Paper

A Novel Cold Cathode Fluorescent Lamp with an Adiabatic Layer

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ABSTRACT

A novel cold cathode fluorescent lamp (CCFL) with an adiabatic layer suitable for backlighting in PDAs (Personal Data Assistants) is described. The adiabatic layer ($100\text{--}200\ \mu\text{m}$) is formed between a light tube and an outer tube and is filled with low-pressure gases. This raises the temperature of the light tube to the suitable value ($50\text{--}70^\circ\text{C}$), which maximizes luminous efficacy even in low lamp wattage operation and at low ambient temperatures. The results of experiments and heat transfer analyses show that the optimum pressure in an adiabatic layer lies between 1Pa and 10Pa. At a pressure of less than 1Pa, the lamp temperature maintains a constant level because the conduction loss is lower than the radiation loss.

KEYWORDS: cold cathode, fluorescent lamp, heat transfer, free-molecule flow

1. Introduction

A cold cathode fluorescent lamp radiates visible rays that are converted by phosphors from ultra-violet rays (mainly 254nm) radiated by mercury, and the lamp has been used primarily for backlighting liquid crystal displays. In recent years, progress has been made in the development of thinner tubes and lower power consumption.

So far, there has been a report¹⁾ on a discharge instability problem with thin tubes and reports²⁾ of an improvement in cathode loss, which accounts for 30% to 40% of the power consumption. Also, a reduction in luminous efficacy due to lamp temperature accompanying lower power consumption has been an issue to be solved³⁾.

The luminous efficacy of the cold cathode fluorescent lamp depends upon the vapor pressure of the mercury enclosed inside the lamp, and this varies in parallel with the temperature of the coldest part of the lamp. The temperature of the coldest part is about 40°C ⁴⁾ in fluorescent lamps for general illumination, while the appropriate temperature in the cold cathode fluorescent lamps is in the vicinity of 70°C ⁵⁾. The efficacy reduction with low temperatures is especially remarkable; the efficacy at 0°C is less than 10% of the peak level. In general, more than 80% of the input power for the cold cathode lamp is dissipated as heat⁶⁾, and the heat generation has a role in maintaining the mercury vapor pressure at an appropriate level by increasing the lamp temperature.

In regard to methods of optimizing lamp temperature, there is a report of increasing the efficacy in the low electric current zone by making the thickness of the glass tube thin³⁾ and a report of a lamp in which the ultra-violet radiation of rare gases that are not dependent on temperature is used⁶⁾. Also, a technology has been put into practical use in mercury lamps and low pressure sodium lamps in which the temperature of the light tube is increased by making a space between the light tube and the outer tube a high vacuum⁴⁾.

The authors have been developing the cold cathode fluorescent lamps with low power consumption and high efficacy by employing an adiabatic layer technology⁷⁾. Although it is necessary to make the thickness of the subject lamp's adiabatic layer about $100\text{--}200\ \mu\text{m}$ due to the need for thin tubes, there never has been a practical lamp realized with such a thin adiabatic layer. Therefore, it is necessary to study in detail the design conditions for the adiabatic layer to secure sufficient heat retentiveness.

In this report, the basic design of the lamp will be shown by the heat transfer calculation of coaxial tubes, and then the efficacy of the adiabatic layer based upon experiments with samples will be described.

2. Heat Transfer Calculation for Coaxial Tubes^{8)–10)}

Fig. 1 shows a heat transfer model for coaxial tubes. It is possible to estimate the temperature of the light tube and the outer tube with various conditions of enclosed gases, pressures, and atmospheric temperatures by means of such a heat transfer model.

It is assumed that the space between the tubes is filled with a gas with a given pressure and that the tubes lie horizontally in an atmosphere. The heat q generated at the light tube is lost due to (1) radiation, (2) conduction through

Fig.1 The heat transfer model of coaxial tubes.

the adiabatic layer (the space between the light tube and the outer tube), and (3) convection in the outer tube. The relative equations for each item are shown below¹²⁾.

(1) Loss by radiation

$$q_{r1} = \frac{\sigma A_1 (T_1^4 - T_2^4)}{1/\varepsilon_1 + (A_1/A_2)(1/\varepsilon_2 - 1)} \dots\dots\dots(1)$$

$$q_{r2} = \sigma \varepsilon_2 A_2 (T_2^4 - T_a^4) \dots\dots\dots(2)$$

Here, q_{r1} is a loss due to the radiation from the inner tube, σ is the Stephen-Boltzman constant, and ε_1 , A_1 , and T_1 are the emissivity, the surface area, and the temperature of the light tube, respectively. The loss due to radiation of the outer tube is q_{r2} , and ε_2 , A_2 , and T_2 are the emissivity, the surface area, and the temperature of the outer tube, respectively, while T_a is the temperature of the atmosphere.

(2) Loss by conduction of the light tube

In general, a condition of free molecular flow is satisfied when the thickness of the adiabatic layer is less than the mean free path of the gas molecules. In this case, the conduction loss does not depend upon the thickness of the adiabatic layer but upon the gas pressure. When a thin adiabatic layer and a small difference between the outer diameter of the light tube and the inner diameter of the outer tube are assumed for simplification, the following equations are valid.

$$q_{cl} = \alpha \lambda p (T'_1 - T'_2) A_1 \dots\dots\dots(3)$$

$$\lambda = \frac{1}{2} \left(\frac{\gamma + 1}{\gamma - 1} \right) \sqrt{\frac{R}{2\pi M T}} \dots\dots\dots(4)$$

Here, q_{cl} is the loss due to the heat conduction from the light tube, α is an adaptation coefficient, λ is the heat conductivity of a free molecule, γ is the specific heat ratio of the enclosed gas, R is the gas constant, M is the molecular quantity, T equals the square root of T'_1 times T'_2 (T'_1 is the temperature of molecules moving from the light tube toward the outer tube and T'_2 is the temperature of molecules moving from the outer tube toward the light tube), and p is the pressure of the enclosed gas.

Then, an approximation is made by the following equation in order to express the average status of the molecular flows and continuous flows through an expansion of the range of calculation¹⁴⁾.

$$q_{cl} = \frac{\kappa \alpha \lambda p}{\kappa + \alpha \lambda d p} (T'_1 - T'_2) A_1 \dots\dots\dots(5)$$

Here, κ is the heat conductivity of the gas enclosed in the adiabatic layer and d is the distance between the two coaxial tubes (the adaptation coefficient was set at 1 for simplicity in the succeeding calculations).

(3) Loss by convection

The thermal quantity lost due to convection from the outer tube to the atmosphere q_{c2} is expressed with heat conductivity h_c as follows.

$$q_{c2} = h_c A_2 (T_2 - T_a) \dots\dots\dots(6)$$

Fig.2 The structure of a sample lamp.

Fig.3 The photograph of the measured lamp. The right half of the outer tube is removed.

Fig.4 The experimental setup.

Table 1 The specifications for samples.

Outer Tube Dia.		2.6, 3.2, 4.0 mm
Light Tube Dia.		1.8, 2.4, 2.6 mm
Lamp Length		100~200 mm
Filling Gas	Adiabatic Layer	Xe or N ₂
		0.01 Pa<P<1000 Pa
	Light Tube	Ne/Ar
		10 kPa

3. Experimental Method

Fig. 2 shows the structure of a sample lamp. Fig. 3 is a photograph of the measured lamp (the right half of the outer tube is removed). An adiabatic layer of 100 μ m to 200 μ m is formed between the light tube and the outer tube. Also, specifications of the lamp are shown in Table 1, and the experimental system is shown in Fig. 4. A conventional cold cathode fluorescent lamp is used for the lighting tube, an end of which is sealed together airtight with the outer tube. The other end of the assembly is open and connected to an exhaust system. The exhaust system is composed of a sorption pump and an ion pump, and it encloses nitrogen or xenon gas after exhausting to 10⁻⁵ Pa. The gas enclosure pressure was measured by a capacitance manometer. The lamp voltage V_L and electric current I_L were observed by a digital oscilloscope (Tektronix TDS460A), and the lamp wattage was calculated from the integral values of V_L and I_L . By the way, V_L and I_L were measured by a high-voltage probe (Tektronix P3000) and a current probe (Tektronix A6302), respectively. The light output of the lamp was measured by an illuminance meter (Topcon IM-3) and the luminance was measured with a luminance meter (Topcon BM-7). In addition, a lamp with the same specification as the light tube, but without the outer tube, was adopted as a lamp for comparison and measured under the same conditions.

4. Results of Experiments and Consideration

4.1 Results of Heat Calculation

The heat lost by the light tube per unit area versus the pressure of the adiabatic layer P is obtained by equation (5). The calculation results for the case of the distance between the bulbs being 100 μ m, the temperature of the inner tube being 50°C, and the temperature of the outer tube being 25°C is shown in Fig. 5. The heat loss is constant regardless of the pressure in the range above 100Pa. On the other hand, the heat loss decreases in proportion to a decrease in gas pressure in the area of molecular flow where the mean free path of the enclosed gas is sufficiently larger than the representative length (thickness of the adiabatic layer). In this case, the heat loss is not affected by the distance of the adiabatic layer as shown in equation (3), since the gas molecules in the adiabatic layer transfer the heat of the light tube without collision with other molecules. Also, the region around 100Pa has an intermediate characteristics between

Fig.5 The calculated relationship between the gas pressure and the conduction loss through the adiabatic layer.

Fig.6 The calculated conduction loss as a function of the distance between tubes.

continuous flow and molecular flow since it is the region where the thickness of the adiabatic layer equals the mean free path.

Now, we would like to check the influence of an aberration in the positions of the light tube and outer tube on the characteristics. Fig. 6 shows the calculated conduction loss as a function of the thickness of the adiabatic layer in the case of nitrogen as the enclosed gas. When an aberration of $\pm 50\mu$ m is assumed for an adiabatic layer of 100 μ m, the obtained changes in the heat loss were $\pm 16\%$ at 100Pa,

Fig.7 The calculation of the dependence of the light tube temperature on the pressure.

Fig.8 The results of calculating the light tube temperature with various ambient temperatures.

$\pm 2.3\%$ at 10Pa, and $\pm 0.22\%$ at 1Pa. Since the heat loss of the light tube does not depend upon the thickness of the adiabatic layer in the molecular flow area, the effect of aberrations in the positions of the light tube and the outer tube is considered to be negligible below 10Pa.

Next, the temperatures of the light tube considering radiation and convection were obtained by equations (1), (2), (5) and (6). Here, the conduction coefficient h was obtained by measuring the temperature at the center of a lamp without an outer tube and then by applying equation (6). Fig. 7 shows the results of the calculation of the dependence of the light tube temperature on the pressure. The following

describes the status of the light tube in the case of nitrogen as the enclosed gas.

Above 100Pa: The temperature of the light tube does not depend upon the pressure since continuous flow dominates.

1 - 100Pa: The temperature of the light tube is increased to an appropriate level (50-70°C) owing to the insulation effect of the molecular flow.

Below 1Pa: The conduction loss of the adiabatic layer is smaller than the radiation loss. The lamp temperature becomes constant since the radiation loss dominates.

Also, we obtained a result that the light tube temperature increased by about 10°C in the continuous flow area (above 100Pa) with xenon gas enclosed compared to nitrogen. This is attributable to a reduction in the thermal loss of the light tube, which is caused by the facts that the heat loss of the adiabatic layer is in proportion to the conduction coefficient α in the continuous flow area and that the conduction coefficient of xenon gas is about one-fifth that of nitrogen gas.

Fig. 8 shows the results of calculating the light tube temperature with various ambient temperatures. In the case of nitrogen gas enclosed in an adiabatic layer of 100 μ m at the pressure of 1Pa, the light tube temperature at 0.4W is 20°C with an ambient temperature of -30°C, 50°C at ambient temperature of 20°C, and 80°C at ambient temperature of 50°C.

From the above results of calculations, it was shown that the lamp temperature can be increased to an appropriate level even in the case of an adiabatic layer with a thickness of 100 μ m. Also, it was predicted that the enclosed gas pressure in the range from 1Pa to 10Pa in the adiabatic layer is a range applicable for designing this lamp.

4.2 Properties of a Trial Lamp

The relationship between the pressure in the adiabatic layer and the luminance is shown in Fig. 9. The luminance increased with a decrease in pressure in the range from 1Pa to 100Pa, while it was constant below 1Pa. Also, the luminance in a lamp with xenon gas enclosed with pressures in the range above 10Pa was higher than that with Nitrogen gas enclosed. These results were congruent with the results of the heat calculations in paragraph 4.1. This is because radiation loss dominates in the range below 1Pa and consequently the temperature of the light tube in this range is not dependent on the pressure.

The pressure in which the luminance shows its peak is 0.01Pa at 0.5W, 1Pa at 1.0W, and 10Pa at 1.5W. Thus, it shifts toward the side of higher pressure with an increase in wattage. Furthermore, in the case of 1.5W, a reduction in the luminance in parallel with a decrease in pressure is seen with pressures in the range below 10Pa. This is judged to be

Fig.9 The relationship between the pressure in the adiabatic layer and the luminance.

Fig.10 The relationship between the gas pressure in the adiabatic layer and the voltage.

Fig.11 The variations of the infrared radiation spectrum when the lamp operated at -15°C .

Fig.12 The relationship between the lamp wattage and the luminance by the wattage.

Fig.13 The luminance run-up characteristics.

a result of a tube temperature higher than the appropriate level accompanying the increase in the generated heat.

Fig. 10 shows the relationship between the gas pressure in the adiabatic layer and the lamp voltage. Similar to the luminance property case, the lamp voltage varied by about 30V in the gas pressure range of 1Pa to 100Pa. Since the lamp voltage varies depending on the light tube temperature, this seems to reflect the changes in the light tube temperature in this range of pressure.

Also, Fig. 11 shows the variations of the infrared radiation spectrum when the lamp is operated at low temperature (-15°C). In general, infrared radiation (700 – 900nm) of rare gases such as argon and neon, which are the buffer gases, is seen when the vapor pressure of the mercury in the cold cathode fluorescent lamp is reduced. Although infrared radiation is observed in the area above 100Pa because the lamp temperature does not increase sufficiently, the infrared radiation is not observed at 10Pa and 1Pa. From these results, it is believed that the mercury vapor pressure increased even at low temperature (-15°C) in the range below 10Pa, and that the infrared radiation of the rare gases could not be seen.

Fig. 12 shows the relationship between the lamp wattage and the efficacy (the luminance by the wattage) when nitrogen gas is enclosed in the adiabatic layer. The efficacy of the comparison lamp (without an outer tube) decreased to a half in the area below 2W, and the developed lamp obtained a two-fold efficacy increase at maximum. Also, the peak position of efficacy at 1Pa shifted to the lower wattage side compared to the efficacy at 10Pa.

Since the temperature of the light tube is determined by the balance between the heat radiation through the adiabatic layer and the wattage, it is necessary to optimize the gas pressure of the adiabatic layer corresponding to the required conditions for the luminance and wattage.

Next, the luminance run-up behavior of this lamp is shown in Fig. 13. Here, the stable luminance at 25°C in the comparison lamp is regarded as the target luminance.

In an ambient temperature of 0°C , the luminance of the comparison lamp showed only a negligible increase, while the developed lamp reached the target luminance 60 seconds after being turned on. Also, the luminance of the developed lamp in the stable state was five times higher than that of the comparison lamp. In the ambient temperature 25°C , the time to reach the target luminance was shortened to one fourth and the stable luminance was 1.2 times that of the comparison lamp. Although the luminance with the ambient temperature 60°C decreased as time elapsed, it eventually converged at the target luminance level.

As described above, a high efficacy in the low wattage consumption zone can be attained in this lamp. On the other hand, the phenomenon that the lamp efficacy is reduced with an increase in wattage was observed, as shown in Fig. 9. This is considered to be a result of an excessive increase in the lamp temperature. Hence, a fluorescent lamp with high

luminance and good low-temperature properties was studied, for which the results are described in the following.

In order to facilitate setting the pressure from the view point of practicality, as wide a range as possible of enclosed pressure is desirable. An experiment was done with xenon gas, which has a high insulation effect, in view of the heat calculations and the results of the above-described experiments.

Fig. 14 shows the relationship between the lamp wattage and the luminance with the xenon gas pressure as a parameter. Although luminance saturation is noted in the area above 1.3W in the case of 1.33Pa, luminance exceeding that of the comparison lamp was obtained up to about 2W in the cases of 66.5Pa and 133Pa. Also, Fig. 15 shows the variations of luminance by ambient temperature. The low temperature property was improved in 66.5Pa and 133Pa, and flat luminance properties were obtained in the range from 0°C to 60°C.

It is considered that these results were obtained by optimizing the light tube temperature by means of having an appropriate amount of heat escape from the light tube.

Lastly, the specifications of the cold cathode fluorescent lamp with an adiabatic layer that was put on the market in 1997 is shown in Table 2.

5. Conclusion

Heat calculations and measurements of lamp properties were performed on a cold cathode fluorescent lamp with a dual-tube structure and an adiabatic layer. As a result, the following items were clarified:

(1) Results of heat calculation

- It is possible to have the light tube temperature increased to the optimum level (50°C - 70°C) even with an approximately 100 μ m thick adiabatic layer.
- When the enclosed gas pressure is set below 10Pa, the light tube temperature is not affected by a certain amount of aberration in the positions of the dual tubes owing to the characteristics of molecular flow.

(2) Characteristics of the dual tubes cold cathode fluorescent lamp

- Two times the efficacy of a conventional lamp was obtained without inviting efficacy reduction under operation with low wattage.
- A flat luminance property in the range from 0°C to 60°C was obtained owing to the selection of the appropriate kind of enclosed gas and gas pressure, and the run-up characteristics in low ambient temperature environments was improved.

There has been a strong demand for low power consumption in backlighting for liquid crystal displays reflecting the spread of personal data units. This lamp can be

Fig.14 The relationship between the lamp wattage and the luminance.

Fig.15 The variations of luminance by ambient temperature.

Table 2 The specifications for a novel CCFL with adiabatic layer.

Type	Low Wattage	High Luminance
Diameter	2.2~2.6 mm	
Lamp Length	100, 200 mm	200, 320 mm
Lamp Current	1.5 mA	3.5 mA
Tc	6500 K	
Luminance	17000~20000 cd/m²	32000~35000 cd/m²
Wattage	0.5, 0.8 W	1.8, 2.5 W

expected to serve as a light source meeting these requirements.

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