Paper

Improved Characteristics of Inductively Coupled Electrodeless Metal Halide Lamps

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ABSTRACT

Methods were investigated to improve the lamp characteristics of inductively coupled electrodeless metal halide lamps to make them practical. First, evaluating lamp efficacy by adjusting the lamp parameters showed that a lamp efficacy of 180 lm/W (Including coil loss: 151lm/W) white color could be attained. Second, the conditions generating free iodine and bulb deterioration, the main factors limiting the life of these lamps, were investigated. For long-life-type lamps, which had 130 lm/W of lamp efficacy, the lamp lumen level did not decrease during 21,000 hours of overload operation (corresponding to 58,000 hours of rated-load operation). These lamps thus have excellent lumen maintenance and life performance compared with conventional electrode metal halide lamps. Third, improving circuit reliability by decreasing the Q value of the resonant circuit was investigated for long-life-type lamps which had 145 lm/W of lamp efficacy. The relationship between the Q value and the lamp parameters was analyzed, and the Q value was decreased to 78% its value while maintaining the same lamp performance.

KEYWORDS: electrodeless metal halide lamp, free iodine, long life, lumen maintenance

1. Introduction

The discharging methods used in electrodeless lamps are the electric field-coupled discharge, the inductively coupled discharge, the microwave discharge, the surface wave, and so on. Various discharging methods are already in practical use in the low pressure type, and lamps that adopt the microwave discharging method and that contain sulfur or ferrous halides have been put into practical use in the high pressure type ¹⁾. However, in the high pressure type, lamps that adopt the inductively coupled discharge method and that enclose metallic halogens (inductively coupled electrodeless metal halide lamps) are not yet at the stage of being in practical use.

Basic studies have been actively made since 1961²⁾ on the induction arc as a heat source, which is obtained by having the rare gases such as argon discharged by a high frequency current flowing through a coil wound around the light emitting bulb. Around the middle of the 1980s, metallic halides were adopted as filling chemicals and the properties of lamps with various kinds of fillings ³⁾ were evaluated and methods for measuring the light efficacy and the electrical properties were studied ⁴⁾.

The inductively coupled electrodeless metal halide lamp was announced as a practical system by C. N. Stewart et alia in 1992 ⁵⁾. After that, a basic analysis of light output operated by a rectangular wave ripple⁶⁾, a study of properties of horizontal lighting ⁷⁾, and a study of lamp ignition characteristics ⁸⁾ were made. Also, in regard to the

circuit, studies were made to improve the lamp ignition characteristics through frequency control ⁹⁾ and to analyze the design parameters of the matching circuit to reduce the influence of the lamp-driving coils ¹⁰⁾. Measuring the plasma in the lamps has been done using the laser-excited fluorescence method and the luminous spectrum method¹¹⁾. However, compared to metal halide lamps with electrodes, which have been studied from various aspects and for which a huge volume of knowledge has been compiled, inductively coupled electrodeless metal halide lamps, which have a quite different discharging method and on which the influence of the circuit is especially large in spite of its being fundamentally the same metal halide lamp, have had very few studies. Therefore, its study from various aspects are required.

This study was made on methods of improving the overall lamp performance with the goal of the practical use of high-performance inductively coupled electrodeless metal halide lamps. The first study was on an improvement of the light efficacy. Although high efficacy in metal halide lamps has been realized through the selection of filling materials, optimization of the discharge, and so on, efficacy is considered to have nearly reached the optimum level in lamps with electrodes. By adopting a discharge method that is different from that used with electrode type lamps and by optimizing the filling materials and the discharge parameters, a high efficacy of 180 lm/W

(Including coil loss: 151 lm/W), which vastly exceeds the properties of the electrode type lamp, could be obtained.

The second study was on the extension of the lamp life and the improvement in life performance. It is known that the lumen maintenance of metal halide lamps with electrodes is very poor in general. In many cases, the poor lumen maintenance is attributable to the electrodes. Therefore, an improvement in lumen maintenance can be expected in the electrodeless type. As a result of the analysis of the life-limiting factors in the electrodeless type and the application of countermeasures, a lifetime of 60,000 hours, high lumen maintenance, and stable properties during the lifetime could be obtained.

The third study was the improvement in the matching characteristics of the drive circuit. The inductively coupled electrodeless metal halide lamp has a resonance (Q) of great sharpness in the induction coil section and, therefore, changes in the resonant state due to deviations in lamp properties and changes in the properties over the lifetime is large. This makes it difficult to design the circuit. In this study, the relationship between the Q value of the long-life-type lamp and the lamp parameters was analyzed, and it was possible to reduce the Q value significantly while maintaining lamp performance.

Although the conditions to achieve a high efficacy lamp could be obtained as shown above, their consolidation is a subject to be solved in the future since high efficacy tends to contradict life performance and drive circuit matching characteristics.

2. Analysis of Lamp Performance

2.1 Structure of Inductively Coupled Electrodeless Metal Halide Lamps

The system's main components are the high frequency electric power section and the matching circuit, the induction coil section, and the lamp section¹²⁾. In this system, a high frequency of 13.56MHz is output from the high frequency power source and it is converted to the load impedance by the matching circuit. Here, the impedance at the induction coil in the state of being electro-magnetically coupled with the discharge resonates with the parallel capacitance in the matching circuit, and the electric power is effectively conducted to the induction coil and lamp.

Although there are various kinds of lamp structures and lamp ignition methods for inductively coupled electrodeless metal halide lamps, the following describes this system.

Let us first discuss the lamp structure. It has a lighting bulb made of silica that is shaped like a rotating ellipse, in which the diameter is greater than the length in the direction of the axis in consideration of the shape of the discharge. Xenon gas, ScI_3NaI or NdI_3NaI as the main luminous chemicals, and SnI_2 as an additive chemical for extending life fill the inside of bulb. The induction coil is wound for two turns on the outside circle at the maximum diameter. In the light-on state, a sphere-like discharge with a high luminance section like a ring is formed in the bulb's inside alongside the section of maximum diameter. An

Fig. 1 Lamp ignition method for inductively coupled electrodeless metal halide lamp.

ignition assistance discharge tube made of silica was connected at a position on the axis of rotation of the lighting bulb. This tube was filled only with a rare gas at a pressure lower than the pressure in the lighting bulb. By the way, an outer envelope surrounding the lighting bulb was attached when necessary.

Next is the lamp ignition method. The conceptual scheme of the lamp ignition method is shown in Fig. 1. To assist ignition an electric conduction plate with an area exceeding a certain level is attached at one end of the discharge tube on the side opposite to the lighting bulb. At the time of ignition, a high frequency, high voltage is initially impressed on this electric conduction plate, and then it is impressed on the inside of the ignition assistance discharge tube by electrostatic coupling through the dielectric silica of the tube wall, and breakdown occurred resulting in the generation of corona discharge. Then, this corona discharge acts as an electrical conductor and a high frequency, high voltage is impressed on the separating wall between the lighting bulb and the ignition assistance discharge tube. Similarly, a high voltage is impressed on the inner surface of the lighting bulb by electrostatic coupling, and breakdown occurs in the lighting bulb. When the high frequency electric current under this state is transferred to the induction coil, resulting in the generation of sufficient magnetic field, it shifts to the arc discharge and the lamp is ignited.

2.2 Measuring Method for Lamp Performance

There are some lamp performance parameters in the inductively coupled electrodeless metal halide lamps that are difficult to measure directly, and this is different from common HID lamps. They are, for example, the whole lumen output and the electrical properties such as the lamp voltage. The following describes the measuring methods for evaluation.

Table.1 Lamp performance of Inductively coupled metal halide lamps.

	Lamp luminous efficacy	Resonance sharpness Q	Relative color temperature	Color rendering properties	Inner diameter of lighting bulb	Enclosed chemicals	Enclosed gases	Outer envelope	Lamp input power	Inner diameter of induction coil
High-efficacy-type	180(lm/W)	23	5000(K)	74	27(mm)	NdI ₃ -NaI-SnI ₂	Xe33(kPa)	Yes (vacuum)	400(W)	33.5(mm)
Long-life-type	145(lm/W)	14	3800(K)	58	29(mm)	SrI ₂ -NaI-SnI ₂	Xe33(kPa)	Nil	300(W)	33.5(mm)

2.2.1 Measuring Method of Whole Lumen Output

In the inductively coupled electrodeless metal halide lamps, it is necessary to install an induction coil in the vicinity of the lighting bulb. Therefore, for measuring the whole lumen output of the lamp alone, it is necessary to make an adjustment for the absorption of the induction coil, which must be measured in advance. Also, the matching circuit as well as the induction coil is placed in the integrating sphere when the light is measured, since it is necessary to place the induction coil in the vicinity of the matching circuit because the induction coil is a part of the resonance circuit. Thus, absorption by the matching circuit also occurs, which should be adjusted jointly with the absorption by the induction circuit. The absorption ratio was obtained by placing a halogen lamp, which had a diffusing bulb with the same shape as the discharge, at the position of the lighting bulb in the induction coil. The induction coil used for the test was made of aluminum plates and with a two-turn coil, for which the lumen absorption ratio was about 10%, while the matching circuit used for the test had a structure designed to eliminate shading and absorption as far as possible, for which the lumen absorption ratio was about 10%. By the way, various luminescence properties were obtained simultaneously with this lumen measuring.

2.2.2 Measuring Method of Electric Properties

The electrical properties such as the lamp voltage and the electric current can not be measured directly in this lamp. Therefore, measuring the electric properties was made by a method to obtain them through calculation using the element value of the matching circuit in the on-state and the impedance of the induction coil that was measured in advance. In the following, Z represents the load impedance including the induction coil, X_c represents the induction coil reactance under a no-load state, R_a represents the resistance component of the discharge ring, and X_a represents the reactance of the discharge ring. The electrical properties of the discharge are expressed by a ratio of a real number component and an imaginary number component of the impedance of the discharge ring, α ; the magnetic coupling coefficient between the induction coil and the discharge ring, k ; and the resonance sharpness of the resonant circuit composed of the matching circuit and the induction coil, which includes both of these data, Q ¹³. Here, Z is expressed by the following equation.

$$Z = k^2 \cdot X_c \cdot \frac{R_a \cdot X_a}{R_a^2 + X_a^2} + j \cdot X_c \cdot \left(1 - k^2 \cdot \frac{X_a^2}{R_a^2 + X_a^2} \right) \quad (1)$$

Also, α and Q are expressed by the following equations.

$$\alpha = \frac{R_a}{X_a} \quad (2)$$

$$Q = \frac{a^2 + 1 - k^2}{a \cdot k^2} \quad (3)$$

Among them, Q is comparatively reproducible, but α and k require higher measuring precision in order to secure reproducibility. In this report, the Q value on which sufficient reproducibility could be obtained was evaluated principally, while α and b were also evaluated.

2.3 Analysis of High-Efficacy-Type Lamp for Efficacy Improvement

In designing the lamp, a design to achieve an especially high luminous efficacy increases the resonance sharpness in the lamp and the induction coil section Q resulting in difficulties achieving circuit reliability. Simultaneously, there is the tendency that reactions between the lamp envelope and the enclosed chemicals are accelerated resulting in problems with the lamp life. In this study, two

Fig. 2 Spectral power distributions for high-efficacy-type lamps and long-life-type lamps. (a)High-efficacy-type lamp(NdI₃-NaI) (b)Long-life-type lamp(SrI₂-NaI).

kinds of lamps — a lamp designed to achieve high efficacy and a lamp designed to achieve long life — were developed and evaluated in order to use the merits of each type¹³⁾. The initial stage properties of each type are shown in Table 1 and the spectral power distributions of each type are shown in Fig. 2.

In the high-efficacy-type lamp, the maximum efficacy obtainable with the inductively coupled method was pursued. Xenon gas, NdI_3 - NaI as the main luminous chemicals, and SnI_2 for long life were enclosed in a lighting bulb with an inner diameter of 27mm, while mercury, which is a load material for environmental conservation, was not used. It had an outer envelope made of silica, and the lamp input power was 400W. By adopting several methods to get higher efficacy, a luminous efficacy of 180 lm/W, which was the highest level in the cool white light source was obtained. The spectral distribution showed an intense continuous radiation of Nd, and the properties obtained were a correlated color temperature of 5,000K and an R_a (CRI) of 74. The lamp parameters that influenced the efficacy as well as the changes in efficacy when they were varied are described in the following.

Fig. 3 Heating method by the thermal refraction effect.

Fig. 4 Comparison of inner bulb temperature for lamp with outer envelope shaped to concentrate light and that for lamp with normally shaped outer envelope.

2.3.1 Relationship between Lamp Parameters and Efficacy

(1) Addition of Outer Envelope with Reflected Light Concentration

The effect of the addition of an outer envelope was evaluated as the first parameter. In this test, an outer envelope with specific functions, as shown in Fig. 3, was installed over the single wall bulb lamp. In many cases, the lower hemisphere of the lighting bulb becomes the coldest portion in the operating direction as shown in Fig. 3, where the plane of the induction coil turns is level. The outer envelope, as shown in Fig. 3, is formed in the shape of a rotating elliptical curved surface in the downward direction of perpendicular line, and this section more than other section of the outer envelope reflects the radiated infrared light toward the lighting bulb, which results in heating the lower hemisphere of the lighting bulb. Furthermore, since the focus of the elliptical surface of the outer envelope is positioned near the exhaust tip where the temperature is the lowest, the temperature of this coldest section can be effectively increased by reflection and concentration at a certain level. An example of the thermal retention effect of this outer envelope is shown in Fig. 4. An intensive temperature increase of about 60°C could be realized in the vicinity of the tip portion, where the reflected light was concentrated, by installing of an outer envelope in which the inside was at atmospheric pressure. Simultaneously, the temperature increased at the portion from -13mm to -5mm, where the chemicals stuck, and the efficacy was improved. Since the maximum temperature remained unchanged during this time, it is considered that the influence of the light-concentrating outer envelope on the life performance is small. The efficacy improvement by the installation of the outer envelope was 19 lm/W with the enclosed chemicals ScI_3 - NaI - SnI_2 and 45 lm/W with the enclosed chemicals NdI_3 - NaI - SnI_2 in the case of xenon enclosed at 33 kPa and the lamp input being 300W.

Fig. 5 Lamp enclosed chemicals and input wattage versus luminous efficacy.

(2) Changes in Lamp Fillings and Changes in Input Wattage

The influences of the lamp chemical fillings and the input wattage on the luminous efficacy were evaluated as the second and third parameters. In Fig. 5, a comparison is made of the enclosed chemicals used for a long-life-type lamp, $\text{ScI}_3\text{-NaI-SnI}_2$, and the luminous chemicals used for a high-efficacy-type lamp, $\text{NdI}_3\text{-NaI-SnI}_2$, both enclosed in a lamp with an outer envelope, with a varied input wattage. The pressure of the enclosed xenon was 33kPa. As a result, the lamp containing $\text{ScI}_3\text{-NaI}$ showed an efficacy peak in the vicinity of 300W. It is considered that this phenomenon is related to $\text{ScI}_3\text{-NaI}$ that has a tendency, at a temperature above a certain level, to saturate the efficacy improvement owing to an increased temperature at the coldest section as well as to an expansion of the discharge diameter accompanied by the wattage increase. On the other hand, in the lamp containing $\text{NdI}_3\text{-NaI-SnI}_2$, the NdI_3 vapor pressure increased drastically in parallel with an increase in the input wattage resulting in an increase in the continuous radiation of Nd and an improvement in efficacy. As a result, $\text{NdI}_3\text{-NaI}$ showed a higher efficacy at wattages above 300W. The maximum efficacy was obtained with an input wattage of 400W in the $\text{NdI}_3\text{-NaI}$ lamp, which was 180 lm/W (Including coil loss: 151 lm/W). By the way, this lamp can not maintain normal operation with an input wattage exceeding this level.

(3) Changes in Enclosed Xenon Gas

The gas pressure of the enclosed xenon was varied as the fourth parameter and the corresponding changes in the luminous efficacy and so on are shown in Fig. 6. With a $\text{NdI}_3\text{-NaI-SnI}_2$ lamp with an outer envelope and an input wattage of 400W, the xenon pressure was varied in the range from 8 kPa to 33 kPa, and the results showed that the luminous efficacy increased when the pressure was higher in this range. This is considered attributable to a reduction in thermal loss to the bulb wall under higher pressure. On the other hand, in parallel with an increase in the xenon pressure, there is a tendency for the breakdown voltage to increase drastically and the ignition characteristic to deteriorate. Therefore, it is necessary

Fig. 6 Rare gas pressure versus lamp performance.

when achieving a high efficacy to enclose the xenon with the highest allowable pressure within the range that will enable ignition breakdown, and xenon at 33 kPa was selected in this study. Also an increase in xenon pressure is considered to be advantageous from the view point of the lamp life since the distance between the discharge ring and the bulb wall gets greater when the pressure is increased.

(4) Changes in Lighting Bulb Diameter

Changes in efficacy due to changes in the lighting bulb diameter, that is the fifth parameter, were studied. Fig. 7 shows the results of changes in the inner diameter in the range from 24mm to 28mm with a $\text{NdI}_3\text{-NaI-SnI}_2$ lamp with an outer envelope and an input wattage of 400W. Changes in efficacy due to changes in diameter were small in this range and the efficacy increased gradually with an increase in the diameter. It is considered to be one of the factors for this small change that, as shown in Fig. 8, the bulb temperature distribution is equalized when the bulb diameter gets larger. In the high-efficacy-type lamp for this study, the diameter of 27mm, at which the efficacy was lower than that of 28mm by 1.4%, was selected in order to use a coil and matching circuit that was prepared for the previous experiment.

Fig. 7 Inner bulb diameter versus luminous efficacy.

Fig. 8 Inner bulb diameter versus bulb temperature distribution.

Table.2 Comparison of energy balance.

	Electrode loss	Ultraviolet rays 280–380nm	Visible light 380–780nm	Infrared rays 780–2500nm	Thermal loss	Efficacy	Color rendering property R_a (CRI)
400W metal halide lamp	9.5 (%)	4.9 (%)	28.7 (%)	10.1 (%)	46.8 (%)	100(lm/W)	65
400W electrodeless lamp	0 (%)	1.4 (%)	58.5 (%)	15.1 (%)	25.0 (%)	180(lm/W)	74

2.3.2 Comparison of Energy Balance

A $\text{ScI}_3\text{-NaI}$ metal halide lamp (400W) with a mercury lamp operation stabilizer was chosen as a regular white light source with the highest luminous efficacy. The spectral distributions of this lamp as well as those of the 400W high-efficacy-type electrodeless lamp were measured in the range from the ultraviolet 280nm to the infrared 2500nm, and the energy balance shown in Table 2 were developed using the measured results and the values of the electrode losses cited from a reference ¹⁴. The electrode losses disappeared in the lamp used for this study due to the lack of electrodes, and also it should be noted that the thermal loss was reduced to a half. Therefore, it is assumed that high efficacy was obtained owing to the conversion of these losses to the radiation of visible light. Also, the sum of the radiation energy in the ultraviolet zone and the infrared zone were equivalent to each other. It is considered as one of factors for the small thermal loss that, since the inductively coupled electrodeless metal halide lamp has a ring-shaped discharge in which the temperature is at the maximum in the vicinity of the bulb wall ¹¹, the transmitted heat from the inner periphery of the ring-shaped discharge is not transmitted to the bulb wall and is re-absorbed by the discharge.

2.3.3 Evaluation of System Efficacy

Although the luminous efficacy of 180 lm/W was obtained in the high-efficacy-type lamp, the practical efficacy obtainable from the lamp is reduced due to shading by the induction coil and power losses. In the case of this experiment, the loss from induction coil shading was 10%, the resistance loss was 6%, and the total coil loss was 16%. The total efficacy of the lamp and the coil section after these reductions was 151 lm/W. Also, the loss in the high frequency power circuit section is comparatively large in the inductively coupled electrodeless metal halide lamp system, and reduced the system efficacy by about 20%. Realizing high efficacy in the power circuit will be a key point for improving system efficacy in the future.

Although the high-efficacy-type lamp was designed taking parameters as mentioned before into consideration, the temperature of the lighting bulb was higher due to the installation of the outer envelope, increased input wattage, and so on. As a result, the vapor pressure of the enclosed metal halide increased and the resonance sharpness, the Q value, increased by 5 compared to the long-life-type lamp with the same lighting bulb diameter. There is a tendency toward lower circuit reliability and higher induction coil loss when the Q value is increased, making it disadvantageous compared to the long-life-type lamp. Also,

an increase in lighting bulb temperature is considered to be disadvantageous for lamp-life compared to the long-life-type lamp.

2.4 Dimming Characteristics of High-Efficacy-Type Lamp

This lamp has the feature that dimming can be accomplished comparatively easily, in spite of its being a metal halide lamp. One of reasons is the low level of color changes caused by temperature changes of the lighting bulb owing to the lack of mercury. Another reason is that a high temperature can be maintained at the coldest section of the lighting bulb with a low input wattage owing to the small mass of the lighting bulb as well as a tendency for the temperature distribution in the lighting bulb to be more equalized with a low input state. Furthermore, one of the reasons is that the power control is easy owing to the use of an electronic ballast. There are no great changes in color and no great deterioration in efficacy with the high-efficacy-type lamp, as shown in Fig. 9, and a deep dimming is possible. Color deviations as shown here can be comparatively freely adjusted by changing the ratios of the enclosed NdI_3 and NaI .

2.5 Ignition Characteristics of Lamp

Changes in the breakdown voltage and the coil current at the time of ignition with the enclosed xenon pressure varied from 8 kPa to 33 kPa are shown in Fig. 6. Here, the breakdown voltage is the impressed voltage on the ignition assistance discharge tube at its end electrode at the time when the corona discharge is generated in the lighting bulb. Also, the coil current in the ignition stage is the coil current at the time of the corona arc transfer when the corona discharge is maintained. Although both increase in parallel with an increase in xenon pressure, the increase in the breakdown voltage is especially drastic. It is believed that the reason why the increase in current is more gradual is related to the fact that the corona discharge shrinks under higher pressure.

Fig. 9 Dimming characteristics of high-efficacy-type lamp.

Fig. 10 Life performance of long-life-type lamps with inner diameter 27mm.

3. Life Performance of Long-Life-Type Lamp

3.1 Life Performance

In designing the long-life-type lamp, the goal was to realize a life exceeding 40,000 hours by means of carefully balancing various properties versus life performance and by adopting methods of improvement as described in section 3.2. The tested lamps were single wall bulbs with inner diameters from 27mm to 29mm, in which xenon gas, the principal luminous chemicals $\text{ScI}_3\text{-NaI}$, and the life-extending chemical SnI_2 were enclosed, but in which no mercury was used. The input wattage was 300W. The lamps had a luminous efficacy of 145 lm/W at a maximum, a relative color temperature of 3800K, and an R_a (CRI) of 58.

3.1.1 Life Performance of Lamp with Inner Diameter of 27mm

An accelerated life evaluation was made under an overload operation with 400W input power to the lighting bulb with an inner diameter of 27mm for which the standard lamp input power was 300W. The acceleration rate is assumed to be approximately 2.7 times based upon another experiment¹²⁾. Changes in properties during the lives of the two test lamps are shown in Fig. 10. The luminous efficacy of these lamps at 300W was 130 lm/W. Sample 1 has been operated for an assumed 58,000 hours equivalent, or for 21,000 hours in actual operation, and its operation is still continuing. A notable point is that there is no tendency for reduction in the total lumen output during this period, and this can be said to be a good example of the effect of being electrodeless. On the other hand, there is no tendency for changes in color temperature and also there is no tendency for large changes in the Q value that correspond to the electrical properties of the discharge. Also, the generation of free iodine, which is a life-limiting factor, has been completely suppressed owing to the added SnI_2 . There is no noticeable change in the condition of the lighting bulb compared to the initial stage of operation; there is utterly no blackening nor loss of transparency, and little increase in translucency. By the way, although these lamps are single wall bulbs, there is no transparency loss on the outer surface.

Fig. 11 Life performance of long-life-type lamps with inner diameter 29mm.

3.1.2 Life Performance of Lamp with Inner Diameter of 29mm

This lamp was designed by adopting the improvement plans in section 4 so that the Q value could be reduced in order to make matching with the drive circuit easier while maintaining the other lamp properties as much as possible. The Q value was reduced to 14 compared to 18 with the 27mm type. The results of the life evaluation are shown in Fig. 11 and, similar to the previously described lamps, the changes in various properties are small after approximately 10,000 equivalent hours of operation.

With the above results, the possibility was shown of realizing a long life exceeding about 60,000 hours in the metal halide lamp by using the electrodeless operation method. At the same time, lumen reduction and color changes can be significantly decreased.

3.2 Problems in Realizing Long Life

It is known that the following problems are the principal limitations on life with electrodeless metal halide lamps¹⁵⁾: (1) poor ignition, (2) unstable arc, (3) cessation, (4) lamp breakage, and (5) poor operation of the drive circuit.

It has been clarified that (1) through (3) are mainly attributable to the generation of free halogen and (4) is attributable mainly to transparency loss and increased translucence of the lighting bulb. By the way, (5) is likely to occur in cases of large Q values.

The free halogen and the conditions that cause transparency loss and increased translucence, as well as the methods of their control, will be explained in the following.

Fig. 12 I_2 absorption function of SnI_2 .

3.2.1 Countermeasures for Free Iodine

(1) Free Iodine Measuring Method

In the lighting bulb in which a metal halide is used, the amount of halogen becomes excessive over the lamp's lifetime due to reactions between the silica and the metal halide as well as because of the disappearance of the metallic ions by transmission through the silica. Although the generation of free halogen gas is low in a lamp containing mercury because of the formation of HgI and so on, free iodine gas is generated in this lamp. This gas snuffs the discharge since it strongly adheres to electrons and results in arc instability, arc cessation, and deterioration in ignition performance. In this study, the addition of SnI_2 as a method of suppressing the generation of free iodine was evaluated. A non-destructive measurement of the amount of free iodine generated was made by a method using the absorption band of free iodine gas with its center in the vicinity of 510nm ¹⁵⁾. In the measured cases, the amount of free iodine generated was reduced to a half when the enclosed chemical was melted by heating to remove the water component before its use. This indicates that controlling the quantity of impurities in the lamp is important.

(2) Effect of Suppressing Free Iodine by SnI_2

An appropriate quantity of SnI_2 was added to lamps with $\text{ScI}_3\text{-NaI}$, $\text{NdI}_3\text{-NaI}$, or NaI-TII-InI enclosed as the principal luminous chemicals, and the lamps were operated for 3000 hours. As a result, it was confirmed that the generation of free iodine was completely suppressed by the addition of SnI_2 , while the generation of free iodine was observed with each chemical combination in cases where no SnI_2 was added. One of mechanisms for SnI_2 suppressing the free iodine generation can be considered to be that the reactions were suppressed by the reduction in the probability of the simple metal existing in the vicinity of the bulb wall owing to an increase in the metal halide vapor pressure in the bulb¹⁶⁾. Other than that, there is the possibility that the SnI_2 functions as a getter of free iodine I_2 . This getter effect regarding iodine was evaluated in this study. Here, the assumed reaction equation was $\text{SnI}_2 + \text{I}_2 \rightarrow \text{SnI}_4$. For evaluation, three electrodeless lighting bulbs were prepared in which SnI_2 and I_2 were enclosed with mole ratios of 2 : 1, 1 : 1, and 1 : 2, and they were heated to the temperature of an operating lighting bulb in an electric furnace for 30 hours. The results are shown in Fig. 12. The

Fig. 13 Photograph of SiO_2 etching region and deposit region for operated lamp. (a) (c): deposit region, (b): etching region.

I₂ in the samples with enclosure ratios of 2 : 1 and 1 : 1 disappeared immediately after the heating started, while the I₂ in the sample with the enclosure ratio of 1 : 2 was reduced to a half. Thus, the free iodine absorption effect of SnI₂ was confirmed by these results, and it is considered that SnI₄ was formed by the reaction.

From the above results, it is understood that there are two kinds of actions with SnI₂. The first effect is the suppression of the reactions at the bulb wall and by this the iodine generation is lowered. The second effect is the absorption of the generated iodine. Since an increase in the enclosed quantity of SnI₂ causes a reduction in the efficacy and increases the *Q* value, it is necessary to reduce the enclosed quantity of SnI₂ as far as possible.

It is considered that the generation of free iodine can be suppressed for a long time even with a small quantity of SnI₂ owing to the first effect.

3.2.2 Countermeasures for Translucence and for Transparency Loss

There are cases of translucence increase and transparency loss generated in this lamp, similar to that of regular metal halide lamps. Various factors such as the kinds of enclosed chemicals, temperature, mixtures of impurities, and electric fields can be considered to be the causes of the generation of these effects, and it is known that they can be suppressed by appropriate lamp design, selection of chemicals, treatment, manufacturing method, and so on.

(1) Phenomenon

An example of translucence generated during operation is shown in Fig. 13. Etching was observed on the inner surface of the silica in the vicinity of the induction coil where the temperature was the highest, while deposits of silica were observed at both ends of the lighting bulb where the temperature was low. A part of the deposited silica was found being changed to Tridymite with crystalline structure causing a loss of transparency. When the crystallization proceeds further, lamp breakage occurs due to a difference in expansion coefficients. It is assumed that translucence increase and transparency loss are generated most conspicuously in the vicinity of the induction coil where the temperature reaches the maximum level in many cases and the strongest electric field is generated.

Through a supplementary experiment on an unused lamp heated in an electric furnace, it was found that etching and deposits were generated by heat at 1100°C for 50 hours. The effect's appearance is shown in Fig. 14, where an etched region and a deposit region are intermixed at random. This is considered to be attributable to a sufficiently small temperature inclination. Surface cracks were found generated on the surface of the deposit region, as was SiO₂ with a crystalline structure of higher density than that detected in an operating lamp. It is believed that the higher density is attributable to the

Fig. 14 Photograph of SiO₂ etching region and deposit region for fired fused silica capsule. (a): deposit region, (b): etching region.

higher temperature applied in the experiment than in an operating lamp.

(2) Suppression Method

The relationship between the OH radical density in the silica and the translucence level was evaluated in an study to reduce the impurities in the silica¹⁵⁾. Test samples were prepared from silica anhydride with an OH radical density below 1 ppm. The silica was formed into bulbs with an oxy-hydrogen burner and the OH radical density was changed by means of controlling the processing time and heat vacuum treatment time as well as by surface etching with fluoric acid. Lamps were made from these bulbs, and the relationship between the translucence level and the OH radical density was evaluated after operation for a certain length of time. The results are shown in Fig. 15. It was demonstrated that the translucence is apparently small in the lamps with a low OH radical density and that there is a correlation between the OH radical density and translucence. It was confirmed with these results that translucence can be suppressed by a reduction in OH radical density. From the practical point of view, the translucence is satisfactorily small with a density of 3 ppm, and its growth over lifetime is small. By the way, the distribution of OH radicals in silica and their penetration channels are under study.

Fig. 15 OH radical density in vitreous silica versus translucence.
Translucence = translucent area × Translucent degree

4. Improvement in Matching Characteristics Versus Circuit

The gradient of the electrical potential of the discharge is high in the electrodeless discharge of an inductively coupled-type HID lamp due to the high discharge density. Also, the distance between the discharge and the bulb wall, the thickness of the lighting bulb, and the gap between the lighting bulb and the induction coil can not be reduced below certain levels. The Q value tends to get comparatively large due to these factors, and, for example, the Q value is about 18 in the case of a long-life-type lamp with an inner diameter of 27mm. However, when the Q value becomes larger, changes in the resonance state get larger, that are caused by changes in the discharge during the lamp's life and by changes in the electrical properties of the induction coil, and a reduction in lamp power input, an increase in power source losses, and increases in the failure ratio are triggered. In order to prevent them, it is desirable to put the Q value below 15 with this system. Thus, changes in the electrical properties with varied lamp parameters were studied in this section, with the aim of reducing the Q value through lamp design.

4.1 Resonance Sharpness (Q) in Induction Coil Section

Calculation was made in order to obtain the relationship between the ratio of a real number component and an imaginary number component in the impedance of the discharge ring, α , and the Q value with the condition that the magnetic coupling coefficient between the induction coil and the discharge ring, k , was varied step by step, and the results are shown in Fig. 16. The actually measured levels for this lamp were, for example, approximately 0.33 for k , 1.9 for α , and 19.3 for Q . When these points are plotted in the figure, the changes in the remaining parameters when one parameter is changed can be predicted.

Fig. 16 Correlation between Q , α and k

4.2 Relationship between Lamp Parameters and Q Value

Changes in the Q value when the lamp parameters were varied were jointly evaluated with α , k , and the luminous efficacy. The varied parameters were (1) the diameter of the lighting bulb, (2) the diameter of the induction coil, (3) the heat maintenance condition, (4) the lamp input wattage, (5) the enclosed gas pressure, (6) the quantity of SnI_2 , (7) the kinds of chemicals, and (8) the chemical ratio.

The results with (1), (2) and (5) above that showed comparatively large changes will be discussed below.

4.2.1 Influence of Sizes of Induction Coil and Lighting Bulb

An appropriate gap is usually set between the high temperature lighting bulb and the induction coil in order to obtain excellent life performance and lighting properties. In this study, the sizes of induction coil and lighting bulb were enlarged or reduced while keeping the gap between them constant. The changes in various properties at that time were assessed as follows. Firstly, in the case of increased diameters of the coil and the lighting bulb while keeping the gap constant, the geometric ratio of the circular area formed by the inner diameter of the coil to the circular area formed by the inner surface of the lighting bulb wall gets smaller. Therefore, it was assessed that the coupling intensity between the discharge ring and the induction coil is increased resulting in an increase in k . In regard to α , a resistance component of the discharge that corresponds to the numerator in equation (2) increases in proportion to the expansion of the discharge ring diameter. On the other hand, since an inductance component of the discharge corresponding to the denominator increases in proportion to the area of discharge ring, α was resultantly determined to be reduced. Meanwhile, although it can be judged from Fig. 16 that the Q value will be reduced owing to an increase in k and a decrease in α , it is believed that the effect of the increase in k is dominant. Also, the luminous efficacy of the lamp is considered to be reduced due to a reduction in the temperature at the coldest section that occurs with the expansion of the lighting bulb. On the other hand, including the shading loss from the induction coil, is judged to increase, since the expansion of induction coil was done so that the coil diameter alone was expanded while the cross-sectional area of the electric conductor section was kept constant. Therefore, the shading loss from the induction coil is reduced when both the coil and the bulb are expanded. As a whole, it is considered that the influence of the reduction in temperature at the coldest section is comparatively large and that the efficacy is reduced gradually with an increase in diameters.

The experimental results are shown in Fig. 17. The gap between the induction coil and the inner wall of the lighting bulb was kept at 2.25mm. There were a reduction in Q value, an increase in k , and a reduction in α with the expansion of the lighting bulb diameter, which were consistent with the above assessment. On the other hand,

Fig. 17 Inner bulb diameter versus lamp performance with fixed coil gap. (a) Q , luminous efficacy (b) α , k

the efficacy including shading loss from the induction coil was maximum with the inner diameter of the lighting bulb at 29mm, which was different from the prediction. It is considered that one of the factors that caused this deviation from the prediction is that, over the range of these load ratios as shown in Fig. 8, the bulb temperature distribution tends to equalize with a reduction in load ratio. It is believed that the case of an inner diameter of 29mm maintained a similar level of luminous efficacy to the case of 27mm owing to this factor and that the efficacy, including coil shading loss, was increased owing to a reduction in the shading loss of the induction coil. In Fig. 8, when the inner diameter was expanded, the temperature at the coldest section was maintained while the maximum temperature was reduced. However, since in reality the chemicals stick to portions of the inner bulb other than the coldest section, the luminous efficacy is considered to be reduced to some extent due to the reduction in the chemicals' temperature in these other portions. It is considered that this influence becomes dominant with a lamp with an inner diameter of 31mm, resulting in a reduction in efficacy. In view of the above results, a lighting bulb with an inner diameter of 29mm was adopted.

4.2.2 Influence of Lighting Bulb Diameter

For this experiment, the induction coil diameter was kept constant while the lighting bulb diameter was expanded. Although it would be undesirable in a practical application, the bulb was expanded in this experiment to the extent that it contacted the induction coil. Following is the assessment of the changes in the various properties.

Fig. 18 Inner bulb diameter versus lamp performance with fixed coil dimension. (a) Q , luminous efficacy (b) α , k

Firstly, it was assessed that, when the bulb diameter is expanded, the discharge ring is expanded with an increase in diameter, causing a drastic increase in its coupling intensity with the induction coil and that, as a result, k increases drastically. In regard to α , it was assessed that an inductance component of the discharge, which is the denominator of α in equation (2), increases drastically in parallel with an expansion of the area of the discharge ring. On the other hand, as described in section 4.2.1, it was assessed that the vapor pressure of the metal halide decreases due to a reduction in the temperature of the chemicals and that the resistance per unit length of discharge gradually decreases. However, it was assessed that a resistance component of the discharge increases simultaneously in proportion to an increase in the discharge ring diameter and that this becomes dominant and that the resistance component of the discharge or the numerator of α increases. As a whole, it was judged that α is reduced because the increased ratio of the inductance component of the discharge is larger than the increased ratio of the resistance component. Meanwhile, when changes in the Q value are checked based upon Fig. 16, both an increase in k and a reduction in α have the effect of reducing the Q value, and it is considered that the Q value decreases drastically mainly due to an increase in k . Furthermore, the efficacy, including shading loss from the induction coil, was assessed to decrease gradually due to an increase in shading loss, which is caused by the movement of the bulb toward the induction coil during its expansion. The measured results are shown in Fig. 18. In parallel with an expansion of the bulb diameter, k increased, the Q value decreased, and the efficacy decreased, and this was consistent with the assessment mentioned above. However, α showed only small changes up to 29mm and it decreased above that level. It is considered as one of the causes for such decrease that, as described in section 4.2.1, since the temperature at a section where the chemicals stick is reduced in the case of a 31mm diameter, the reduction in α due to the reduction in the vapor pressure of the metal halide became dominant. For a long-life-type lamp, an inner bulb diameter of 29mm was adopted based upon the results in section 4.2.1.

Fig. 19 Rare gas pressure versus lamp performance. (a) Q , luminous efficacy (b) α , k

4.2.3 Influence of Rare Gas Pressure

Since mercury is not enclosed in this lamp, the pressure in the bulb under operation depends upon the pressure of the enclosed xenon, which has a large influence on the electrical properties of the discharge. In an experiment, the pressure of the enclosed xenon gas was varied from 8 kPa to 33 kPa. Following is an assessment of the changes in various properties under such conditions. It was assessed that k is reduced since the discharge has a tendency to contract when the xenon pressure is increased. In regard to α , it was assessed that, although the resistance component of the discharge per unit length was predicted to increase with an increase in the operating pressure, the discharge length gets shorter due to the contraction of the discharge ring and that the changes in resistance are offset. On the other hand, it was assessed that the inductance component of the discharge, or the denominator of α , decreases as a result of the contraction of the discharge ring and that α is increased as a result. Regarding the changes in Q value, it is assessed based upon Fig. 16 that Q increases drastically due to the multiplication effect of k and α . Also, it is judged that the luminous efficacy of the lamp is considered to be improved owing to a reduction in the heat conduction loss accompanying a contraction of the discharge ring.

Measured results are shown in Fig. 19, and pictures of the discharge ring with varied xenon pressure are shown in Fig. 20. In Fig. 20, it can be seen how the discharge contracts and luminance increases with an increase in xenon pressure. In Fig. 19, α and Q increased and the efficacy was improved accompanying an increase in xenon pressure, and such changes are consistent with the above assessment. However, k slightly increased up to 17 kPa in deviation from the assessment, although it decreased in the higher range of pressure. One of the causes for this deviation from the assessment is believed to be that, simultaneously with the contraction of the discharge ring under increased xenon pressure, there arose a phenomenon in which a comparatively thin discharge at the central portion of the discharge ring was reduced and

the coupling intensity increased substantially. In this case, it is considered that the latter phenomenon was dominant up to 17 kPa and the former phenomenon was dominant above 17 kPa. Here, α also increased up to 17 kPa while k was increasing. The reason is considered to be that an increase in the resistance component of the discharge, or the numerator component of α , becomes dominant compared to an increase in the reactance component of the discharge, or the denominator component of α . By the way, xenon at 33 kPa has been adopted for the long-life-type lamp in view of these results as well as those in section 2.3.1 item (3).

As a result of the evaluation of the above, the Q value was improved from 18 to 14 while an equivalent luminous efficacy was maintained in the lamp after improvement of the Q value.

5. Conclusion

Efficacy changes under varied lamp parameters were evaluated in inductively coupled electrodeless metal halide lamps, and a white illuminant with the maximum luminous efficacy of 180 lm/W (Including coil loss: 151lm/W) was obtained in the high-efficiency-type lamp. Also, evaluation was made on conditions of generation and suppression methods in regard to the generation of free halogen, transparency loss, and increased translucence of lighting bulbs, which are the main factors limiting the life of these lamps. A long-life-type lamp with a luminous efficacy 130 lm/W and an inner diameter of 27mm, on which these suppression methods were applied, was operated for about 21,000 hours in an over-load condition (equivalent to 58,000 hours in standard condition) without reduction in lumens, and an expectation of being able to attain the life performance of 60,000 hours was ensured. Through the experiment, it was proved that the lumen maintenance property of electrodeless metal halide lamps is excellent compared to metal halide lamps with electrodes. Also, in the long-life-design lamps, improvement

Fig. 20 Rare gas pressure versus discharge ring diameter. (a)8kPa, (b)16kPa, (c)33kPa

in the reliability of the drive circuit by a reduction in the resonance sharpness between the discharge ring and induction coil, Q , was studied. As a result of the evaluation of changes in the electric properties, including Q , under varied lamp and induction coil parameters, a lamp with a luminous efficacy of 145 lm/W, in which the Q value was reduced by 22% while suppressing a reduction in efficacy, was obtained.

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