A Review on Fluorescent Lamps Having Noncircular Cross-sections

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Abstract
We review discharge characteristics of fluorescent lamps having noncircular cross-sections. The developmental and theoretical history of noncircular cross-section lamps is summarized chronologically. In particular, discharge characteristics of noncircular cross-section lamps will be summarized and analyzed including plasma contraction, electron temperature, and ambipolar diffusion loss, which might give us some insights into the way to develop more efficient and uniform flat fluorescent lamps, which have recently arisen as a new light source of large-size backlight units for LCD TV applications.

1. Introduction

Backlight unit(BLU) has become one of the key components of liquid crystal display(LCD) that could innovate the technology of large-size LCDs. New light sources such as flat fluorescent lamps(FFL)[1-3], light-emitting diodes(LED)[4] and field-emission based lamps[5] have been suggested and under development for LCD BLU. Among them, FFL has attracted much attention owing to its possibility of higher efficiency and better uniformity than conventional tubular cold-cathode fluorescent lamps(CCFL). Moreover, it is expected that FFL will innovate and simplify manufacturing processes of BLU and LCD panel, which might be a very favorable condition for cost reduction of large-size LCDs. Accordingly, many companies have been trying to develop efficient FFLs and FFL-BLU for successful commercialization up to the present.

An ideal FFL, which may be constructed from a parallelepiped discharge space, can not be realized except small sizes for automobile applications, because the discharge space cannot withstand the force arising from the pressure difference between inner and outer spaces of the lamps without any supporters. Therefore, multi-channel structures have usually been suggested and adopted for mercury(Hg)-type FFLs[1-2] while point supporters have been used in some of xenon(Xe)-type FFLs[3]. In the former case, the cross-section of each channel is different from circle, a typical cross-section of the conventional tubular fluorescent lamps. It will thus be very important to analyze the discharge phenomena imposed by the boundary condition of the noncircular cross-sections. However, there are only few reports on discharge characteristics of noncircular cross-section fluorescent lamps (abbreviated as NCFLs).

The present contribution aims at reviewing and summarizing discharge characteristics of fluorescent lamps having noncircular cross-sections. In particular, the positive column in the discharge structure will mainly be discussed. The discharge phenomena near electrodes will not be mentioned in this review. It might give us some insights into how we can understand discharge characteristics of multi-channel FFLs, which are at the moment of paramount importance for the development of new BLU technology for large-size LCDs.

2. History of Fluorescent Lamps Having Noncircular Cross-sections

2.1 Before 1970s

Originally, NCFLs appeared as a candidate for higher-wattage lamps than the conventional tubular fluorescent lamps[6]. Lamps having U-shaped cross-section were commercialized in 1950s[7-8]. The main reason for adopting noncircular cross-sections was to increase the electron temperature in the discharge. As is well known, driving fluorescent lamps at higher currents results in a saturated UV output and a lower efficiency owing to increasing quenching collisions between slow electrons and excited atoms and decreasing electron temperature. One way to compensate for this loss in efficiency of high-load lamps was to increase the ambipolar diffusion loss for obtaining higher electron temperature, which may be induced by noncircular cross-sections. For example, if the circular cross-section is changed into a rectangular cross-section with the same cross-sectional area, the total diffusion loss rate of the rectangular cross-section is about 1.9 times larger than that of the circular cross-section[6]. This concept was adopted in the “Power Groove” lamps by General Electric Co., where the rectangular cross-section was bent into a U-shaped cross-section[7], resulting in a higher efficiency than tubular lamps at the same discharge length and power consumption.

The concept of FFL having a noncircular serpentine channel structure first appeared in 1946[9]. This structure has been improved into other structures, and the first experimental 'square' lamp appeared in 1959 for the purpose of general lighting by General Electric Co.

Along with experimental and commertial efforts on NCFLs and FFLs, theoretical interests in the discharge phenomena of NCFSs appeared. In the early stages of lighting industry, it had been a common knowledge among lighting engineers that a low-pressure discharge does not tend to fill a noncircular tube depending on the aspect ratio. Cayless developed a theory of d.c. low-pressure metal-vapor rare-gas discharges in tubes of noncircular cross-section for the cases of one-stage and two-stage ionization processes[10]. He found that when the aspect ratio of the rectangular cross-section is greater than about 3:1 multi-stage ionization prevents the discharge from occupying the discharge space resulting in "constriction".

2.2 1970-1990s

Theoretical and experimental studies on discharge phenomena in noncircular tubes had continued in this period, but no clear relationship between the condition of positive column having noncircular cross-sections and ionization processes has been revealed. Papers on NCFLs were based on Schottky's original ambipolar diffusion theory with single-stage ionization[11-13], and thus it was difficult to discuss the plasma contraction phenomena in rectangular positive column. Kaneda *et al.* measured the plasma parameters of the Ne positive column in a rectangular tube and found that the plasma density exhibited a slight bell-shaped profile that is different from the prediction of the Schottky's diffusion theory, but no clear explanation was given to this discrepancy.

One report in 1991[14] showed that the condition of the positive column in a discharge space having a rectangular cross-section is sensitive to the kind of ionization process and dimensions of the cross-section. If the one-stage ionization dominates the discharge process, the positive column will fill the discharge without any contraction, while it will be contracted if the ionization process is mainly two-stage and if the horizontal length of the rectangular cross-section is larger than the vertical length by more than three times. In the latter case, the diffusion loss, that will control the electron temperature of the positive column, will occur through only two surfaces separated by a shorter distance.

2.3 After 1990s

From 1990s, as the LCD industry grew and the size of display became larger, intense efforts on the development of FFL for LCD BLU began. The first version of FFL in this period was a serpentine-type FFL, where internal electrodes were inserted into both ends of the serpentine channels[15]. There is an advantage of this electrode configuration for the serpentine structure that the positive column becomes very long, which is a favorable condition for obtaining higher light-generating efficiency. However, the ignition voltage also increases rapidly, becoming more severe as the size of FFL increases. In addition, the existence of dark regions between channels needs a diffuser over the FFL. Several experimental FFLs without any supporter between upper and lower glass plates have been realized, but only in small-sizes below about 10". For larger sizes, multi-channel structure had to be adopted for supporting the stable discharge space between upper and lower glass plates. Both Hg-type[16-19] and Xe-type[20-24] FFLs have been demonstrated. Several kinds of electrode structures have been tried such as internal hot cathode, cold cathode, hollow cathode, and external electrodes. The uniformities of constructed FFLs were in general superior to tubular CCFLs, but Xe-type FFLs suffered from their low light-generating efficiency.

Recent technological efforts have been put into the development of large-size FFLs more than 30" as the main product of LCD industry is moving towards TV applications. Both Hg-type[25] and Xe-type[3] FFLs upto 32" have been developed and the size of Hg-type FFL has recently been extended up to 40"[2]. Since cost reduction of BLU for LCD TV applications has become one of the most important factors for successful commercialization of LCD TV, it is of paramount importance to develop highly-efficient FFL for removing expensive optical sheets in BLU. For this, it is necessary to look into the discharge phenomena in the positive column of low-pressure noncircular fluorescent tubes.

3. Discharge Characteristics of NCFLs

As is well known, fluorescent lamps convert ultraviolet(UV) light, which is generated from excited atoms in the discharge, into visible light via phosphor materials. The theoretical descriptions of positive column in a circular cross-section have already been established in detail[6,26], and the plasma density profile along the radial direction is well described by the Bessel function of the 0^{th} order.

As is mentioned above, previous theoretical studies[10,14] revealed a close correlation between the ionization process and plasma contraction of the positive column when the aspect ratio of the rectangular cross-section is greater than 3:1. That is, if one-stage ionization dominates the discharge process, the positive column will fill the discharge without any contraction irrespective of the aspect ratio, whereas the positive column will be contracted if the ionization process is mainly two-stage. The diffusion loss will occur through four surfaces and two surfaces in the former and latter cases, respectively.

As is well known, multi-stage ionization process is a dominant mechanism occurring in the positive column of low-pressure metal-rare gas discharges[27]. Under this condition, consideration of diffusion equations which describe the behaviors of electrons, ions and excited atoms in the positive column enables us to solve numerically the density profile along horizontal(longer) and vertical(shorter) directions of rectangular cross-section[14]. The horizontal variation in electron density is much more rapid than the sinusoidal variation along the vertical direction if the aspect ratio is greater than 3:1. Since ambipolar diffusion losses are linear in electron density, multi-stage ionization processes cannot balance diffusion losses in the outer regions of the rectangular tube. If the aspect ratio is less than 3:1, the electron density shows a sinusoidal variation along both directions. Experiments on hot-cathode neon and mercury-argon d.c. discharges exhibited bell-shaped electron density along the horizontal direction[13-14]. However, it should be reminded that the relationship between the contraction phenomena in noncircular cross-section and other discharge conditions such as gas pressure, discharge current, the kind of rare gas and electrode-type is to be revealed clearly in further studies.

4. Summary

From the above review, it can be clarified that:

(1) the electron temperature in the discharge can be controlled and optimized by confining the discharge in noncircular cross-section and thus controlling the ambipolar diffusion loss;

(2) the spreading condition of the positive column in the fluorescent lamps having rectangular cross-section is very sensitive to both the ionization process and aspect ratio of the cross-section;

(3) the relationship between the contraction phenomena in noncircular cross-section and other discharge conditions such as gas pressure, discharge current, the kind of rare gas and electrode-type should be revealed more clearly.

Theoretical and experimental results about NCFLs should be scrutinized and used for the design and optimization of FFL for LCD TV applications. In addition, it is required to investigate the density distribution of the ions, electrons, and excited atoms in the noncircular discharge space, since the degree of phosphor deterioration is closely related to the density or distribution of ultraviolet radiation generated from the noncircular positive column in addition to the wall-load.

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6. References

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