Investigation of luminous efficacy in scandium-sodium iodide arc lamps

Masato SAITO*, Shoichi TAGUCHI*, Ryo SUZUKI* and Keiji WATANABE*

Sc-Na metal halide lamps are occupying an important place as energy saving light sources because of the high luminous efficacy and the good color rendition. In order to realize higher luminous efficacy, authors have investigated the effect of lamp design factors on radiation properties and luminous efficacy under the condition of higher $NaScI_4$ mole fraction.

Based on the results of the precise measurements, the effects of the lamp design factors related to the cold sport temperature on the radiation properties have been well understood. The novel approach as well as the optimization of the lamp design factors at lower cold temperature have realized a high luminous efficacy of 121 lm/W in 400 W scandium-sodium iodide lamps.

1. Introduction

Among the various kinds of metal halide arc lamps, scandium-sodium iodide arc lamps are occupying an important place as a light source because of a high luminous efficacy and good color rendition. The spectral power distribution emitted from this light source mainly consists of several lines from Hg, *D*-lines from Na, and a large number of lines radiated from Sc. The radiation from the additives is significantly affected by chemical and physical phenomena, which are roughly classified into two groups. One is thermochemical properties of ScI_3–NaI molten salt which determine the vapor pressure and composition over the molten salt. The other is axial and radial energy flow in the arc column. Concerning the thermochemical properties, solution ideality of ScI_3–NaI molten salt and formation of both complex compound and polymers must be considered. Concerning the energy flow, such a theoretical arc model is needed including transport of reaction energy due to diffusion, heat conduction fluxes, radiation fluxes, axial convection, and axial and radial demixing effects.

Since higher vapor pressure of the additives is primarily preferable for lamp efficacy, various kinds of complex compounds have been studied[1)~3)]. In scandium-sodium iodide arc lamps, it can be assumed that the complex compound of $NaScI_4$ is predominant in the vaporizing process from the molten salt[2)]. The vapor pressure of $NaScI_4$ is much greater than that of either NaI or ScI_3.

This paper describes the relationship between several factors for lamp design and radiation properties in scandium-sodium iodide arc lamps, specifically for high $NaScI_4$ mole fraction in the molten salt. A novel approach to realize higher luminous efficacy is also described.

* Mitsubishi Electric Corporation, Consumer Products Research Laboratories. 14-40, Ofuna 2-chome, Kamakura 247 JAPAN

2. Experiments

2.1 Factors in the design of scandium-sodium iodide arc lamps

We picked up additive composition, quantity of the salt, and the cold spot temperature as the factors which affected the vapor composition and the vapor pressure from the molten salt. Work pointed out that the deviation of ScI_3–NaI molten salt from ideal solution was little[4)]. Therefore, the vapor pressure of the molten salt can be described as a function of $NaScI_4$ mole fraction in $NaScI_4$–NaI salt.

We also picked up an inner diameter of arc tubes and specific wall loading, as the factors which affected the axial and radial energy flow. The specific wall loading was defined as $W/\pi DL$, where W was lamp wattage, D was inner diameter of the arc tube and L was electrode separation. The above two factors also had a certain influence upon the cold spot temperature of the arc tube. We examined the effect of inner diameter only with constant wall loading, because measurement of radiation properties was made for the lamp with an outer bulb and for the arc tube dipped in molten indium to control the vapor pressure. More precise experiments are required for strict consideration.

Table 1 shows a list of lamp design specification. From 1–A to 1–D, the effect of $NaScI_4$ mole fraction (X) in $NaScI_4$–NaI melts was examined with constant inner diameter and constant wall loading. Different mole fraction of $NaScI_4$ was realized by changing quantity of NaI, while quantity of $NaScI_4$ was constant. From 2–E to 4–J, the effect of iodides-quantity, inner diameter (I.D.) and wall loading (W.L.) were examined with constant $NaScI_4$ mole fraction of 0.39.

Cylindrical arc tubes which had been pressed from fused quartz were used. The configuration of arc tube was not modified. Heat conserving end-coatings were not painted on the arc tube ends.

Table 1 *A list of lamp design specification.*

		INNER DIA (cm)	WALL LOADING (w/cm²)	NaScI4MOLE FRACTIN	DOSE of IODIDE
1	A	1.95	15.55	0.39	1.00
	B			0.78	0.77
	C			0.20	1.47
	D			0.10	2.42
2	E			0.39	0.50
	F				2.00
3	G		18.14		1.00
	H		21.76		
4	I	1.8	15.55		
	J	2.2			

The arc tube was charged with 25 Torr of argon and the outer bulb was charged with 360 Torr of nitrogen. Therefore, the cold spot temperature of the arc tube in the outer bulb was estimated to be lower than usual.

2.2 Luminous efficacy

It is well known that the overall luminous efficacy can be split into the visible radiant efficiency and the luminous efficiency of the visible radiation. The visible radiant efficiency is the fraction of the electrical input power radiated in the visible wavelength range of the spectram (380~780 nm).

$$\eta=\eta_e \cdot K \ (\mathrm{lm/W}) \cdots\cdots(1)$$

$$\eta_e=\int_{380}^{780} P\lambda d\lambda \Big/ \mathrm{Win} \cdots\cdots(2)$$

$$K=680\int_{380}^{780} V(\lambda)\cdot P\lambda d\lambda \Big/ \int_{380}^{780} P\lambda d\lambda \ (\mathrm{lm/W}) \cdots(3)$$

2.3 Experimental measurements

The arc tubes were always operated vertically at 400 W input power, and at first, measurements of electrical characteristics and luminous flux in the integrating sphere were made for the test lamps with an outer bulb, and measurements of the spectral power distribution were also made by the spectroradiometer. Spectroradiometry involves the comparison of the standard source and test sources. Then we can calculate the visible radiant efficiency and the luminous efficiency of the visible radiation.

As a second step, the lower end of the arc tube of test lamps was dipped in an bath of molten indium, as shown in the literature[3)5)]. But we did not use auxiliary heater for the upper end of the arc tube. Nitrogen pressure charged with the bell jar was kept constant during measurement. The indium was contained in an alumina crucible with an independent heater, and the temperature of the indium was monitored by thermocouples. Radiation from the arc tube in the indium bath in the bell jar was diffusely reflected into the spectroradiometer. Then the relative spectral power distribution of arc tubes was measured in the wide range of the cold spot temperature. Measurements were repeated with the different cold spot temperatures until the arc constriction was observed at higher cold spot temperature. Since the arc tube of test lamps was kept the constant distance from a diffuser of the radiometer, we can compare the relative luminous flux, the relative value of the visible radiant efficiency and the luminous efficiency of the visible radiradiation calculated from the relative spectral power distribution. In order to estimate the change in radiation from Hg, Sc and Na in the arc column, the representative peak wavelength for the above three atoms was selected, namely 577 nm for Hg, 567 nm for Sc, 819 nm for Na. The relative energy in each peak wavelength, which is multiplied by the spectral correction, was also compared.

3. Results

3.1 Radiation properties of test lamps with an outer bulb

Radiation properties were shown as the average values for a set of five lamps with identical design specification. **Figure 1** shows radiation properties as a function of mole fraction of $NaScI_4$. In this figure the measured value is normalized by using the standard value of 100 to represent the radiation properties with the mole fraction of 0.39 (1–A). As shown in this figure, overall luminous efficacy depends on the visible radiant efficiency, and the change in the visible radiant efficiency is corresponding to that in radiation power of Sc and Na. As explained previously, it can be assumed that higher $NaScI_4$ mole fraction results in higher vapor pressure of $NaScI_4$. The change in radiation power of Sc and Na is consistent with the above hypothesis at mole fraction up to 0.39. But radiation power decreases in higher mole fraction range of more than 0.39. This tendency can't be explained by the above hypothesis. More precise experimentation was required.

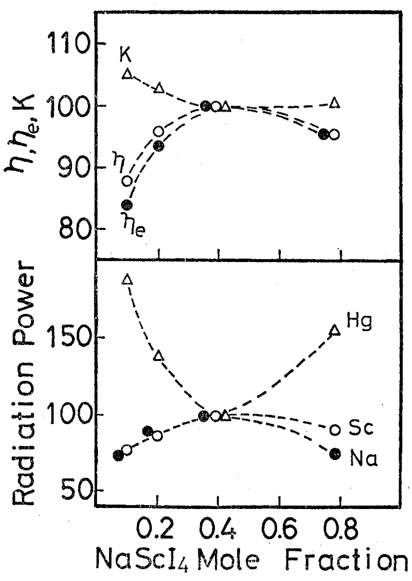

Fig. 1 *Radiation properties as a function of $NaScI_4$ mole fraction.*

Figure 2 shows radiation properties as a func- of the relative quantity of iodides. The measured value is also normalized by using the standard value of 100 to represent the radiation properties with relative iodides quantity of 1.0. Less change in luminous efficacy of the visible radiation was observed for different quantities of iodide as compared with that in the visible radiant efficiency. Overall luminous efficacy, therefore, is dependent upon the visible radiant efficiency. The change in the visible radiant efficiency is corresponding to that in radiation power of Sc and Na. These results are the same as shown in Fig. 1. The difference of radiation properties with iodides-quantity of 1.0 and 2.0 is not so clear, but the reduction in the radiation power of Sc and Na and the consequent reduction in the visible radiant efficiency and luminous efficacy were much greater with the decrease of relative iodides-quantity in smaller quantity range.

Figure 3 shows radiation properties as a function of inner diameter (I.D.) of arc tube with constant specific wall loading. The measured value is also normalized by using the standard value of 100 to represent the radiation properties with inner diameter of 1.95 cm. The dependence of the overall luminous efficacy on the visible radiant efficiency and the dependence of the visible radiant efficiency on the radiation power of Sc and Na were also observed. As well known, the increase in inner diameter results in the increase in convection, and consequently reduces the additive segregation[6)7)]. The reduction of additive segregation may be effective to increase radiation power of Sc and Na. Since this measurement was made for constant lamp wattage and constant specific wall loading, the change in inner diameter includes the change in input power per unit arc length and also includes the change of the cold spot temperature. Therefore, it could be estimated that the increase of inner diameter and the accompanying increase of input power per unit arc length might result in the increase of radiation power of Sc and Na. But the curve of radiation power and overall luminous efficacy in Fig. 3 has a maximum value at the inner diameter of about 2.0 cm. It might be based on the difference in the cold spot temperature. More precise experiments and quantitative measurements are required for strict consideration.

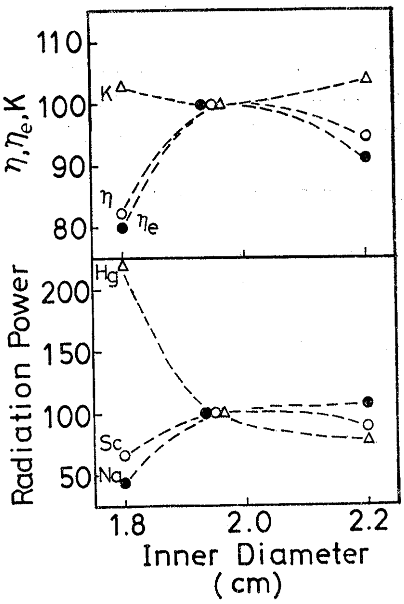

Fig. 3 *Radiation properties as a function of inner diameter of the arc tube.*

Figure 4 shows radiation properties as a function of specific wall loading. The measured value is also normalized by using the standard value of

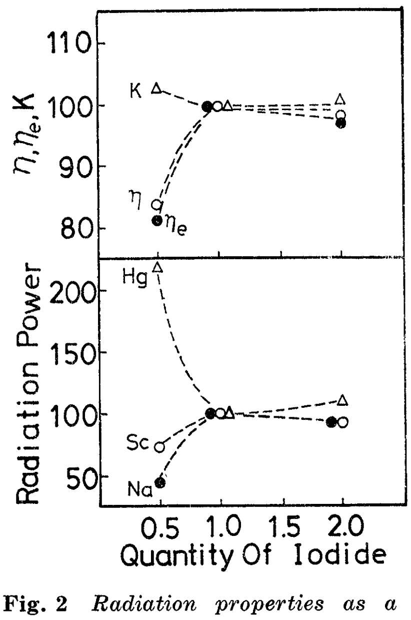

Fig. 2 *Radiation properties as a function of the relative Quantity of iodides.*

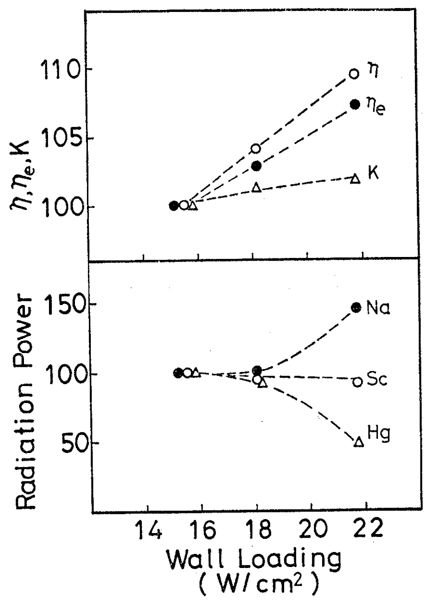

Fig. 4 *Radiation properties as a function of the specific wall loading.*

100 to represent the radiation properties with wall loading of 15.55 W/cm^2. The dependence of the overall luminous efficacy on the visible radiant efficiency was also observed. The increase in the visible radiant efficiency, however, resulted from the increase only in the radiation power of Na.

3.2 Radiation properties measured for the arc tube in the indium bath

Figure 5 shows radiation properties with two kinds of $NaScI_4$ mole fraction as a function of the cold spot temperature. In this figure the measured value defines the dependence of radiation properties on the cold spot temperature by the standard value of 100 to represent each value of radiation properties with mole fraction of 0.57 at the cold spot temperature of 600°C. As shown in this figure, radiation properties are strongly dependent upon the cold spot temperature. In the case of mole fraction of 0.57, when the cold spot temperature was increased from 500°C to 675°C, about 70% increase in luminous efficacy could be realized. And higher $NaScI_4$ mole fraction is advantageous to get higher radiation power of Sc and Na, and consequently about 10% increase in luminous efficacy can be obtained with mole fraction of 0.87 at the same cold spot temperature. The above advantage cannot be maintained at higher cold spot temperature due to arc constriction.

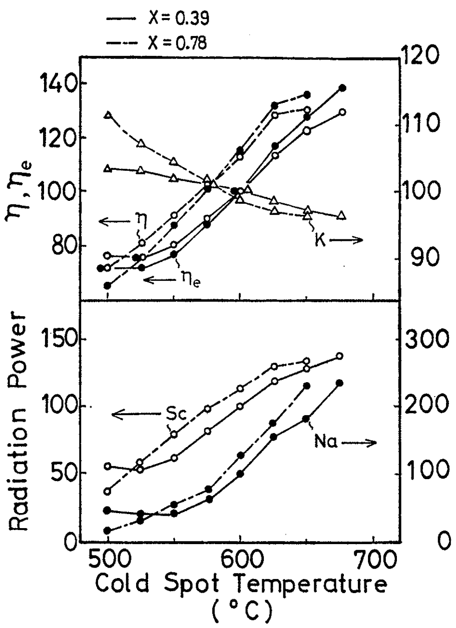

Fig. 5 *Radiation properties with different mole functions as a function of the cold spot temperature.*

Figure 6 shows the effect of inner diameter of the arc tube. In this figure the measured value is also normalised by using the standard value of 100 to represent each radiation properties with inner diameter of 1.95 cm at the cold spot temperature of 600°C. As shown in this figure, the increase in inner diameter combined with higher $NaScI_4$ mole fraction is effective to realize higher radiation power of Sc and Na, and more effective for Na at lower cold spot temperature. But at the cold spot temperature above 600°C, the arc with inner diameter of 2.2 cm cannot be effective because of arc constriction. When we can realize the cold spot temperature above 600°C, inner diameter of 1.95 cm is advantageous to realize higher luminous efficacy.

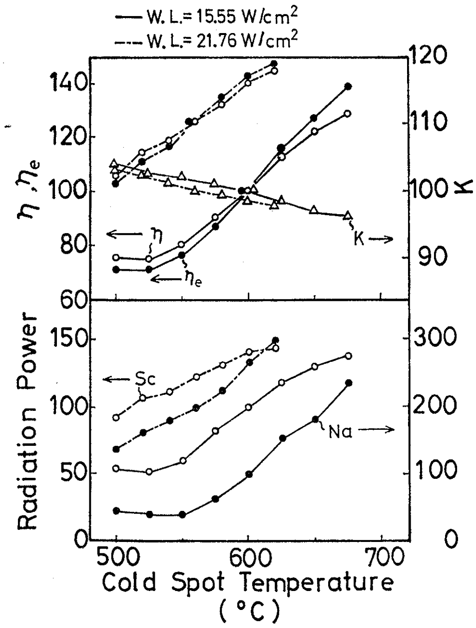

Fig. 6 *Radiation properties with different inner diameters as a function of the cold spot temperature.*

Figure 7 shows the effect of wall loading. In this figure the measured value is also normalised

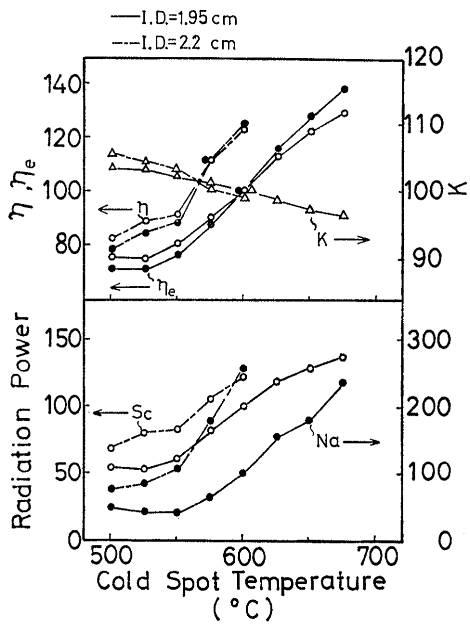

Fig. 7 *Radiation properties with different wall loadings as a function of the cold spot temperature.*

by using the standard value of 100 to repsesent each radiation property with wall loading of 15.55 W/cm at the cold spot temperature of 600°C. As shown in this figure, the increase of wall loading is significantly effective to increase radiation power of Sc and Na at the same cold spot temperature. About a 40% increase in luminous efficacy can be attained with higher wall loading in the cold spot temperature range from 550°C to 625°C.

It is very impressive that the effect of increasing wall loading is great even when the cold spot temperature is relatively low. This phenomenon implies the increase in input power per unit arc length, and resultant increase in convection and change in arc temperature are much more preferable to increase a large amount of radiation power of Sc and Na. But at the cold spot temperature above 620°C, the above effect cannot be realized because of arc constriction.

4. Novel approach to realize higher luminous efficacy

Novel approach to realize higher luminous efficacy was made based on the above investigation. We believe non-end-coating is basically preferable to utilize the visible radiation from the arc. As explained previously, the cold spot temperature of such an arc tube seems to be lower than that of usual end coated arc tubes. Our approach to realize higher luminous efficacy is basically to optimize the lamp design factors under the condition of relatively lower cold spot temperature without increasing wall loading. Because the increase in wall loading usually results in the significant decrease of lumen maintenance.

Measured cold spot temperature of the arc tube with inner diameter of 1.95 cm and wall loading of 15.55 W/cm² (1–A in Table 1) was about 600°C. At this cold spot temperature, mole fraction of 0.78 is most effective to realize higher luminous efficacy according to Fig. 5. But as a heat conserver is applied to prevent nitrogen gas in outer bulb from cooling the arc tube, mole fraction of 0.87 might not be preferable for arc stability. Mole fraction of 0.57 is, therefore, chosen as the optimum composition of additives. Concerning inner diameter of the arc tube, diameter of 1.95 cm is more preferable to get stable and efficient arc around the above mentioned cold spot temperature. **Table 2** shows

Table 2 *The lamp design specification for a newly designed lamp.*

Newly designed 400 W metal halide lamps	
Inner diameter	1.95 cm
Wall loading	15.55 W/cm²
$NaScI_4$ mole fraction	0.39
Heat conserver	Quartz cap

the design specification for a newly designed 400 W scandium-sodium iodide arc lamp. And **Fig. 8** shows a photograph of the lamp with a heat conserver made of quartz.

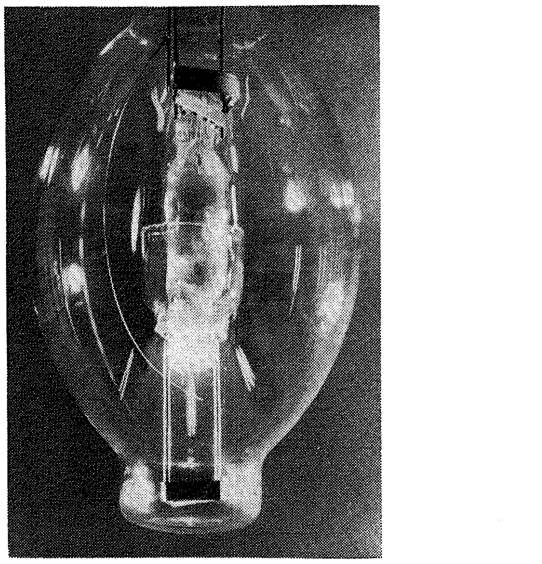

Fig. 8 *A photograph of the lamp with a heat conserver.*

As shown in experimental results, in order to realize higher luminous efficacy it is preferable to increase the cold spot temperature as high as possible, taking arc constriction into consideration. The above heat conserver enable to get higher cold spot temperature without absorption of visible radiation from arc. We believe it also contributes to realize more uniform temperature distribution of arc tube wall.

Table 3 shows radiation properties of a newly designed lamp comparing with them of the lamp

Table 3 *Radiation properties of a newly designed newly 400 W lamp (A) comparing them of the lamp without the heat conserver (B)*

No.	η (lm/W)	η_e	K (lm/W)	Radiation (%)	
				Sc	Na
A	121	.413	294	112	119
B	109	.371	295	100	100

B: Without quarz cap.

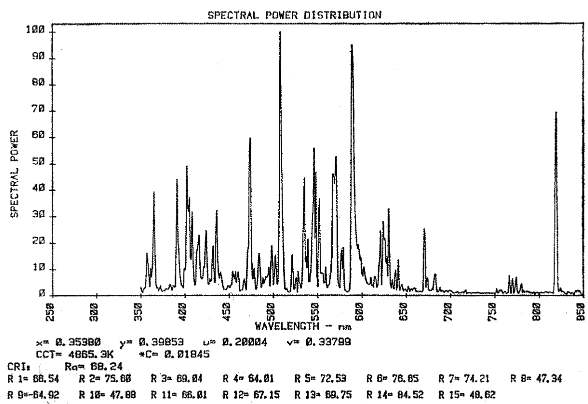

Fig. 9 *The spectral power distribution of the newly designed 400W lamp.*

without the heat conserver. By utilizing the heat conserver, the increase in radiation from Sc and Na was obtained, consequently the increase in the visible radiant efficiency was realized. 11% increase of luminous efficacy was realized based on the effect of the heat conserver. High luminous efficacy of 121 lm/W was realized (after 20 hours aged). **Figure 9** shows the spectral power distribution of the new lamp. Correlated color temperature was 4870 K, and color rendering index of 68 was obtained.

5. Discussion

The authors have investigated the effects of the lamp design factors related to the cold spot temperature on the radiation properties in scandium-sodium iodide arc lamps. Our measurements of the radiation properties have been mainly concerned with higher mole fraction of $NaScI_4$ comparing with the investigation by Ishigami et al.[5].

According to Fig. 5 higher $NaScI_4$ mole fraction is advantageous to realize higher radiation power of Sc and Na at the same cold spot temperature in relatively wide cold spot temperature range. In this temperature range the increase in the radiation of Sc is roughly equal to that in the radiation power of Na accompanied by the increase of $NaScI_4$ mole fraction. It should be noted that the maximum values of Sc and Na radiation power are almost same for different mole fractions. Hirayama et al. determined the NaI/ScI_3 ratios of the vapor over the molten mixtures by the condensate analysis, and confirmed that the vapor over the mixtures with the $NaScI_4$ mole fraction higher than 0.53 was dominated by the $NaScI_4$ complex, and the vapor over the mixtures with the $NaScI_4$ mole fraction lower than 0.19 was contributed by other complexes of Na_2ScI_5 and so on[2]. Therefore, we estimate that the vapor over the mixtures with $NaScI_4$ mole fraction of 0.39 may be still dominated by the $NaScI_4$ complex.

We examined the effects of the inner diameter on the radiation properties under the condition of the same wall loading. In this case the increase of the inner diameter results in the increase of Sc and Na radiation power at the same cold spot temperature in lower cold spot temperature range, and more effective for the increase of the Na radiation power. From Fig. 6 and Fig. 7, we can also compare the radiation properties for 1.95 cm of the inner diameter and for 2.2 cm of the inner diameter under the condition of the same input power per unit arc length. 2.2 cm of the inner diameter in Fig. 6 corresponds to 108.1 W/cm, while 15.55 W/cm^2 and 21.76 W/cm^2 of wall loading in Fig. 7 corresponds to 95.2 W/cm and 133.3 W/cm, respectively. Based on the comparison of the radiation powers at the same input power per unit are length for the different inner diameters, it is confirmed that the increase in the inner diameter is still effective for the increase in Na radiation power, but is not effective for the increase in the Sc radiation power.

The increase in the wall loading is significantly effective for the increase in the Sc and Na radiation powers. The arc with 21.76 W/cm^2 of the wall loading constricts at lower cold spot temperature comparing with the arc with 15.55 W/cm^2 of the wall loading, but it realizes significantly higher maximum radiation power of Na and a little higher maximum radiation power of Sc. It is noted that the increase of the Na radiation power is much greater than that of the Sc radiation power with the increase of the wall loading at the same cold spot temperature.

As shown in the literature, the Na particles segregate significantly due to the axial and radial demixing. The dominant increase in the Na radiation power with the increase in the inner diameter and the wall loading seems to be caused by the reduction of the demixing.

Arc constriction is also important phenomenon because it suppresses the increase in the Sc and Na radiation powers. It is useful to note the maximum Sc radiation powers from Fig. 5 to Fig. 7, because they are roughly proportional to the Sc density in the arc when the arc begins to constrict. The maximum radiation power of Sc is not affected by the mole fraction, and it is also shown that larger inner diameter results in lowering the maximum radiation power of Sc and higher wall loading results in increasing it. Based on Zollweg's investigation that the arc constriction may be due to ScI radiation at relatively lower arc temperature region in the presence of higher iodine partial pressure[8], the maximum radiation power of Sc may be dependent upon the partial pressure of ScI and arc temperature gradient. But more precise investigation will be required for the strict consideration.

Based on the above consideration, our novel approach has been performed by applying higher mole fraction than conventional one to the arc tube with lower cold spot temperature and optimizing the lamp design factors. Utilizing the quartz cap, which prevents the end portion of arc tube from cooling and also contributes to more uniform temperature gradient of arc tube wall, as well as the optimization realize a high luminous efficacy of 121 lm/W (after 20 hours aged) in 400 W Sc–Na iodide arc lamps.

6. Conclusion

Precise measurements of the radiation properties in scandium-sodium iodide arc lamps, especially for high mole fraction in which the $NaScI_4$ complex is dominated in the vapor phase, have been performed. Based on the results of the measurements, the effects of the lamp design factors related to the cold spot temperature on the radiation properties have been well understood. The novel approach as well as the optimization of the lamp design factors at lower colld temperature have realized a high luminous efficacy of 121 *l*m/W (after 20 hours aged) in 400 W scandium-sodium iodide lamps.

References

(1) Lorenz, R.: Ltg. Res. and Technol. **8**-3 (1976) 136.
(2) Hirayama, C., Castle, P. M., Liu, C. S. and Zollweg, R. J.: J. Illum. Engng. Soc. **4**-4 (1977) 209.
(3) Whittaker, F. L.: Ltg. Res. and Technol. **13**-1 (1981) 11.
(4) Work, D. E.: Ltg. Res. and Technol. **13**-3 (1981) 143.
(5) Ishigami, T., Sasaki, H., Nagano, S. and Higashi, T.: J. Light and Vis. Env. **4**-2 (1980) 1.
(6) Zollweg, R. J.: J. Illum. Engng. Soc. **5** (1975) 12.
(7) Saito, M., Tsuchihashi, M., Watanabe, K. and Baba, K.: J. Illum. Engng. Soc. **10** (1981) 133.
(8) Zollweg, R. J., Liebermann, R. W. and Mclain, D. K.: J. Appl. Phys. **52**-5 (1981) 3293.

Received 26 Oct. 1983; Revision Received 13 Apr. 1984.