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Preheating Characteristics of a Fluorescent Lamp Cathode (II)

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ABSTRACT

High-frequency fluorescent lamp operation requires proper cathode preheating by electronic ballasts incorporating a preheating function. This paper examines minimum thermionic emission curves for three different ways of measuring emission times. One is based on a lamp ignition test, another on the ratio of hot to cold coil resistance (R_h/R_c), and the third on the lamp voltage monitoring. The observation that the emission time measured by the lamp ignition method tends to be shorter than that measured by the lamp voltage monitoring method in a short preheat time may be understood in terms of the relaxation of the limited thermal conductivity of the emissive material due to the initial flow of the discharge current. We do not believe that the shorter emission time measured by the lamp ignition method causes premature thermionic emission. On the other hand, when the duration of the heterogeneous heating in a cathode is negligible, then the R_h/R_c method may be used as well.

This paper points out that the average resistance of a standardized cathode over the period up to the emission time should be regarded as a substitution resistor. Furthermore, a maximum curve similar to the minimum preheating requirement curve, being examined to replace the maximum preheating broken lines for the present requirement in the IEC, is helpful for determining a new coming maximum required energy line.

In the last part of this paper, an approach to the standardization by a preheating energy line together with a suitable value for the substitution resistor is supported.

1. Introduction

It is greatly important to preheat cathodes preferentially for a high-frequency operated fluorescent lamp before ignition in order to obtain an adequate lifetime for the lamp. The requirement of current-controlled preheating mode was standardized by the IEC (International Electrotechnical Commission), while the requirement of voltage-controlled preheating mode has not yet been implemented¹⁾. The substitution resistor value in the preheating requirement and the cathode characteristics on voltage-controlled preheating mode have been reported recently²⁾. On the other hand, a new approach to the standardization described by energy lines has been progressing for a few years through work by ELMAPS (European Lamp Manufacturers' Association for the Preparation of Standard)^{3,4)}.

The point to be taken into account is the difference in the measuring methods of emission times among the above-mentioned approaches. So far three methods have been proposed. One is based on a lamp ignition test⁵⁾, another on the ratio of hot to cold coil resistance (R_h/R_c)^{3,4)}, and the third on the lamp voltage monitoring^{2,6)}. The precondition on which these methods should be proposed is to reach the final purposes of preventing lamp ends from blackening and obtaining an adequate lifetime for the lamp. The IEC concept according to this idea requires preheating cathodes up to the thermionic emission temperature before the

lamp starts.

The main intention of this study is to investigate which method is most suitable for both the final purpose and the IEC concept^{7,8)}. The paper, furthermore, points out our way of thinking as to the maximum preheating requirement. The different point of view in this paper from previous ones^{7,8)} is to lead to an agreement that the energy expression proposed by ELMAPS is useful for the preheating requirements.

Before describing these methods, the authors' viewpoint regarding the theory on the present preheating requirements in the IEC¹⁾, including the substitution resistor value, will be discussed.

2. Theory on the Present Requirements in IEC

2.1 Current-Controlled Preheating Mode

When the preheating performance of an electronic driver more closely approaches the current-controlled preheating terminal condition than the other one, the current i_s running through a substitution resistor R_{cs} combined with the electronic driver over the heating time t_h produces an energy E_{cs} . It is expressed as follows:

$$E_{cs} = \int_0^{t_h} i_s^2 R_{cs} dt = R_{cs} \int_0^{t_h} i_s^2 dt = R_{cs} t_h (1/t_h) \int_0^{t_h} i_s^2 dt$$

$$= R_{cs} t_h \langle i_s^2 \rangle \quad (1)$$

where $\langle i_s^2 \rangle$ is the average of square of the current i_s over the heating time t_h .

On the other hand, when a certain test current i_k running through a standardized cathode produces an emission time t_e , the relationship is given as follows:

$$i_k = (a / t_e + i_m^2)^{1/2} \quad (2)$$

where a and i_m are constants. This curvature is the minimum thermionic emission curve, and when t_e is replaced by t_h , it can be treated as a preheating requirement curve¹⁾. The emission points of the practical cathodes should be almost on, and not more than the curve. A certain current i_k running through the standardized cathode r_k over the heating time t_h produces an energy E_{ck} . It is expressed as follows:

$$E_{ck} = \int_0^{t_h} i_k^2 r_k dt = i_k^2 \int_0^{t_h} r_k dt = i_k^2 t_h (1/t_h) \int_0^{t_h} r_k dt$$

$$= i_k^2 t_h \langle r_k \rangle \quad (3)$$

where $\langle r_k \rangle$ is the average cathode resistance.

When the energy E_{cs} is larger than the energy E_{ck} , that is, $E_{cs}/E_{ck} > 1$, then the electronic driver can make the cathode reach the thermionic emission temperature. When the value of average cathode resistance $\langle r_k \rangle$ is equal to that of substitution resistor R_{cs} , the E_{cs}/E_{ck} is expressed as follows:

$$\frac{E_{cs}}{E_{ck}} = \frac{\langle i_s^2 \rangle}{i_k^2} \quad (4)$$

The condition of $E_{cs}/E_{ck} > 1$ follows the relationship below:

$$\langle i_s^2 \rangle > i_k^2 \quad (5)$$

As the values of both i_s and i_k are natural ones(>0), the mathematical induction leads to the following inequality.

$$\langle i_s \rangle > i_k = (a / t_h + i_m^2)^{1/2} \quad (6)$$

where $\langle i_s \rangle$ is the average current running through the substitution resistor over the heating time t_h . When the value of $\langle i_s \rangle$ is larger than that of i_k , the electronic driver can make the cathode reach the thermionic emission temperature.

As for the eq. (3), in the case where $\langle r_k \rangle$ is constant, the energy E_{ck} is expressed as follows:

$$E_{ck} = a \langle r_k \rangle + i_m^2 \langle r_k \rangle t_h \quad (7)$$

This energy has a linear relationship to the heating time t_h . This result corresponds to the recent approach by European lamp manufactures⁴⁾.

2.2 Voltage-Controlled Preheating Mode

The requirement for this preheating mode is under consideration. However, the way of thinking is almost the same as that for current-controlled preheating mode.

When the preheating performance of an electronic driver more closely approaches the voltage-controlled preheating terminal condition than the other one, the voltage v_s impressed across a substitution resistor R_{vs} combined with the electronic driver over the heating time t_h produces an energy E_{vs} . It is

expressed as follows:

$$E_{vs} = \int_0^{t_h} v_s^2 (1/R_{vs}) dt = (1/R_{vs}) \int_0^{t_h} v_s^2 dt = (1/R_{vs}) t_h (1/t_h) \int_0^{t_h} v_s^2 dt$$

$$= (1/R_{vs}) t_h \langle v_s^2 \rangle \quad (8)$$

where $\langle v_s^2 \rangle$ is the average of square of the voltage v_s over the heating time t_h .

On the other hand, a certain voltage v_k impressed across a standardized cathode r_k over the heating time t_h produces an energy E_{vk} . It is expressed as follows:

$$E_{vk} = \int_0^{t_h} v_k^2 (1/r_k) dt = v_k^2 \int_0^{t_h} (1/r_k) dt = v_k^2 t_h (1/t_h) \int_0^{t_h} (1/r_k) dt$$

$$= v_k^2 t_h \langle 1/r_k \rangle \quad (9)$$

where $\langle 1/r_k \rangle$ is the average of inverting r_k .

Following the eqs. (4) to (6), the condition that the electronic driver can make the cathode reach the thermionic emission temperature is expressed below:

$$\langle v_s \rangle > v_k \quad (10)$$

where $\langle v_s \rangle$ is the average voltage impressed across the substitution resistor over the heating time t_h .

At present an equation, which shows the relationship between the impressed voltage v_k and its emission time t_e , is under consideration in the IEC. However, if the energy E_{vk} in eq. (9) is assumed to have a linear relationship to the heating time t_h , then the value $\langle 1/r_k \rangle$ is required to be constant and the equation of the voltage v_k impressed across the cathode as a function of the emission time t_e should be as follows:

$$v_k = (b / t_e + v_m^2)^{1/2} \quad (11)$$

where b and v_m are constants. The energy E_{vk} over the heating time t_h , therefore, is expressed by

$$E_{vk} = b \langle 1/r_k \rangle + v_m^2 \langle 1/r_k \rangle t_h \quad (12)$$

The explanation so far stresses that the minimum preheating requirement curve has a relationship to the energy line with an intermediary of the average resistance value of a cathode over the period up to the emission time. Over and above that the average resistance value of a standardized cathode should be regarded as a substitution resistor value in the preheating requirement.

3. Methods to Measure Emission Times

The final purpose of preheating cathodes is to obtain an adequate lifetime for the lamp. The IEC concept requires preheating cathodes preferentially before igniting the lamp. Both the final purpose and the IEC concept have almost the same meaning, but in detail there is a distinction between them. It would be helpful for understanding the distinction to investigate three methods. Here, each method including the measuring condition employed in this study, is introduced.

3.1 Lamp Ignition Method

The lamp ignition circuit, almost entirely based on the previous study⁵⁾, is illustrated as shown in Fig.1. The power sources, consisting of a power amplifier S-4750A and a function generator 1930A (NF Corporation, Japan), can supply

a voltage over around 700 V. The operation frequency in the test is 45kHz. The total resistance value of resistors A, B and D is much larger than that of the cathode resistance in order to maintain the current-controlled preheating condition. The value of open circuit voltage in the test is large enough to correspond to that of above-mentioned total resistance, and it is smaller than that of cold-start voltage. The adjustment of preheat current value should be done by employing a mean value ampere meter connected in the closed circuit including the resistors of A, B, C, C' and D (path #1). Each value for resistors C and C' is given as 4 times as large as the cold-coil resistance value of the cathode according to the previous study⁵⁾. These values need to be distinguished from the substitution resistor value addressed in Chapter 2. The resistors of all in the test are free from having an inductivity because they consist of a going and returning coil.

Fig.1 Measuring circuit for thermionic emission time based on lamp ignition test.

After adjusting the value of preheating current, the switching to the path #2 enables the actual cathodes in both lamp ends to start heating. After heating cathodes for a certain period given by the timer-relay, the path #3, having the ballast of resistor B, can start the lamp. The discharge current value, which is determined by both values of the open circuit voltage and the resistor B, should be almost the same as the rated value. The heating current after ignition in the previous study⁵⁾ remained during operation, while in this test it was eliminated after ignition in order to make clear the preheating condition. Here, the switching duration of timer-relays employed in the test is less than 20 ms.

The measuring criterion of this method is to detect a step-wise decrease in voltage by using an oscilloscope from the open circuit to lamp voltages after preheating cathodes. Fig.2 shows the time variations of voltage in two different preheat times under two different preheat currents. In Fig.2 the whole preheat time is not shown in order to focus attention on the transition time from the open circuit to lamp voltages. When starting the lamp just after preheating the cathodes, if the voltage decreases gradually or does not reach its minimum value (see the left side of Fig.2), the cathode preheating is considered to be insufficient, whereas if the voltage decreases rapidly, the cathode preheating is considered to be sufficient. In addition, Fig.2 shows the increasing discharge current just after igniting the lamp.

Fig.2 Experimental results: time variation of open circuit to lamp voltages using the measuring circuit for thermionic emission time based on lamp ignition test.

Repeating measurements in various preheat time periods can provide an emission time. As it is based on the actual lamp starting procedure, it is important to compare this method with the other methods

3.2 Lamp Voltage Monitoring Method

Fig.3 shows a circuit diagram for the lamp voltage monitoring method to measure emission times of both the current- and voltage-controlled preheating modes. All test cathodes were placed at the negative end of the lamp. The voltage across the lamp having a fairly small discharge current of around 0.5mA is monitored during the measurement. The criterion to measure emission times by this method is based on detecting the decrease in lamp voltage, depending on the decrease in the cathode fall voltage from cold to hot²⁾⁽⁶⁾.

Fig.3 Measuring circuit for thermionic emission time based on lamp voltage monitoring.

The time when the lamp voltage reaches its minimum value can be determined by using one of the two defined lines which crosses the curvature of the first derivative of lamp voltage with respect to time as shown in Fig.4(a)⁷⁾. Although the measuring concept to detect the decrease in lamp voltage in the recent studies²⁾⁽⁶⁾ has not been changed, this new criterion is

much easier to understand regarding the physical meaning of the decrease in lamp voltage than previous ones.

Fig.4 Measuring criteria of thermionic emission time for the lamp voltage monitoring method and its experimental results

The measuring condition in detail of the method in this study is addressed as follows:

(1) Each signal of the lamp voltage and the heating voltage (or current) passes through the low-pass filter to get rid of its noise. Each 5 data of the 2ms-pitch lamp voltage is averaged into a 10ms-pitch datum. All 10ms-pitch data of each signal are input to a computer for processing.

(2) After igniting a lamp and finding its stabilized operation automatically, a certain preset current (or voltage) is applied to the test cathode, which will start heating.

(3) The first derivative of lamp voltage with respect to time defined below is calculated.

$$dv_L/dt = \{v_L(t + \Delta t) - v_L(t)\} / \Delta t \quad (13)$$

where v_L is lamp voltage, t is heating time and Δt is a differential pitch for the first derivative. Here, $\Delta t = 0.3$ s was employed provisionally in this study.

(4) The two defined lines, which will cross to the curvature of the first derivative of lamp voltage with respect to time, are described below:

- Current-controlled preheating mode (provisional)

$$y = 10t - 30 \quad (0 < t \leq 2.5) \quad (14)$$

$$y = -5 \quad (2.5 < t) \quad (15)$$

- Voltage-controlled preheating mode (provisional)

$$y = 25t - 30 \quad (0 < t \leq 1.0) \quad (16)$$

$$y = -5 \quad (1.0 < t) \quad (17)$$

where y -axes of eqs. (14) to (17) are the same as that of eq. (13). This procedure can provide an emission time when the curvature of the first derivative of lamp voltage after passing

through its negative peak is more than one of the two defined lines at least for the duration of more than a series of several 10ms-pitch points.

(5) After determining an emission time, all of the circuits connected to the test lamp will be switched off.

(6) To get rid of the thermal history from the test cathode, the measurement should be done at more than 3 minutes intervals.

The first defined lines of eqs. (14) and (16) are introduced in consideration of the actual lamp starting condition including a relaxation of the limited thermal conductivity of the emissive material by a somewhat larger discharge current just after starting the lamp. This phenomenon will be considered below. Another reason for introducing the first defined line is that it tends to be able to avoid crossing with the fluctuation of the derivative of lamp voltage function. This procedure can minimize the tolerance of the measuring data of emission times. The intercept value of the second defined lines of eqs. (15) and (17), depending on the value of Δt , almost can be regarded as $y=0$.

At a glance it seems that the measurement of emission times after ignition by the lamp voltage monitoring method does not meet the IEC concept. It is, however, a misunderstanding because the discharge current is small enough to prevent cathodes from heating and basically does not allow relaxing the limited thermal conductivity of the emissive material (see Chapter 5).

Fig.5 Estimation curve of minimized cathode fall voltage in various combinations of lamp and filament currents.

Fig.5 shows the estimated curvature in the minimized cathode fall voltage of a 25mm-diameter (T8), 4-foot length tubular fluorescent lamp under the combination of discharge and heating currents. Both currents in the measurement were in a static condition of the circuit in Fig.3, where the heating current was gradually increased at each discharge current. The curve in Fig.5 can give an outline for the direction of the magnitude of the cathode fall voltage. The cathode fall voltage will be higher with a decrease in the heating current. The point A, where the thermionic emission current can cover the whole discharge current of around 0.5 mA, is much smaller

than the rated discharge current of 0.255 A, whose lamp is employed in the test. Although the discharge current increases from point A to the rated value by way of the region (or period) where the cathode fall voltage is a little bit high, it follows from the observation below that the discharge current never flows by way of the region where the cathode fall voltage is too high to achieve a long lamp life.

Fig.4(b) shows the emission points given by a criterion of the lamp voltage monitoring method in Fig.4(a), together with emission points by the lamp ignition method. The graph in Fig.4(b) illustrates that emission times by the lamp voltage monitoring method are generally longer than those by the lamp ignition method. This result demonstrates that the lamp voltage monitoring method is useful for measuring emission times even if the discharge current, which will be covered with the thermionic emission current, is fairly small.

3.3 R_H/R_C Method

The ratio of hot to cold coil resistance (R_H/R_C) in a static heating condition can be regarded as a function of temperature. Further, the value of $R_H/R_C=4.0$ corresponds to the thermionic emission temperature of a normal emissive material made of activated alkaline earth oxides coated on a tungsten coil. It was found in previous studies³⁾⁴⁾ that this method provided an emission time when the dynamic value of R_H/R_C reached up to 4.0.

The dynamic cathode information of a heating voltage or current in the lamp voltage monitoring method in the previous section can also lead to obtain another emission time of $R_H/R_C=4.0$. Therefore, each emission time by both the lamp voltage monitoring and R_H/R_C methods is given simultaneously. Caution is necessary in this dynamic measurement of R_H/R_C in the case when the heterogeneous heating occurs in the uncoated and coated parts of a cathode, where the heat capacities differ²⁾. As long as the duration of heterogeneous heating is fairly short and is less than 0.4 s, the R_H/R_C method can be used.

Fig.6 Frequency variations of equivalent inductance and resistance of a filament coil.

The cathode preheating in the lamp ignition method operates at the frequency of 45kHz, whereas that in the cases of the lamp voltage monitoring and R_H/R_C methods operates at d.c. Fig.6 shows the frequency variations of equivalent inductance and resistance of a triple coiled cathode employed in a

25mm-diameter (T8), 4-foot length tubular fluorescent lamp. Due to the fact that the inductive reactance from the equivalent inductance of 46nH at the frequency of 45kHz is calculated to be only 0.7% of the coil resistance, it is concluded that the high-frequency operation to heat a cathode can be treated almost the same as that for the d.c. operation.

4. Comparison in Emission Time among Three Methods

Fig.7 shows the comparison in emission time among three methods under the current-controlled preheating mode. Two types of cathodes in 25mm-diameter (T8), 4-foot length tubular fluorescent lamps are employed in the test. The results of two kinds of stick coils are shown in Figs.7(a) and 7(c), and the result of a triple coil is shown in Fig.7(b). In Figs.7(a)-7(c) the lamp ignition method provides one emission curve, whereas the lamp voltage monitoring and R_H/R_C methods each provide two emission curves for cathodes in both lamp ends.

Fig.7 Comparison in emission curves among three methods under current-controlled preheating condition employing two types of cathodes, stick coil type (a),(c) and triple coil type (b).

We can see from Figs.7(a)-7(c) that each emission curve is almost the same, but they are different from each other in detail. Generally, the difference in emission curve in Figs.7(a) and 7(b) is not so large, whereas that in Fig.7(c) is much larger.

In the former cases it may demonstrate that it is easy to achieve a thermal balance in the whole cathode before the heating time reaches 0.4 s. From this reason there may be some cases statistically where the R_h/R_c method can be used. On the other hand, the latter case in Fig.7(c) clearly shows that emission times by the R_h/R_c method tend to be shorter than those by the lamp voltage monitoring method. That may result from the cathode coil type, in which a large amount of emissive material is coated in a limited part.

The emission times in Fig.7(c) by the three methods at the heating current of 0.6 A are examined. Fig.8 demonstrates that the emission time of $R_h/R_c = 4.0$ is shorter than that by the lamp voltage monitoring method, and then it is at the time when the lamp voltage, that is, the cathode fall voltage has not reached its minimum value. On reflection, the lamp ignition method provides almost the same emission time as the R_h/R_c method as shown in Fig.7(c).

Fig.8 Comparison between emission times by the method based on the ratio of hot to cold coil resistance (R_h/R_c) and by the lamp voltage monitoring method at the fixed cathode current of 0.6A.

The observation that the R_h/R_c method provides a shorter emission time when the heating current is rather high is understood in terms of the heterogeneous heating of a cathode at the time of $R_h/R_c = 4.0$. It means there might be a possibility that when $R_h/R_c = 4.0$, the surface of emissive coating does not reach the thermionic emission temperature²⁾. We should take into account here that according to cathode types including the coating forms and emission properties of emissive material, there are also the opposite cases where the emission time of $R_h/R_c = 4.0$ could be longer than that by the lamp voltage monitoring method.

How can we understand why the lamp ignition method is able to provide a shorter emission time, then?

5. Thermal Conductive Model in Emissive Coating

To make clear this idea, a theory on thermal conductivity of the uncoated and coated parts should be proposed. Fig.9 shows its model. Generally the emissive material is coated in the middle of the filament coil. In Fig.9(a) the area on the right side of the emissive coating illustrates its surface adjacent to the discharge space. It is presumed here that the dashed.

Fig.9 Thermal conductive model from the coil to the surface of emissive coating.

box is a thermal conductive model by electrons

The only way of heating a cathode is due to Ohmic heating in the filament coil made of tungsten. A rapid rise in temperature of the uncoated part of cathode can be understood in terms of the heating by itself and a lower heat capacity of the uncoated part. Since the way of conducting heat in a metal is by electrons, the electrons in tungsten coil dominate the thermal conductivity in the uncoated part.

There are two ways of conducting heat in emissive material, that is, by firstly the lattice vibration of atoms in crystal oxides and secondly electrons raised in the conduction band. When the increased electrons begin to dominate the thermal conductivity in emissive material more, then the above-mentioned thermal conductive model can be used. Here, we need to consider the time-variable distribution of electron temperature in the box model.

If the discharge current is absent or fairly small in the lamp voltage monitoring method, then both high- and low-energy electrons diffuse to each other, being almost free from electricity. As a result, it takes the cathode surface a long time to reach the thermionic emission temperature as shown in Fig.8. On the other hand, if the discharge current increasing just after ignition is rather high (see Fig.2), then high-energy electrons can immediately arrive at the cathode surface with some electricity as shown in Fig.9(b). It follows from this that it takes the cathode surface no time to reach the thermionic emission temperature. The observation of getting a shorter emission time by the lamp ignition method, of which the heating current is rather high, can be understood in terms of the presumed rapid-decrease in lamp voltage as shown in Fig.10. We do not believe that the shorter emission time causes premature thermionic emission. According to this idea, the lamp ignition method is worth standardizing because it meets the final purpose of obtaining an adequate lifetime of a lamp even though it does not meet the IEC concept excluding a lamp starting. To use this method, it is necessary to establish a measuring procedure for the voltage-controlled preheating mode.

Fig.10 Time variation of expected lamp voltage by the method based on lamp ignition tests.

6. Preheating Energy and Substitution Resistor

It is important to know the consumed energy to preheat cathodes up to the thermionic emission temperature. The energy has a relationship to the minimum emission curve, together with the average resistance of a cathode as explained in Chapter 2. Fig.11 shows one of measuring results, including each curve of minimum thermionic emission, average resistance of a cathode and consumed preheating energy. They are measured by two methods of the lamp voltage monitoring and R_h/R_c methods under the current- and voltage-controlled preheating modes.

Fig.11 Comparisons of emission curves, average resistance curves of a cathode and emission energies between two preheating modes and two measuring methods.

It follows from Fig.11 that emission curves are well characterized according to their preheating modes, whereas for energy lines it is more difficult to find the difference in characteristics between measuring methods and preheating modes as compared to emission curves⁹⁾. Even then, we can see that the slope of the energy line by the voltage-controlled preheating mode tends to be larger than by the other preheating mode.

The above-mentioned content is an only aspect from a viewpoint of preheating characteristics of a cathode but not from the requirement. Indeed the energy line has less capability of describing the preheating characteristics, but the

point we should consider here is that the expression by an energy line has a possibility to be useful for the preheating requirement. That will be addressed below.

Fig.12 Average resistance curves of a cathode together with thermionic emission points by the lamp voltage monitoring method.

It seems that the average resistance value of a cathode over the period up to the emission time in Fig.11 is almost constant over a range of emission times. This idea is confirmed further by Fig.12, which shows the average resistance curves of a cathode for 16mm-diameter (T5), 2-foot length tubular fluorescent lamps together with minimum thermionic emission points. These results were obtained by the new measuring criterion in Section 3.2, not by the previous one⁶⁾. According to the theory in Chapter 2, the average resistance value can be taken as a substitution resistor value. Therefore, the following equations for the requirement by an energy line are derived from eqs. (7) and (12).

$$E_{min} = aR_{sub} + i_m^2 R_{sub} \cdot t_h \quad (18)$$

$$E_{min} = b/R_{sub} + v_m^2/R_{sub} \cdot t_h \quad (19)$$

where E_{min} is a common required preheating energy between the current- and voltage-controlled preheating modes, and R_{sub} is a common substitution resistor in place of R_{cs} and R_{vs} . The value of R_{sub} is almost equal to, but not less than the values of R_{cs} and R_{vs} . According to this idea, R_{sub} is given as the value similar to that of R_{vs} , which is always larger than that of R_{cs} . This value is much less than that in the present IEC data sheet, and is similar to 3.1 times R_c value reported by European lamp manufacturers¹⁰⁾.

Fig.13 Time variation of R_h/R_c value of a cathode under current- and voltage-controlled preheating conditions.

The quantity of 3.1 may correspond to the average R_H/R_c value over the period up to the emission time as shown in Fig.13. It is apparent from Fig.13 that the way of determining a substitution resistor value, $X(=3.1)$ times R_c , has a similar relationship to measuring the average resistance value of a cathode over the period up to the emission time. We can, therefore, understand that the way of X times R_c will become a practical way to determine a substitution resistor value in the case where there is no means of measuring the average resistance of a cathode. Incidentally, the determination of the quantity X requires much more discussion because it depends on the emission times by each method.

Figs.14 (a)-14(c) show the preheating requirements of the current- and voltage-controlled thermionic emission curves (a), (b) and the energy line (c). The cathodes, whose lamp-cap type was GX24q(multi)32W in compact fluorescent lamps, were examined by the lamp voltage monitoring method. The circular marks ○ and ● in Fig.14 indicate the current-controlled thermionic emission points, and the square marks □ and ■ indicate the voltage-controlled thermionic emission points. The black-and-white marks show the differences in test cathodes between European lamp manufacturers.

According to the emission points in Fig.14(c), the intercept and slope values of minimum required energy line are determined provisionally as 1.0 and 0.6, respectively, so that almost all the emission points are less than the line. If the energy line in Fig.14(c) is much larger than the suitable one, the minimum current- and voltage-controlled preheating requirement curves in Figs.14(a) and 14(b) will go upward together far from each emission point. Furthermore, if the substitution resistor value is much smaller than the suitable one, the minimum current-controlled preheating requirement curve in Fig.14(a) will go upward and the minimum voltage-controlled preheating requirement curve in Fig.14(b) will go downward, and vice-versa according to eqs.(18) and (19).

It follows from the significant idea that the substitution resistor value needs to be determined preferentially. It is concluded here that by careful determination of the intercept and slope values of a minimum required energy line, together with a suitable value for the substitution resistor we can arrive at the goal of finding the most practical preheating requirements. As a result, three kinds of the preheating requirements in Fig.14 could be balanced with each other. It means that the determination of a minimum required preheating energy line together with a substitution resistor value can also result in the determination of both the minimum current- and voltage-controlled preheating requirement curves.

The larger value for the average resistance of a cathode in two manufacturers employed in this measurement was 7.4 ohms. The value was obtained under the lamp voltage monitoring method of voltage-controlled preheating condition. This value corresponds to $X=2.8$ in the way of X times R_c , where the resistance of lead-wire is excluded from R_c when multiplying X , and is added again after multiplying X . In such a discussion, there could be some other cathode cases where the value X will be determined to be around 3.1. After

all, the required values in Fig.14(c) will be determined in consideration of the standardization.

Fig.14 Preheating requirement by energy lines(c) together with another requirements of current- and voltage-controlled preheating modes(a),(b).

7. Maximum Preheating Requirement

The present maximum preheating requirement in the IEC is expressed by the broken lines as shown in Fig.12. It is better to amend the requirement in more detail to prevent lamp ends from blackening. As for the voltage-controlled preheating mode, to determine a maximum preheating requirement is not so important due to the limited flow of the heating current through a cathode. That is more important in the case of the current-controlled preheating mode. It should be given as a

curvature similar to the minimum preheating requirement curve, which can provide an useful information for helping to standardize a new maximum preheating requirement by energy expressions. The way to determine the curve is addressed below:

Fig.15 Lamp end blackening points and their curve.

A certain current by the lamp ignition method is applied to a test cathode for some duration repeatedly to examine whether lamp ends blackening occurs at less than 10 times. The relationship to blacken the lamp ends between the applied current and the heating time is investigated. The continuous current which blacken the lamp ends within 3.0 h, which should be called as the absolute maximum current i_{max} , is also determined simultaneously. When the preheat time is supposed to be 1.0 s, the three-hour duration corresponds to a short-cycle operation test of more than 10,000 times. From these data the new maximum preheating requirement curve, as shown in Fig.15, is provided as follows:

$$i_k = (c/t_h + i_{max}^2)^{1/2} \quad (20)$$

where c is a constant. As the value of i_{max} is already given, the value c can be easily determined by substituting a typical point (t_h, i_k) , which makes lamp ends blacken, for eq.(20). The proper cathode-preheating condition by an electronic driver combined with a suitable substitution resistor should be given in a region enclosed with the minimum and maximum preheating requirements of eqs.(2) and (20).

The maximum preheating requirement by an energy line is needed as well as the minimum one. As pointed out previously, the above-mentioned approach is very helpful for determining it. Both energies on the maximum and minimum preheating curves up to the same heating time measured in the test are shown in Fig.15. They were compared to each other. As a result, the ratio of the maximum to minimum preheating energy is estimated modestly to be around 2.5. According to the idea by ELMAPS the maximum energy is recommended to be 1.75 times as large as the minimum energy¹¹⁾. The ratio 1.75 is acceptable as a requirement because the ratio, which is less than our estimation, can prevent cathodes from overheating. After all, as for the determination of a maximum energy requirement line according to this manner, it is greatly important to obtain a minimum energy requirement line

preferentially.

The maximum requirement curves in Figs.14(a) and 14(b) are derived from the maximum energy line in Fig.14(c). As a result, electronic ballast manufacturers will need to design their electronic drivers so that their preheating functions will obtain emission points in each region of Figs.14(a), (b) and 14(c) by using a suitable value for the substitution resistor.

8. Conclusions

This paper summarizes the presentations made at the PRESCO/COMEX Panel at BSI held in London in June 30, 1998 and the 8th International Symposium on the Science & Technology of LIGHT SOURCES at Institute for Low-Temperature Plasma Physics and Department of Physics University of Greifswald held in Germany in August 31, 1998. The essential points of our view including the other significant ideas have been expressed in the preceding pages. The conclusions are summarized as follows:

- (1) According to the IEC concept excluding lamp ignition, the lamp voltage monitoring method can be used to measure emission times.
- (2) From the viewpoint of preventing lamp ends from blackening, but making an allowance for including lamp starting, the lamp ignition method can also be used.
- (3) When the duration of the heterogeneous heating in a cathode is negligible, the R_h/R_c method can provide emission times.
- (4) The average resistance value of a cathode over the period up to the emission time can be regarded as a substitution resistor value, and closely corresponds to the value of around 3.1 times as large as that of the cold coil resistance. The value mainly depends on the emission time by each method.
- (5) The maximum preheating requirement in the present IEC data sheet should be amended in more detail. It is to be expressed by an energy line.
- (6) The energy expression having an intercept and a slope values, together with a suitable value for the substitution resistor, has a possibility of achieving good performance for common preheating requirements, and is apart from both the current- and voltage-controlled preheating terminal conditions. On the other hand, it can be transformed again into both the current- and voltage-controlled preheating curves for the requirements of each mode.

9. Acknowledgement

With new trends in reconstructing preheating requirements for fluorescent lamp cathodes in the IEC, this paper examined various points as to the requirement issues raised over the last couple of years. We are greatly pleased if we could contribute something to colleagues who are challenging in PRESCO to complete the preheating requirements by energy expressions. We appreciate their efforts. We also thank Dr. H. Akutsu of ex-Matsushita Electronics Corporation for his encouragement.

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