The convection phenomena in the high pressure sodium lamp

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High pressure sodium lamp is known as a light source in which convection phenomena of the arc are so small. Recently, arc tubes with larger diameter and high pressure xenon filling have been used for the HPS lamps with high color rendition or high luminous efficacy. It was found that the convection phenomena were not negligible in such HPS arc tubes. This was confirmed by measuring the 475 nm sodium line intensity and knowing by the displacement of the arc axis. The results are:

(1) **The convection becomes larger with increase in arc tube diameter and filling xenon pressure.**

(2) **The convection becomes smaller with increase in the power input.**

The temperature difference between the upper and lowerside of the arc tube wall in the horizontal operation reaches 40-50°C and this local heating of the arc tube will be a problem in the life of HPS lamps.

1. Introduction

High Pressure Sodium (HPS) Lamps have been known as the light source with highest efficacy in the general lighting. Lately HPS lamps with better color rendition[1)2)] and high color rendition[3)] have been developed in the world. In such developments, larger diameter arc tubes or high pressure xenon filling have been used. It is found the convection phenomena were not negligible in such HPS arc tubes.

Convection phenomena have been known and studied in the high pressure mercury lamps and metal halide lamps[4)5)]. These phenomena have been studied mainly on life characteristics of the lamps and radiation characteristics, not on the energy loss process. Elenbaas[4)] calculated the convection loss in case of 1.75 kW mercury lamps and obtained the value of 0.5 W/cm (1.5% of power input.) This value was fairly smaller than the radiation loss of about 60% power input or the conduction loss of 10 W/cm and it is estimated that the convection loss was negligible in the energy balance.

The direct influence of the convection in the HID (High Intensity Discharge) arcs is considered to be some non-uniform phenomena caused by deviated arcs. For instance, the wall temperature of the upper side of the arc tube in the horizontal operation is not the same as the lower side of the arc tube. In the vertical operation, non-uniformity of the temperature distribution of the upper and the lower side of the arc tube causes the poor life characteristics. In the metal halide lamps, the aditive segregation appears with the convection flow[5)] and on the contrary this segregation decreases with more active convection[6)7)].

In this report, we studied the convection phenomena in HPS arc by knowing the radial intensity distribution of a sodium line.

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2. Convection flow in the arc

In the convection phenomena of the arc, the heat source is the center core of the arc both in the vertical and horizontal operation. Light gas heated at the arc core moves upward and heavy gas moves into the arc core. This movement makes a circular flow as shown in **Fig 1**. This flow is decided by 3 forces, the buoyancy force produced by pressure difference $\mathbf{F}_b$, the viscous force between the arc core and outer layer $\mathbf{F}_v$ and the gravity force $\mathbf{F}_g$. A mechanical balance equation is;

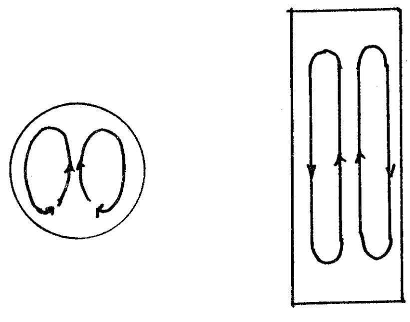

Fig. 1 *Gas flow of the convection.*

$$F_b - F_g - F_v = 0 \quad \cdots\cdots (1)$$

The convection velocity at each point of r (r : radius) has been calculated for knowing the convection characteristics.
From Elenbaas[4)], the equation (1) is written in the analytical form;

$$-2\pi r dr \cdot (dP/dZ) + \frac{d}{dr}(2\pi r\eta \cdot dv/dr) - 2\pi r\rho g = 0 \quad \cdots\cdots (2)$$

where Z coordinates is set up to arc axis and P : pressure of gas, ρ : gas density, η : viscosity and

v : convection velocity.

$v(r)$ is solved as follows [at the boundary condition $(dv/dr)_{r=0}=0$ and $v(R)=J$, R : tube radius]

$$v(r)=\frac{A}{2}\int_0^r r/\eta dr+g\int_0^r 1/\eta_r\int_0^r \rho r dr dr+C \quad \cdots\cdots(3)$$

where $A(\equiv dP/dZ)$ and C are constants.

The calculated results will be discussed in 4. One of the experimental method for the confirmation of the convection phenomena had been made by Suit in 1939[8]. He mixed Boron Nitride in the vertical gap between the carbon electrodes and measured the convection velocity by the incandescent particle. (v=130 cm/sec) In this report, these phenomena will be discussed by the deviation of the arc from the tube axis.

The arc moves upward by the buoyancy force caused from the convection. This movement increases with the convection until the buoyancy force is balanced with the wall stabilizing force. So, if the convection is not so large, (while the buoyancy force is not balanced) we are able to know the magnitude of the convection phenomena by such arc deviations.

3. Samle lamps and the measuring method

The sample lamps used in this measurement had 8.0 mm ID and 11 mm ID sapphire arc tubes filled with the sodium-mercury amalgam and 20~300 Torr pressure of xenon gas. Measurement of the deviation of the arc was carried out by measuring the radial intensity of the arc. The operating position was a little bit inclined to the vertical axis (about 13°) in order to obtain "arc deviating effect" as in the horizontal operation. Three positions of the arc tube were selected in this measurement; top portion (13~15 mm distanced from the top electrode) middle and bottom portion (13~15 mm distanced from bottom electrode.)

The measuring device was almost the same as reported before[9]. The different point from the former device was to put a slit in order to measure the inclined image of the arc (**Fig. 2**). In this case, the radial distance was measured from $-R/\cos\theta$ to $+R/\cos\theta$ instead from $-R$ to $+R$ (**Fig. 3**), however, the excess distance was 2.5 mm in 11 mm ID arc tube, so it is considered not to be effective to the result. Measured line was selected to be Na 475 nm. The obtained data were not inverted to the emission coefficient because it is not necessary to know in this measurement.

4. Result

Figures 4~7 show the results of this measurement in the form of the radial intensity data. **Figure** 4 shows the case of the 8 mm ID arc tube with 20 Torr pressure of xenon (arc length 89 mm) which has been considered to have less convection phenomena. The arc axis is almost in accord with the tube axis. In order to know the magnitude of arc deviation in more quantitative form, deviation value D was defined as follows;

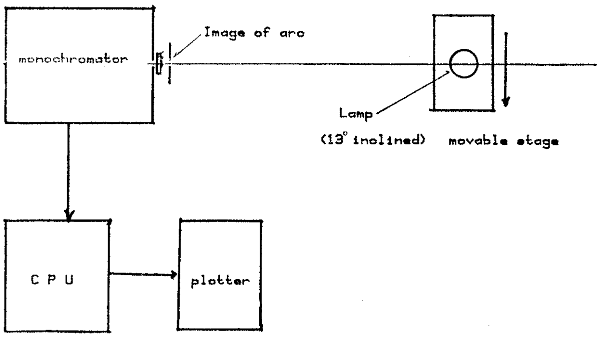

Fig. 2 *Optical measuring system.*

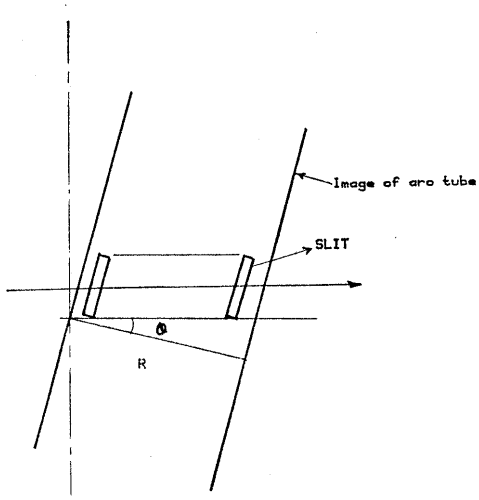

Fig. 3 *The radial intensity measurement.*

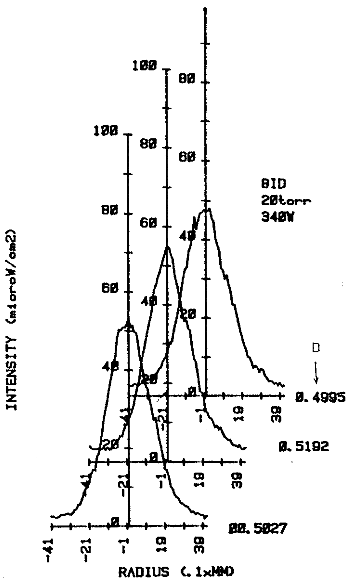

Fig. 4 *The radial intensity data (1).*

$$D=\int_0^{+R'/2}\Big|\int_{-R'/2}^{+R'/2}P(r)\,dr\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

where $P(r)$: the radial intensity, R': the measured distance across the inclined arc tube.

D represents the ratio of (+) side section to the total section of the intensity distribution and if the shape of the distribution is symmetry, D is estimated to be 0.5. Each value of D was written at the right bottom portion in Figures 4~7.

Although the radial intensity distribution should be symmetry in Fig. 4, D is not just 0.5. It may come from the inaccuracy of this measurement. (including the surface condition of SCA) Therefore, the error of D value should be estimated to be in less than ± 0.02.

Figures 5~7 show the results of the case of 11 mm ID arc tube with 300 Torr of xenon gas (arc length 57 mm). In **Fig. 5** (260 W), we could find D~0.7 at the bottom of the arc tube. From **Fig. 6** and 7, D value decreases with the power input.

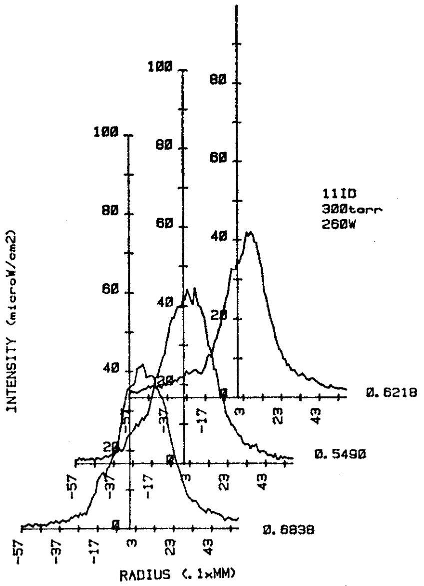

Fig. 5 *The radial intensity data (2).*

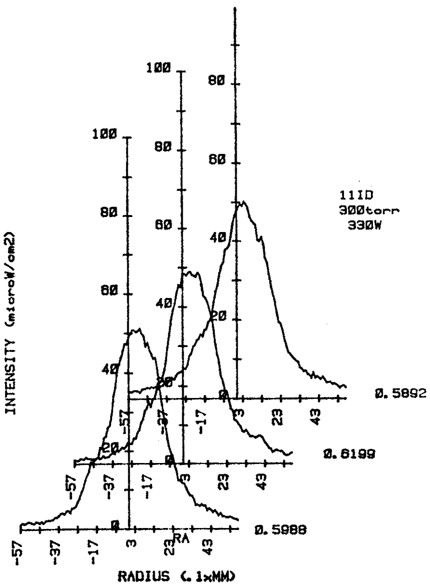

Fig. 6 *The radial intensity data (3).*

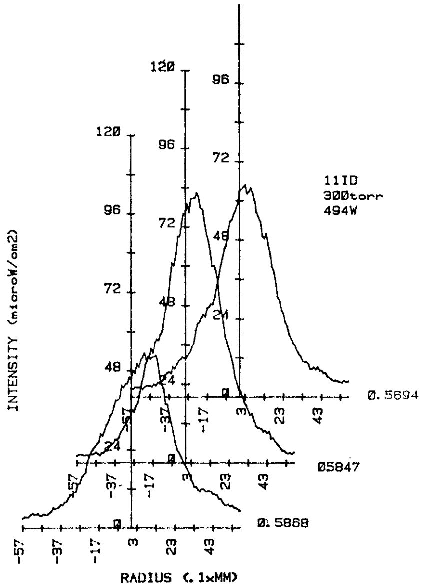

Fig. 7 *The radial intensity data (4).*

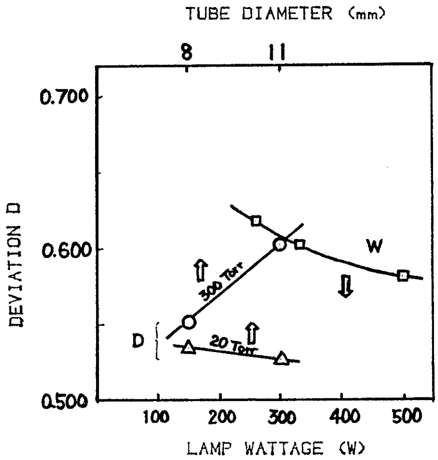

Fig. 8 *Deviation D, function of tube diameter and lamp wattage.*

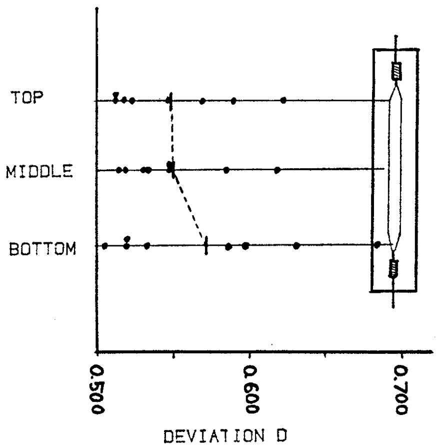

Fig. 9 *Deviation D at the various positions (Dashed line: average).*

Figure 8 shows the summarized result of Fig. 5~7. If we consider D value as the magnitude of convection phenomena, it is easily found from Fig. 8,

(1) the convection decreases with the power input.

(2) the convection increases with xenon gas pressure and arc tube diameter.

Figure 9 shows D value of the different arc tube position, top, middle and bottom. D value of the bottom is larger than any other position. This result suggests that the lower side (bottom) of the arc is dynamically unstable where colder gas flows into by the convection.

5. Convection velocity and viscosity

In this section, we will discuss about the result obtained before. At the first, we calculate the convection velocity by the mechanical balance equation (3). The procedure of the calculation was the same as the literature (Elenbaas)[4]. Several conditions concerned with the arc temperature profile and arc tube radius were used in this calculation.

(1) Arc temperature distribution in the literature[4] was approximated as,

$$T=5885-(5885-765)\left(\frac{r}{2.05}\right)^2 \quad \cdots\cdots(5)$$

(2) and the other profiles,

$$T=5885-(5885-765)\left(\frac{r}{2.05}\right)^{1.5} \quad \cdots\cdots(5a)$$

and

$$T=5885-(5885-765)\left(\frac{r}{1.00}\right)^2 \quad \cdots\cdots(5b)$$

The profile of (5a) was introduced by the consideration on the high pressure xenon filling arc which has the "thin" arc temperature profile. The profile of (5b) was introduced by the assumption that the arc deviation originated from the convection phenomena decreased with decrease in the arc tube diameter. **Figure 10** shows the calculated result based on the former conditions. In this figure, the curve of "Elenbaas" denotes the convection velocity calculated by the arc temperature profile (5). "(1)" and "(2)" denote the velocities calculated by the profile (5a) and (5b) respectively.

From Fig. 10, it is evident that the convection velocity in case of "thin" arc temperature distribution is larger than that of "thick" distribution. This result supports that the convection velocity in high pressure xenon filling arc is larger than low pressure xenon filling arc. The convection velocity in case of (5b) suggests that the convection phenomena decreases with decrease in the arc tube diameter. These results are seemed to fit our experience.

In the equation (3), $v(r)$ is a function of viscosity η. ($v(r)$ decreases with η) We will calculate the viscosity of Na-Hg-Xe gas mixture, using the semi-empirical equation,

$$\eta_j=\eta_{1j}\cdot N^2_{1j}+\eta_{12j}\cdot N_{1j}N_{2j}+\eta_{2j}N^2_{2j} \quad \cdots\cdots(6)$$

where N_{ij}: molar ratio, j; the suffix of combinations of Na, Hg, Xe and the empirical value of η_{12j} was approximated to be

$$\eta_{12}=(\eta_1+\eta_2)/2 \quad \cdots\cdots(6a)$$

For example, $\eta_{Na+Hg}=\eta_{Na}N_{Na}+(\eta_{Na}+\eta_{Hg})N_{Na}\cdot N_{Ng}/2+\eta_{Hg}N_{H}{}^2{}_{g}$

The value of η of Hg was used from Elenbaas (5). η of Na was conducted from the thermal conductivity equation[10)11)] and η of xenon was lead by the Sutherland's formula[12)],

$$\eta\mathrm{Hg}=5.5\times10^{-6}T^{3/4},\quad \eta\mathrm{Na}=4.44\times10^{-7}T,$$

$$\eta\mathrm{Xe}=210\times10^{-6}\left(\frac{525}{T+252}\right)\left(\frac{T}{273}\right)^{3/2} \quad \cdots\cdots(7)$$

Figure 11 shows the calculated results of η of the function of xenon pressure, using (6a) and (7). From Fig. 11 it is evident that the viscosity of the gas mixture decreases with xenon pressure. This result means that the convection velocity increases with xenon pressure. From these facts obtained above, xenon gas plays a role which varies arc temperature profile and also the viscosity of gas so as to increase the convection phenomena with pressure. From Fig. 11 and the equation (7), the

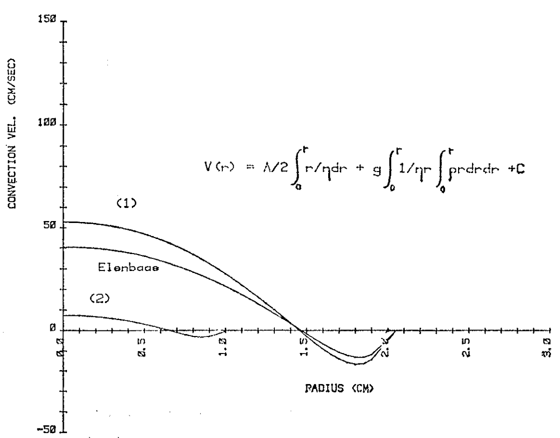

Fig. 10 *Calculated convection velocity.*

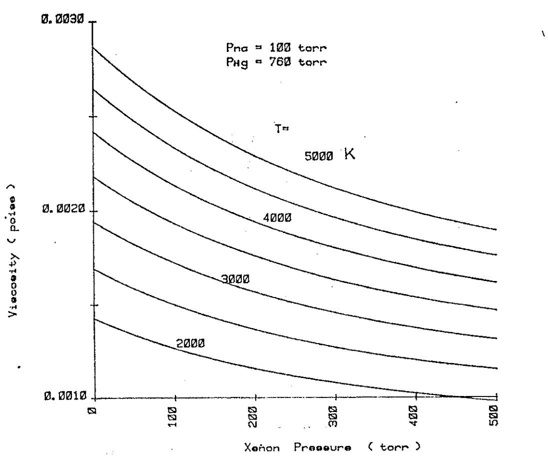

Fig. 11 *Viscosity vs. xenon pressure.*

viscosity increases with arc temperature. (effective temperature in this case.) From the fact that arc temperature increases with the power input, the tendency of the Fig. 8 can be understood that the viscosity increases with the power input so as to decrease the convection and it leads smaller deviation in Fig. 8.

Increasing the power input also leads an uniform temperature profile and it means to decrease the convection phenomena.

From these considerations and the experimental results, it is reasonable to know the convection phenomena by measuring the arc deviation.

6. Wall temperature and convection loss in the horizontal operation

Maclain et al[5] reported that the temperature difference between the upper and lower side of the arc tube wall in the horizontal operation of the high pressure mercury arc became 300°C at 2.89 atom of mercury. If the convection occurs in HPS arc, the arc would float and make the temperature difference as in the mercury arc.

Figure 12 shows the result of HPS arc with 11 mm ID arc tube and 300 Torr xenon filling measured by a 0.3 mmϕ PR thermo couple. The temperature of the upper side of the arc tube was 40°C higher than that of the lower. Although such a difference would decrease with power input, the convection affects the wall temperature difference at least in the range of less than 400 W power input.

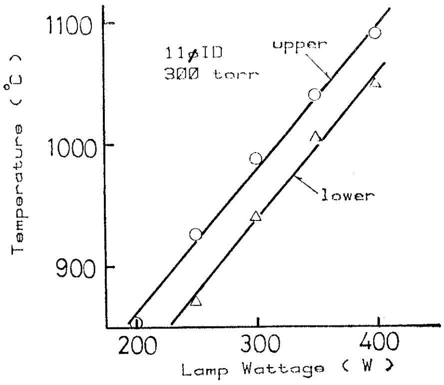

Fig. 12 *Wall temperature (Horizontal operation).*

Using the wall temperature data of Fig. 12, the convection loss was estimated by the energy balance at the wall. Introducing the convection loss Pconv, the energy balance equation is,

$$P_{\rm rad}^{\rm out}=\tau(P-{\rm Pcond})\quad\text{(no convection arc)}\cdots(8a)$$

$$P_{\rm rad}^{\rm out}=\tau(P-{\rm Pcond}-{\rm Pconv})\quad\text{(convection arc)}\cdots\cdots(8b)$$

where $P_{\rm rad}$; the radiation loss through the arc tube (W/cm) τ; the transmittance for the radiation, P; the power input (W/cm), Pcond; the conduction loss (W/cm). If τ in convection arc is the same as in no convection arc and if Pconv could be expressed in the linear function of P (Pconv$=AP+B$. A, B constant), $P_{\rm rad}$ can be written as follows;

$$\begin{aligned}P_{\rm rad}^{\rm out}&=\tau(P-{\rm Pcond}-AP-B)\\&=\tau(1-A)\left(P-\frac{{\rm Pcond}+B}{1-A}\right)\\&=\tau'(P-{\rm Ploss})\cdots\cdots(9)\end{aligned}$$

where $\tau'=\tau(1-A)$ and ${\rm Ploss}=\dfrac{{\rm Pcond}+B}{1-A}$

If we know τ, Pcond, τ' and Ploss, Pconv can be estimated by (9) and the relation of Pconv$=AP+B$. These values can be decided by measuring the wall temperature of the arc tube. (see ref. (13) (14)) The wall temperature data of Fig. 12 were used for the convection arc. The heat loss at the wall was devided into the upper side and lower side in this case.

Figure 13 shows the result. From this Figure, we know $\tau=0.84$, Pcond$=7.98$, $\tau'=0.772$ and Ploss$=1.4$. So we obtain $A=0.08095$ and $B=6.693$ and

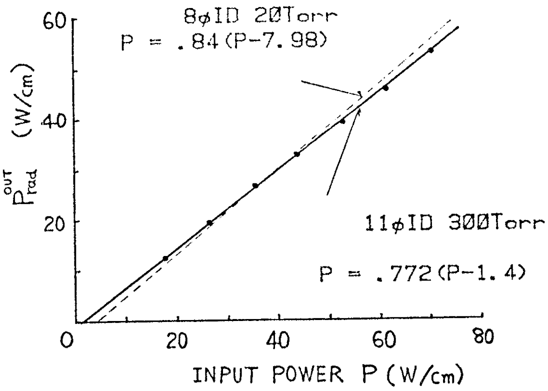

Fig. 13 *The radiation loss.*

$${\rm Pcond}=0.08095(P-82.7)\cdots\cdots(10)$$

In the equation (10), the convection loss increases with the power input, and it is different from the former consideration.

The main reason of this difference may be that these calculations were carried out by the assumption without a consideration on the change in the arc temperature distribution, although more work on details is needed.

However, the convection loss can be estimated to be 0.6 W/cm at 90 W/cm of P (only 0.7% of P) and the convection mainly appears at the lower power input in this experiment, so the convection loss may be negligible in the energy balance of the arc. Therefore the main problem of the convection phenomena in the HPS lamps would be for the life characteristics such as arc tube cracking or evaporation of the arc tube material caused by non-uniformity of the wall temperature.

7. Conclusions

The consideration of the convection phenomena in the HPS arc was studied. The following results were obtained,

(1) The convection phenomena become larger with increases in arc tube diameter and filling xenon gas pressure.

(2) The convection phenomena become smaller with the power input.

(3) The wall temperature difference of the upper and lower side of the arc tube wall in the horizontal operation becomes larger (40~50°C in this experiment) and it may be a problem for the HPS lamps.

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