Axial Magnetic Field Effects on Xenon Short-Arc Lamps

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Axial Magnetic Field Effects on Xenon Short-Arc Lamps*

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Abstract The effect of an axial magnetic field (AMF) on an old xenon short-arc lamp is experimentally investigated in this work. As the AMF increases up to 18 mT, the visible radiation power and electric power ascend more than 80% and 70% respectively, and the radiation efficiency is improved by 23% for the best increment at 12 mT AMF. The measurement of radiation intensity shows that the increment of radiation intensity comes mostly from the plasma area close to the cathode tip, and partially from the other area of the arc column. Successive images of the arc indicate that the arc column not only rotates about its axis, but revolves around the axis of electrodes with the AMF. The arc column structure is constricted, distorted and elongated as the AMF increases. It is suggested that the improvements of the radiation intensity and radiation efficiency are attributed to the constriction of the arc column, which is mainly induced by the enhanced cathode jet.

Keywords: xenon lamp, axial magnetic field (AMF), radiation intensity, cathode jet

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(Some figures may appear in colour only in the online journal)

1 Introduction

Compared with conventional filament lamps, short-arc discharge lamps feature better efficiency and higher luminance. They are widely used in film and video projection systems, solar simulators and high-temperature chemical reactors [1−6]. However, a long time usage usually causes a degradation in the performance of the electron emission, erosion of the electrodes and depressed gas pressure in the bulb, which reduces the output power greatly [7]. To improve the lamp performance, the application of a magnetic field to the lamp was investigated. Randall et al. [8] reported that the plasma geometry was distorted by applying a small transverse magnetic field (3 G), and the intensity values of lamp output were increased by as much as 127%. Unfortunately, the arc anodic attachments are always strongly constricted and located in a fixed position, which prematurely aged the lamp electrodes. Applying an external axial magnetic field (AMF) to the arc lamp to increase its radiation intensity has been reported in some literatures [9,10], but no detailed evaluations are available. The enhanced output power has usually been ascribed to the volumetric compression effect of the magnetic field on the arc plasma [10]. This mechanism has been confirmed in a vacuum and low pressure arc plasma [11,12], but no significant effect at high pressure has been found [13].

In this paper, we present an evaluation of an old xenon short-arc lamp performance with an AMF. The spectral characteristics, radiation power, electric power and radiation efficiency with an applied AMF ranging from 0 mT to 18 mT are studied. In addition, successive images of the evolution of arc plasma are captured by a high-speed CCD camera. The influence and mechanism of the AMF on xenon lamps are presented and discussed in detail.

2 Experimental setup

Fig. 1 shows a schematic diagram of the experimental setup. A 1500 W power supply operating at 30 A constant current is used to power the 1000 W xenon short arc lamp. The gap between the electrodes of the lamp is 6 mm and the internal gas pressure is 6 atm. The lamp, which has been used for more than 500 hours, is employed to test the effects of axial magnetic field on the old lamp. A magnetic coil with a 0.1 m diameter is placed outside the bulb at a height approximately 5 mm from the cathode tip. An adjustable DC power is used to support the coil, which provides a magnetic field at the arc area ranging from 0 mT to 100 mT. Actual measurements show that the flux lines are almost parallel to the axis of electrodes, and the AMF difference is less than 5% within the gap. The

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arc plasma configuration is captured by a high-speed CCD camera, and its radiation spectral characteristics are recorded by a spectrograph. All measurements are operated after altering the magnetic field for 10 minutes to ensure the stability of the output.

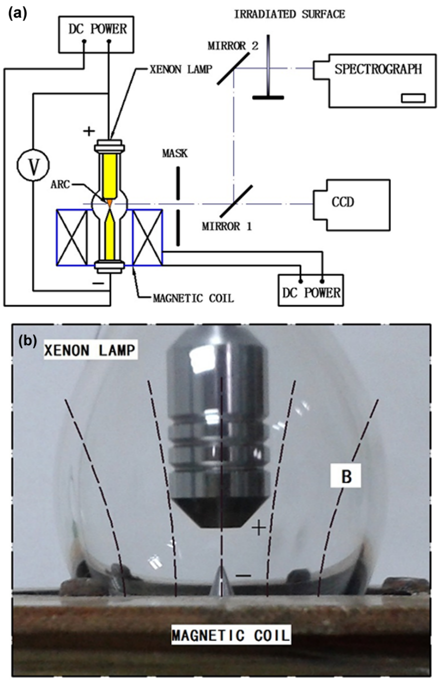

Fig.1 (a) Schematic diagram of the experimental setup, (b) Xenon lamp and distribution of flux lines

3 Results and discussion

3.1 Radiation intensity variation by the AMF

Fig. 2 shows the 350-800 nm wavelength visible light range of the lamp spectra with and without AMF. The results illustrate that the AMF would enhance the visible spectrum intensity of the lamp. Integration of the area under 350-800 nm spectra indicates that the radiation power grows by as much as 60% with a magnetic field of up to 10 mT.

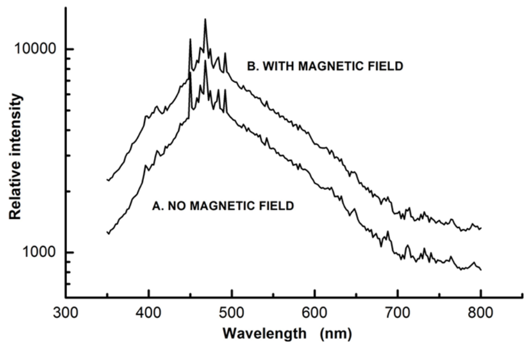

Fig.2 Relative intensity of visible spectrogram of xenon short arc lamp (A) without and (B) with 10 mT AMF

Fig. 3 shows increments of relative intensity (integration from 350-800 nm), arc power (voltage) and visible spectrum radiation efficiency of the lamp with AMF ranging from 0 mT to 18 mT for 30 A constant currents. It is shown that both the visible spectrum radiation intensity (R) and arc power (P) monotonously rise as AMF increases. The increasing rate of the radiation intensity is amazingly up to 80% at 18 mT, meanwhile the arc power is up to 73%.

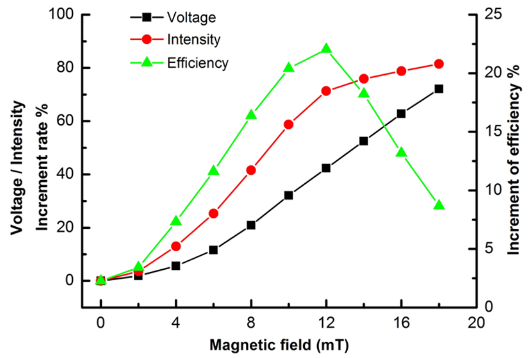

Fig.3 Increasing rates of radiation power, electric power and radiation efficiency vs. magnetic field

It is also found from Fig. 3 that the increasing rate of the radiation intensity is greater than that of the arc power. This means that the irradiation efficiency of the lamp increases with the AMF. Defining the increasing rate of radiation efficiency as:

$$\Delta\eta/\eta_0 = (R/P - R_0/P_0)/(R_0/P_0). \tag{1}$$

In the formula, $\Delta\eta$ is increment of radiation efficiency, and η_0 represents the radiation efficiency without AMF. Then:

$$\begin{aligned}\Delta\eta/\eta_0 &= (R/P - R_0/P_0)P_0P/(R_0P)\\ &= (P_0R - R_0P)/(R_0P)\\ &= (P_0/P)[(R/R_0) - (P/P_0)]\\ &= (P_0/P)[(R/R_0 - 1) - (P/P_0 - 1)]\\ &= (P_0/P)[(R - R_0)/R_0 - (P - P_0)/P_0]. \end{aligned} \tag{2}$$

In the last-written formula, $(R - R_0)/R_0$ and $(P - P_0)/P_0$ are the increasing rates of the visible radiation and the arc power, respectively. It is shown that the increasing rate of the radiation efficiency ascends as the AMF increase from 0 mT to 12 mT and descends for AMF from 12 mT to 18 mT, maintaining a positive value with AMF throughout the whole test, and the maximum increasing rate of the efficiency is 23% at 12 mT.

The experiment results reveal that the radiation intensity and radiation efficiency of the lamp are enhanced by AMF, which is very promising from a practical perspective.

Fig. 4 shows the arc radiance along its axis recorded by a high-speed CCD camera (exposure time of 1 μs). The radiation intensity along the overall axis apparently grows with the AMF, while most radiation of the arc still comes from the area close to the cathode tip, which should result in increments of the radiation power and the radiation efficiency of the lamp. A similar phenomenon was reported in welding arcs with imposed AMF [14−17]. A numerical simulation study in Ref. [17] indicated that the AMF makes the arc column rotate to accelerate plasma flowing, which boosts the shrinkage of the cathode spot. Consequently, the enhanced cathode jet induced by the shrinkage of the arc cathode spot increases plasma temperature near the cathode tip, and this high temperature zone expands towards the anode simultaneously.

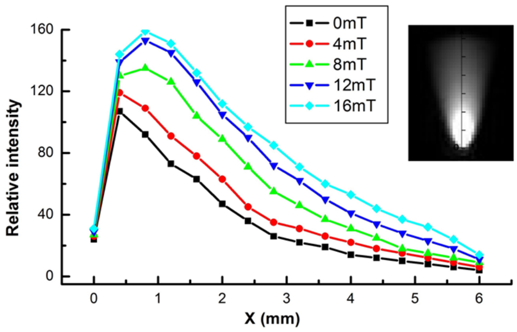

Fig.4 Radiance distribution within the arc vs. magnetic field

Moreover, it does not need too much AMF (about 10 mT in Ref. [17]) to satisfy the requests to enhance the cathode jet. That is further proven by the facts shown in Fig. 4: with an increase of AMF, the position of peak intensity shifts and the higher intensity area expands towards the anode. However, there is a different anode configuration between the welding arc and xenon short-arc lamp: the former is a plate, and the latter is a rod with a chamfer. Being baffled by the anode plate, the axially flowing plasma of the welding arc column turns centrifugal flowing toward the anode, which makes the arc column near the anode radially expand to be larger than that in xenon arc lamp, whose rod anode has a smaller area. With AMF, the increased radial current component from the radial expansion of the arc column further enhanced the rotation of arc column, so that a hollow formed near the anode when the AMF was greater than 10 mT [15−17]. In the xenon arc lamp, the rod anode, which is only six millimetres in diameter, greatly restricts the radial expansion of the arc near the anode, so the increment of rotating speed with AMF is lower than that in the welding arc. As a result, it is unlikely to form a hollow like in the welding arc, and the arc radiation intensity of the xenon arc lamp always increases along its overall axis as AMF increases from 0 mT to 160 mT.

3.2 Arc column revolving and its instability

Because the arc column axis always has a tiny departure from the imposed magnetic field line, the arc column not only rotates about its own axis, but also revolves around the axis of electrodes. Fig. 5 gives successive images of the arc for different AMFs. Without an AMF the arc presents a stable conical configuration, and its axis is approximately coincident with those of the electrodes. With an AMF, the arc column obviously deviates from the electrodes' axes, and revolves around the axes with a fixed root at the cathode tip and a movable root on the anode. As shown in Fig. 5, the deviation increases as AMF increases, and the arc column shows curve structure. Fig. 6 presents revolving speed of the arc column vs. the AMF, which is highly similar to the increasing rate of radiation intensity with AMF shown in Fig. 2. So we infer that the arc column revolving around the electrodes' axes is another factor in the ascending of its radiation intensity. Like accelerated plasma flowing induced by arc column rotating about its own axis, arc column revolving around the axes of electrodes also enhances plasma flowing away from the cathode, so that the cathode jet is enhanced, which would result in an increase of plasma intensity, especially near the cathode tip. Besides, the revolving of the arc column makes the arc column cool down, which limits the column's transverse expansion, so that the current density in the column increases, which would boost the radiation intensity and its efficiency. The elongated arc column also enhances its electric power and radiation power, as well as its radiation efficiency. With a fixed root on the cathode, the arc column is close to the cathode, from which most increments of the radiation power come, and revolves in a narrow region around the electrodes' axes. So the cooling effect and elongated arc column are not main factors of radiation power enhancement.

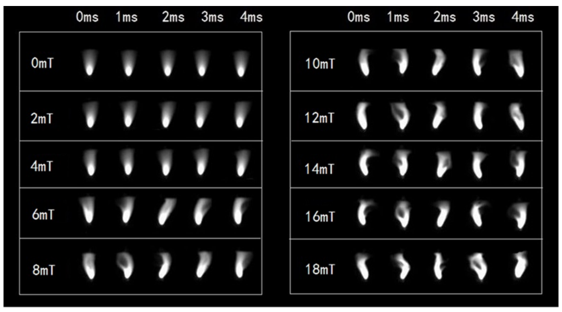

Fig.5 Evolution of the arc vs. magnetic field (CCD, exposure time of 1 μs, 1000 frames per second)

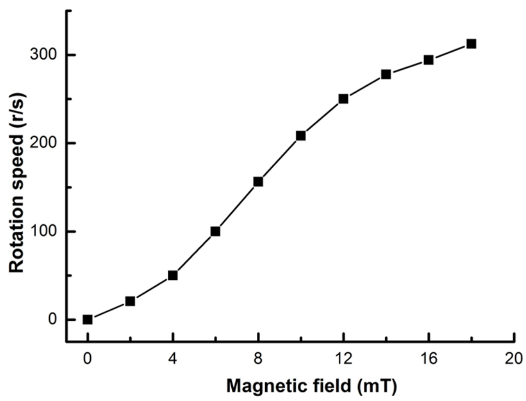

Fig.6 Revolving speed of the arc vs. magnetic field

When the field exceeds 8 mT, the arc column near the anode appears unstable, with frequent occurrence of re-strike between the arc column and the anode, which would cause major fluctuation of the radiation intensity of the lamp.

The fluctuation of the radiation intensity is described by the following formula:

$$\delta = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \times 100\%, \tag{3}$$

where $E_{\max}$ and $E_{\min}$ are respectively the maximum and the minimum irradiance at the irradiated surface. The variation obtained by a spectrograph over a 20 min period is presented in Fig. 7. Because the segment of the column near the anode does not contribute much output power compared to the segment of the column near the cathode tip, the fluctuation is not too much: from 1.7% without AMF to 2.3% at 8 mT, 3% at 12 mT, and up to 5% at 16 mT. Afterwards, the instability enhances further. When the field is over 20 mT, the lamp extinguishes frequently.

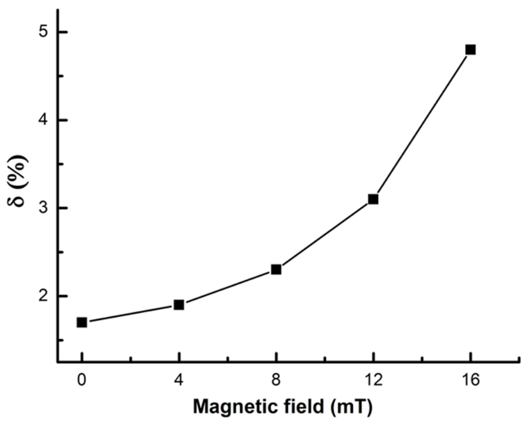

Fig.7 The output instability vs. magnetic field (integration time: 10 ms)

4 Conclusion

The AMF effects on a 1000 W (30 A) universal xenon short-arc lamp (used for 500 h) are investigated under an AMF ranging from 0-240 mT. It is concluded that:

a. The AMF can effectively improve its visible radiation power and radiation efficiency. The best increment of radiation efficiency is 23% at 12 mT, meanwhile the radiation power and arc power increase respectively by 70% and 43%.

b. The increment of radiation intensity and its efficiency mostly comes from the plasma area close to the cathode tip, and partially from the other area of the arc column.

c. The AMF makes the arc column not only rotate about its own axis, but also revolve around the axes of electrodes. Both induce plasmas to flow away from the cathode, so as to enhance the cathode jet, which makes the most contribution to the enhancement of radiation power and its efficiency.

d. Arc column revolving around the axis of electrodes would induce instability of the arc column with a 3% radiation power fluctuation when the AMF is 12 mT, while the basic fluctuation without an AMF is 1.3%. The extinguishment occurs continually when the magnetic field exceeds 20 mT.

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