tubes with d = 6.8 mm.

The analysis of the functions $U_B = f(l,d,p)$ enabled us to point out the following. Even for the shortest arc tubes with $l = 1.8$ cm and $d = 6.8$ mm and the usual xenon pressure of 20 mm Hg, the problem of starting has not been solved: the values of U_B are 550-600 volts. Extrapolation of $U_B = f(l)$ up to l = 1.0 cm (for d = 6.8 mm) results in U_B of about 400-430 V. With the decrease of d to 4.8 mm, the starting voltage improves by

25-30% for $l \leq$ 3.0 cm and by 10-15% for $l \geq$ 5.0 cm. The decrease of the xenon pressure down to 10 mm Hg does not provide reliable starting at the commercial net voltage for the described arc tube configurations. According to our calculations, the lowest U_B =320-350 V is to be observed for the arc tube with 150W electrodes, $l =$ 1.0 cm, $d \geq 6.8$ mm. The igniters with pulse voltages up to 1800 V provide reliable starting for a wider variation of burner fill and geometry. For all arc tube configurations with $l \leq 5.0$ cm, p of xenon can be increased up to 80 mm Hg. Comparison of the calculated results for electrodes of different sizes shows, that for short arc tubes, larger electrodes are less beneficial for better starting.

According to [6], lamps with krypton fill have only slightly lower efficacy than xenon filled lamps, but they have significantly lower U_B . We analyzed the effect of l and p on U_B in krypton. The results shows, that arc tubes with $l =$ 1-1.5 cm, compact electrodes and $p =$ 10 mm Hg can start from a commercial line voltage. The increase of krypton pressure to 20 mm Hg can provide reliable starting of burners with $l \leq$ 7.0 cm if a glow discharge starter is used. For burners with $l \leq$ 4.0 cm the pressure of krypton can be increased up to 50 mm Hg.

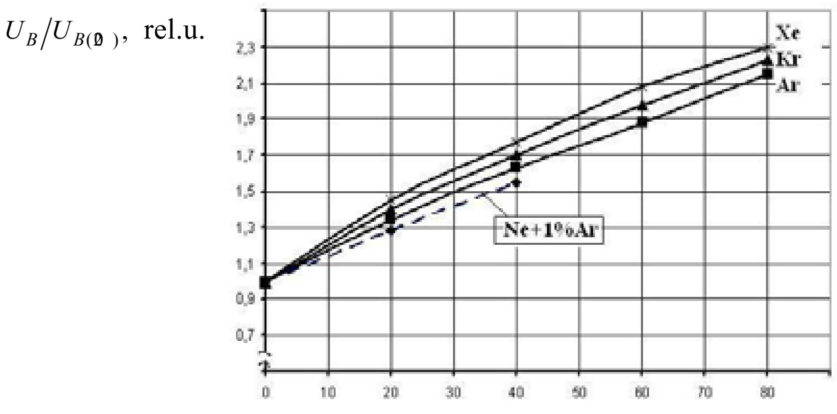

Fig.2. The relative change in the breakdown voltage versus pressure of various fill gases.

Similar calculations of $U_B = f(l, d, p)$ were performed for argon fill. The results show insignificant advantages of Ar in comparison with Xe for starting burners with $l \leq$ 1.5 cm from line voltage. Moreover, the lamp efficacy with Ar fill is lower than with Kr fill. Therefore, using Ar fill is not a promising method of achieving easier starting of the HPSL.

Figure 2 shows the relative change in the breakdown voltage $U_B/U_{B(0)}$ versus pressure change from 20 to 100 mm Hg for Xe, Kr and Ar. Also, the experimental curve for starting voltages $U_S/U_{S(0)}$ is shown for the mixture of Ne+1%Ar taken from data of reference [7]. On can see that the relative changes of the starting voltage increase in the sequence corresponding to Ne+1%Ar, Ar, Kr, Xe. At higher pressures, the ratio $U_B/U_{B(0)}$ increases.

In order to assess the effectiveness of a starting aid in the form of a metal ring on the outer surface of an arc tube we calculated the breakdown voltage between an electrode and the ring for argon, krypton and xenon at $p = 20$ mm Hg. Our modeling shows that U_B decreases by 25-30% when the ring is located where it is the most effective [3].

Conclusions and recommendations. Since HPSL igniters generate starting pulses as high as 4.5 kV to 6.0 kV, it is possible to increase xenon fill pressure. For example, if the electrode gap is decreased from 8.0 cm to 2.0 cm, the pressure of Xe can be increased from 20 to 80 mm Hg for the same U_B. For burners with small diameters the chances of increasing p are worse.

Using krypton fill instead of xenon will result in 30-40% decrease in U_B depending on given l, p and d. Since Xe and Kr filled compact lamps with larger diameters do not start reliably from the line voltage, it is worth discussing HPSL designs with indirect heating of the burner's cold area.

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