Thermionic Emission Characteristics on Current-Controlled Preheating of Fluorescent Lamp Cathodes

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ABSTRACT

This paper proposes a method for measuring the emission time under an optimum condition of current-controlled preheating of fluorescent lamp cathodes. Using this method, a thermionic emission curve equation for practical lamp cathodes has been newly arrived at and the relationship between supplied energy for cathodes and its emission curve has been clarified. In addition, it has become clear that the supplied energy, till the emission time is reached, has a minimum value which varies with time and the average cathode resistance changes with a short emission time. These indicate the necessity of some improvements on the present IEC standard for the preheating condition of fluorescent lamp cathodes.

1. Introduction

Recently fluorescent lamps are being operated preferentially on high-frequency electronic ballasts incorporating a preheating function for lamp ignition. The most significant technical aspect of the ballast design is that the electronic ballasts provide enough preheating energy to the cathodes to reach the appropriate thermionic emission temperature. The information for ballast design in the present IEC standard shows the minimum thermionic emission curve equation for current-controlled preheating system and a constant value as a substitution resistor. Furthermore, more detailed information was presented in the previous study, which described a method for measuring the thermionic emission time and then determining two kinds of constant values in the above emission curve equation of the IEC standard.

The purpose of this study is to propose some technical improvements to the IEC standard for the current-controlled preheating condition of fluorescent lamp cathodes. The paper describes a newly developed method for measuring the emission time, and then clarifies more detailed thermionic emission characteristics of fluorescent lamp cathodes.

2. Advantages of the IEC Standard

In the authors' view, the most significant technical aspect of the ballast design information of the IEC standard is that the electronic ballasts incorporating a preheating function can be easily designed by using the defined substitution resistor value almost equivalent to the cathode coil resistance. When the supplied energy \( Q_1 \) for the substitution resistor, during preheat time, is higher than the energy \( Q_2 \) specifically supplied for the standardized cathode, electronic ballasts are able to supply cathodes with enough preheating energy to reach the appropriate thermionic emission temperature. Here, emission curves of practical lamp cathodes must be designed so as to be near and below the standardized emission curve. The values \( Q_1 \) and \( Q_2 \) are represented as follows:

\[
Q_1 = \int_0^{t_e} i_{\text{sub}}^2 R_{\text{sub}} \, dt = R_{\text{sub}} \int_0^{t_e} i_{\text{sub}}^2 \, dt \tag{1}
\]

\[
Q_2 = \int_0^{t_e} i_k^2 R_k \, dt = i_k^2 \int_0^{t_e} R_k \, dt
= i_k^2 t_e \cdot \langle R_k \rangle \tag{2}
\]

where \( i_{\text{sub}} \) is the current through the substitution resistor \( R_{\text{sub}} \) connected to the test electronic ballast, \( i_k \) is a certain preheat current through the standardized cathode, \( R_k \) is the standardized cathode resistance and \( t_e \) is emission time.

The relationship between the cathode current \( i_k \) and the emission time \( t_e \) as shown in Fig.1 of the IEC standard is represented as a standardized minimum thermionic emission curve by

\[
i_k = \left( \frac{a}{t_e} + i_m^2 \right)^{1/2} \tag{3}
\]

where \( a \) is the cathode constant and \( i_m \) is the absolute minimum current.

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The average resistance \( <r_k> \) of the standardized cathode in eq.(2) corresponds to the substitution resistor \( R_{sub} \) in eq.(1). When the value of \( <r_k> \) is equal to that of the substitution resistor \( R_{sub} \), the ratio \( Q_1/Q_2 \) is,

\[
Q_1 = \int_0^{t_e} i_{sub}^2 dt = \int_0^{t_e} i_{sub}^2 dt
\]

\[
Q_2 = \frac{1}{k^2 t_e} = \frac{1}{a + i^2 t_e}
\]

Equation(4) shows that when the ratio \( Q_1/Q_2 \) is larger than 1.0, the test electronic ballast connected to the substitution resistor has the capacity of heating electrodes to thermionic emission temperature during preheat time. In this equation, emission time \( t_e \) can be replaced by preheat time. One of the advantages in the IEC standard is that the electronic ballasts can be designed independent of lamp cathodes that are connected to the ballasts.

### 3. Measurement of Emission Time

Fig.2 shows a new method for measuring the emission time, in which lamp current is kept small and constant at only a few hundred microamperes during the measurement. The fall of lamp voltage, depending on the decrease in the cathode fall from cold to hot cathode, is used for measuring the emission time. As monitoring lamp voltage, the time difference between the instant of the supply of preheating energy and the time at just after the fall of lamp voltage is dynamically expressed by the following equation:

\[
d^2V_L/dt^2 = \frac{V_L(t+\Delta t)+V_L(t-\Delta t)-2 \cdot V_L(t)}{(\Delta t)^2}
\]

where, \( V_L \) is lamp voltage. This equation is based on the expression of the second derivative of lamp voltage with respect to time. The time at the maximum value of the numerator in the right-hand side of eq.(5) is a measure of emission time. Here, \( \Delta t \) is changed in order that the peak point is at just after the fall of lamp voltage.

Fig.3 shows the suitable value of \( \Delta t \) depending on the emission time. After the examination of various types of cathodes characterized in Fig.3, it has become clear that \( \Delta t \) has a variable value in proportion to the emission time as shown in Fig.4.
In connection with this measurement, the static thermionic emission characteristics of electrodes are investigated. Fig. 5 shows the light emission spectra in the proximity of electrode in a static operating mode of the fluorescent lamp filled with gaseous argon and some mercury. During the measurement, the cathode current is slowly increased. The lamp current of this measuring system is controlled as small as that of the dynamic thermionic emission measurement. The small lamp current hardly affects the thermionic emission measurement against having some errors because it is small enough to prevent electrodes from heating and the argon emission spectrum is likely to be seen near the lead wire when the electrode is operating in the cold cathode mode. This is shown in Fig. 5. This figure also shows that the static point at just after the fall of lamp voltage can be regarded as the thermionic emission point because it doesn't include an argon spectrum due to the high cathode fall. This point relates to the decision of \( \Delta t \) in eq.(6) for the dynamic emission measurement.

Consequently, proper values of \( \Delta t \), for instance, can be shown as follows:

\[
\Delta t = 0.2 \cdot (t_e + 1)
\]  

(6)

By transferring from \( t_e \) to \( t \) in eq.(6) and its combining with the numerator in the right-hand side of eq.(5), emission time can be measured automatically.

Fig. 4  Relationship between \( \Delta t \) and emission time. Two data point shapes indicate two types of cathodes.

Fig. 5  Light emissions in the vicinity of electrode which is in a static operating mode (4-foot length FL).
4. A practical Emission Curve

After the measurement of the emission time of various types of cathodes, it has become clear that their emission curves are not always expressed by the equation given in the IEC standard.

\[
Y = k n \cdot t_o = i_m^n \cdot t_o + a
\]

\[
a = 0.222
\]

\[
i_m = 0.069
\]

Fig. 6 Scatter diagram of eq.(3) in the case of 13-watt compact fluorescent lamp cathode.

Fig. 6 shows one of the scatter diagrams of eq.(3) in the case of 13-watt compact fluorescent lamp cathode. The equation in this figure is one of the regression lines derived from eq.(3) of the IEC standard. Both constants \(a\) and \(i_m\) are given from the intercept and the slope of this regression line, respectively. In the case of this lamp cathode, most of emission points are not on this line.

Consequently, a new emission curve equation for each practical cathode is presented as follows:

\[
i_k = \frac{(a/t_o + i_m)^n}{1/n}
\]

(7)

Where, exponent \(n\), which is a variable and originated from practical cathodes, is introduced instead of the second power in eq.(3) of the IEC standard.

Now, the determination of the value of \(n\) requires some discussion. Equation (7) can be rearranged as follows in two regressions:

\[
i_k^n = a \cdot (1/t_o) + i_m^n
\]

(8)

\[
i_k \cdot t_o = i_m^n \cdot t_o + a
\]

(9)

These equations resemble the following equation.

\[
y = (\text{slope}) \cdot x + (\text{intercept})
\]

These relationships are numerically expressed in Fig.8. Curves in Fig.8(a) are for two types of cathode constant \(a\) of each regression line which varies with exponent \(n\). Also, curves in Fig.8(b) are for two types of absolute minimum current \(i_m\) of each regression line. Furthermore, for reference, contribution ratio curves in Fig.8(c) are represented at the same time. Each constant in these Figs.8(a) and (b) has two values in all ranges of exponent \(n\) except for an intersection of each regression line. It seems strange to have two values of each constant, that is, have two curves for the minimum thermionic emission like that in Fig.2. Therefore, it is necessary for each constant to have a single value, that is, an intersection of two curves from each regression line. It is reasonable because each regression line, having each constant, is originally derived from the same emission curve, eq.(7).
According to this procedure, exponent $n$ can be determined together with both constants $a$ and $i_m$. In the case of this lamp cathode (Fig.8), exponent $n$ equals 1.2 and cathode constant $a$ equals approximately 0.29, and further, absolute minimum current $i_m$ equals approximately 0.16. The value of exponent $n$ is completely different from that of the IEC standard. After the measurement on various types of cathodes, it is found that exponent $n$ varies widely as shown in Fig.8. This variation seems to be due to various properties, such as the coiling structure or dimensions of electrodes, materials or amount of the emission mix, surface conditions of electrodes like the aging factor which affects its work function, and others. Of course, there are some cases that exponent $n$ equals about 2 in the same way of eq.(3) in the IEC standard as shown in Fig.9. Anyhow, more detailed study is required for the purpose of determining the value of exponent $n$ for each type of cathode. On the other hand, it can also be perceived that eq.(3) is a special case where exponent $n$ has a value of 2 for a standardized cathode.

5. Preheating Energy

Next, the subject which deals with the supplied energy for cathodes, till the emission time is reached, is investigated. The supplied energy for cathodes and its average resistance till the emission time are measured in order to make the relationship clear between the supplied energy and the emission curve. The procedure is as shown in Fig.10. After the settlement of a fixed cathode current, the emission time and the supplied energy for cathodes, till the emission time is reached, are measured. The energy is automatically calculated by the quantity of the fixed cathode current times the integral from zero to emission time of cathode voltage as shown in the left-hand diagram in Fig.10. Then, the average cathode resistance till the emission time is easily obtained. After that, both constants $a$ and $i_m$ and exponent $n$ can be determined by using the procedure as mentioned above shown in Fig.8 or 9.
Settlement:
Fixed cathode current \(i_k\)

Measurement:
Emission time \(t_e\)
Cathode voltage \(v_k\)
Supplied energy \(Q\)
\[Q = i_k \int_0^{t_e} v_k \, dt\]
Average resistance \(<r_k>\)
\[<r_k> = \frac{Q}{(i_k^2 \cdot t_e)}\]
Cathode resistance \(r_k\)
\[r_k = \frac{v_k}{i_k}\]

Calculation:
Determination of \(a, i_m, n\)
\[i_k = \left(\frac{a}{t_e + i_m^n}\right)^{\frac{1}{n}}\]
\[Q = \int_0^{t_e} i_k v_k \, dt = i_k^2 \int_0^{t_e} r_k \, dt\]
\[= i_k^2 t_e \cdot \left(1/t_e\right) \int_0^{t_e} r_k \, dt\]
\[= \left(\frac{a}{t_e + i_m^n}\right)^{\frac{2}{n}} t_e \cdot <r_k>\]

In the case that \(i_k = 0.45\)A
\[Q = 2.33\] J

Preheat time (s)

Fig. 10  The procedure for obtaining the relationship between the supplied energy for a cathode and the emission curve.

Consequently, a practical emission curve is given. Also another expression of the supplied energy for cathodes is represented in the following by using the practical emission curve and the average cathode resistance.

\[Q = \left(\frac{a}{t_e + i_m^n}\right)^{2n} t_e \cdot <r_k>\]  \hspace{1cm} (11)

Fig. 11 shows the relationship in the case that exponent \(n\) equals 2.0. In this figure the dashed curve is the average cathode resistance, till the emission time is reached, that is \(<r_k>\), and the dotted curve is the quantity of square of cathode current as the practical emission curve times the emission time, that is \(\left(\frac{a}{t_e + i_m^n}\right)^{2n} \cdot t_e\).

Fig. 11  Relationship between the supplied energy and the emission curve (4-foot length FL). The dashed curve changes when emission time is short.

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When exponent \( n \) equals 2.0, this dotted curve will become a straight line, that is, \( (a + i m^2 \cdot t) \). Then, the solid curve, the supplied energy for cathodes till the emission time, is represented by the quantity of the dotted curve times the dashed curve. Fig. 12 shows the similar relationship in the case that exponent \( n \) equals 1.2. In this case, the dotted curve is not a straight line.

Whenever exponent \( n \) has any value, the average cathode resistance at short emission time is higher than that at long emission time. This average resistance, which is changeable as shown in Figs. 11 and 12, should be noticed to be related to the substitution resistor which is a constant value in the IEC standard. This result seems to show that the temperature of the cathode except emission mix is higher than the temperature of emission mix when the emission time is short. In other words, when a large amount of energy is supplied for the cathode in a short time, the temperature on the emission mix will reach to the thermionic emission temperature before performing the thermal balance in a whole cathode. This probably shows that it is difficult to relate the thermionic emission temperature dynamically with the cathode resistance such as an \( R_h/R_{(hot/cold)} \) resistance ratio measurement.

Owing to this high cathode resistance, the supplied energy for cathodes till the emission time is high when the emission time is short. On the other hand, owing to the sum of losing energy till the time of reaching to the thermionic emission temperature, this supplied energy will increase as the emission time becomes longer. Consequently, this energy has a minimum value which varies with time.

In connection with the similar study of this, eq.(11) is investigated. In both cases that the curve of \( (i_k^2 \cdot t) \) is in a linear portion and the thermal balance in a whole cathode is performed, exponent \( n \) can be given as the value of 2.0 and the average cathode resistance \( <r_k> \) will be constant. In these cases, eq.(11) is changed as follows:

\[
Q = a <r_k> + i m^2 <r_k> \cdot t_e \tag{12}
\]

This equation corresponds to the next equation in that study.

\[
E = a \cdot t_s + b \tag{13}
\]

where \( E \) is supplied energy, \( t_s \) is preheat time, and both \( a \) and \( b \) are constants, and then it is necessary to pay the attention that constant \( a \) is different from that of this study.

6. Discussions

With the increase in the application of the electronic ballast in fluorescent lamps, the standardization of procedure for the preheating condition of fluorescent lamp cathodes will become more and more important. This study was carried out in those circumstances. The most significant matter in this study is that it has become clear that the average cathode resistance till the emission time, which is related to the substitution resistor having a constant value in the IEC standard, changes when the emission time is short. This aspect suggests strongly that the JEL (Japan Electric Lamp Manufacturers) recommend that the substitution resistor should have two values within each stage of the preheat time. Also another significant aspect in this study is that it is likely to be difficult to relate the thermionic emission temperature dynamically with the cathode resistance such as an \( R_h/R_{(hot/cold)} \) resistance ratio measurement. After the standardization for current-controlled preheating system, the subject of voltage-controlled preheating system for electronic ballast designs, in a proposal to the IEC, has generated lot of discussion.

Based on the present study, thermionic emission characteristics on voltage-controlled preheating condition of fluorescent lamp cathodes will be reported at a later date.

![Fig. 12 Relationship between supplied energy and emission curve (13-watt compact FL). The solid curve has a minimum value which varies with time.](image-url)
7. Conclusion

A new method for measuring the emission time provides several significant information concerning the standardization of procedures in the IEC, which include under considerable matter such as the ballast design information for voltage-controlled preheating system. In this paper, the current-controlled preheating system is studied using the method of emission time measurement. As a result, a new concept concerning the substitution resistor is examined. The knowledge on the existence of various thermionic emission curves for each practical cathode against the standardized emission curve in the IEC, is also obtained. Furthermore, this information provides some other significant issues concerning the preheating condition of fluorescent lamp cathodes in the IEC standard.

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References

(1) The IEC standard: 81-IEC-7210, etc.
(8) The JEL standard: JEL212(1992)