Numerical Prediction of Influence of Gas Species on Gas Convective Pattern of Short Arc Lamp*

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We have investigated factors affecting the short arc lamp characteristics using a unified numerical model by changing filling gas species (Xe, Kr and Ar). The influence of the arc voltage, temperature and flow field, radiative efficiency and gas convective pattern and also the blackening location was examined. The arc voltage, temperature and flow field were found to be affected by the gas species. The thermodynamic and transport properties were in turn found to affect the radiative efficiency and gas convective pattern, and were thus finally reflected in the location of blackening position. This indicates that the light intensity and life time of the short arc lamp can be controlled by optimizing a mixture composition taking into account the arc characteristics such as arc volume, temperature, velocity and heat load to the electrodes. For example, mixing of Xe, which has a larger arc volume and a smaller heat load on the electrode, with Kr or Ar is suggested to lead to a higher arc temperature and gas velocity.

Key Words: Short Arc Lamp, Gas Species, Radiative Efficiency, Gas Convective Pattern, Blackening, Tungsten Vapour

1. Introduction

Electrical lighting is ubiquitous throughout general and industrial light sources, and is an indispensable part of life and many industries. An arc lamp is a light source that uses light radiated from the arc formed between electrodes. Typically, electrodes are tungsten (W), which has a high melting point, and the operating gas is an inert gas such as xenon (Xe), krypton (Kr) and argon (Ar). The bulb is made of quartz glass (SiO2), which has with high transparency and strength.

The operating gas species is adequately selected depending on the application. Xe arc lamps [1-4] are mainly used as a light source for apparatus such as digital cinema projectors [5], searchlights [6] and solar simulators [7]. Kr arc lamps are used as the pump in solid-state lasers [8]. Ar arc lamps can be used to thermally processes semiconductor wafers [9]. During operation of the arc lamp, the temperature of the tungsten electrode reaches a value around the melting point of tungsten, leading to evaporation of the electrode material. Then, the W vapour is transported by gas convection to the inner surface of the bulb, which blackens the bulb by adsorption [10]. This problem generally occurs in arc lamp operation [11]. This wall blackening effect decreases radiative efficiency and increases the thermal heat load to the lamp walls to break the bulb. Therefore, it is crucial to understand the gas convection in detail, in order to control it and reduce influence of the blackening.

Redwitz et al. [12] measured the anode temperature of HID (high-intensity discharge) lamps, which were operated at 1-5 A and filled with Xe, Kr or Ar at pressure of 0.26 MPa. However, the differences among the results obtained with the three gases were very small, and then detailed discussion was not given. Although there are a few studies of the influence of the gas species on the electrode, the blackening and the gas convection of the arc lamps operating at high pressure and high current have not been clarified.

Recently, the thermodynamic and transport properties were presented for pressure range from 0.1 to 10 MPa, and temperature range from 300 to 30 000 K by Murphy and Tam [13], which cover the parameter ranges of the arc lamp operation. This study showed that each property is greatly influenced not only by gas species but also by temperature and pressure. Moreover, a unified model, which self-consistently calculates various characteristics of the short arc lamp operated under air cooling, has been developed [14, 15]. The computational domain consists of a single "electrode-gas-bulb" region. The transport of the W vapour evaporated from the electrodes was also taken into account.

In the present paper, the factors that affect the short arc lamp characteristics are investigated using the above unified model. The lamp characteristics such as the voltage, temperature and velocity field, radiative efficiency and gas convective pattern and also the blackening location are examined in case of Xe, Kr and Ar lamps as a virtual experiment. The basic knowledge obtained in this paper is considered to contribute to optimize a mixture composition for adequately controlling the lamp characteristics.

2. Simulation model

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In this study, a short arc lamp operated with a constant direct current (DC) under air cooling has been modelled. Since the lamp has a symmetrical structure, a 2D axisymmetric domain is defined as shown in Fig. 1. The domain has a maximum length of 116 mm in the axial direction (X-axis) and 30 mm in the radial direction (Y-axis). The domain consists of the four regions corresponding to the anode, cathode, gas, and bulb, and all of the regions are coupled. Note that the cathode sheath region is defined in those gas region cells adjacent to the cathode surface, and is composed of a space charge layer (sheath) and an ionization layer (pre-sheath); in this study they are considered together. The maximum sheath thickness obtained experimentally is approximately 0.1 mm [16, 17], so its mesh size is set to 0.1 mm. The anode sheath mesh size is also chosen as 0.1 mm according to the LTE--diffusion method [18]. The lamp is filled with pure Xe, Kr or Ar. The total mass of the gas in the lamp is conserved. The length and maximum diameter of the W anode, which has a tip diameter of 3 mm with a 90° tapered angle, are 40 mm and 20 mm respectively. The length and maximum diameter of the Th-W cathode, which has a diameter of 1 mm with a 40° tapered angle, are 18 mm and 10 mm respectively. The arc gap during the lamp operation is 3.5 mm. The lamp is filled with pure Xe, Kr or Ar gas at 1.7 MPa at 300 K. The lamp is operated with DC 100 A. The calculation is performed using ANSYS Fluent 19.1.

The thermodynamic and transport properties are determined as functions of the gas temperature and the operating pressure. As examples of the properties, the thermal conductivity, specific heat and viscosity at 5 MPa [14] are shown in Fig. 2. The net radiative coefficients can be found in [19, 20].

The structure of the model is the same as that of the Xe arc lamp used in the previous study [15], in which the model was validated by comparison with the experimental results. An arc model that treats the electromagnetic thermo-fluid phenomena is coupled with sub-models consisting of a radiation transport model, a cathode sheath model and a W vapour model. In case of Kr and Ar, the maximum temperature of the electrode is expected to exceed the melting point. However, the melting phenomenon is neglected. The detailed descriptions of governing equations, assumptions and boundary conditions are omitted in this paper for want of space. However, those can be found in our previous work [15].

The equations of the arc model consist of a set of coupled equations as follows. The mass production and consumption rates of the W vapour by evaporation and deposition are considered in the mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = S_{\text{evp}} - S_{\text{dep}}$$  \hspace{1cm} (1)

and in the equation for the mass conservation of the W vapour;

$$\frac{\partial \rho Y}{\partial t} + \nabla \cdot (\rho Y \mathbf{u}) = \nabla \cdot (\rho D_{\text{W}} \nabla Y) + S_{\text{evp}} - S_{\text{dep}}$$  \hspace{1cm} (2)

where $\rho$ is the mass density [kg/m$^3$], $\mathbf{u}$ is the velocity [m/s], $S_{\text{evp}}$ is the source term relating to the production of the W vapour by the evaporation from the electrodes [kg/m$^3$/s] and $S_{\text{dep}}$ is the source term relating to the consumption of the W vapour by the deposition onto the inner wall of the bulb [kg/m$^3$/s]. The W vapour source term $S_{\text{evp}}$ is calculated from the evaporation rate obtained with the Hertz–Knudsen–Langmuir equation and Clausius–Clapeyron equation taking into account the evaporation as well as the

Fig. 1 Numerical simulation domain.

Fig. 2 (a) Thermal conductivity, (b) Specific heat and (c) Viscosity of Xe, Kr and Ar at 5 MPa [13].
deposition [21]. The deposition rate of the W vapour onto the inner bulb wall is given based on the thermal velocity of the W vapour. In equation (2), $Y$ is the total mass fraction of the W vapour species. $D_{W-G}$ is the diffusion coefficient of the W vapour in the Xe, Kr or Ar [m$^2$/sec.], and is expressed as a function of the masses of the gas and W atoms and the momentum transfer cross-section between the gas and W atoms. It should be noted that this expression overestimates the diffusion coefficient under the condition in which the degree of ionization is high, since it only considers neutral atoms [22]. In the lamp, the degree of ionization is low except in the vicinity of the cathode, so the error associated with the use of equation for $D_{W-G}$ is negligible. The influence of admixture of the W vapour into the arc on thermodynamic and transport properties except for the mass density is ignored in this study.

The momentum conservation equation is
\[ \frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \tau + \vec{j} \times \vec{B}, \]
where, $p$ is the pressure [Pa], $\tau$ is the viscous stress tensor [Pa], $\vec{j}$ is the current density [A/m$^2$], $\vec{B}$ is the magnetic field strength [T] induced by the current.

The energy conservation equation is
\[ \frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho h \vec{u}) = \nabla \cdot (k \nabla T) + \vec{j} \cdot \vec{E} - U + Q_l - Q_t, \]
where $h$ is the enthalpy [J/kg], $k$ is the thermal conductivity [W/m/K], $T$ is the temperature [K], $\vec{E}$ is the electric field [V/m], $U$ is the net radiative coefficient [W/m$^2$], $Q_l$ is the latent heat for the vaporization of the tungsten [W/m$^2$], $\sigma$ is the electrical conductivity [S/m] and $\varphi$ is the electric potential [V]. The electrical conductivity in the cathode sheath region is treated differently from the arc column in order to describe the arc attachment [23].

The current continuity equation is
\[ \nabla \cdot \vec{j} = 0, \]
where the current density $\vec{j}$ is obtained from the electric potential and Ohm’s law;
\[ \vec{j} = -\sigma \nabla \varphi = \sigma \vec{E}. \]

The magnetic field strength $\vec{B}$ is calculated by solving an equation for the magnetic potential $\vec{A}$;
\[ \nabla^2 \vec{A} = -\mu_0 \vec{j}, \]
and using
\[ \vec{B} = \nabla \times \vec{A}, \]
where $\vec{A}$ is the vector potential [T m] and $\mu_0$ is the magnetic permeability in vacuum [H/m]. The electron and the ion current on the cathode surface are defined based on the Richardson–Dushman equation of thermionic emission taking into account the influence of the Schottky effect [24].

3. Results and discussion

Fig. 3 (a), (b) and (c) shows the distributions of the gas temperature and velocity vectors in the vicinity of the arc. The arc temperature and flow velocity in Kr and Ar were larger than those in Xe. The Ar arc was seen to be significantly constricted, leading to an arc voltage of 40.0 V and a maximum arc temperature of 17 450 K and maximum velocity of 19.4 m/s, respectively. Those in Xe were 28.7 V, 13 390 K and 10.7 m/s, respectively. The values other than arc voltage in Kr were found to become between those in Xe and Ar. The arc voltage in Ar was lower than that in Kr, which is because of the relatively large high temperature region of the arc.

In the vicinity of the cathode tip, the thermal conductivity was lower in Kr and Ar than that in Xe, and the specific heat was higher in Kr and Ar than that in Xe. For this reason, the thermal diffusion ($\propto k/C_p$) in the Ar and Kr arc was low, and the arc route was...
limited to the high temperature region of the arc. This effect is termed the thermal pinch effect [25].

Fig. 3 (d), (e) and (f) show the distributions of the radiation power density in the vicinity of the arc. The radiative efficiency (= radiative power / input power) was lower for Ar (65.1 %) than that for Kr (76.8 %) despite the arc temperature had the highest value. This is due to the volumetric compression and low radiation power density of the Ar arc. Thus, the radiative efficiency is determined by the balance between the volume and the radiation power density of the arc.

Fig. 4 shows the temperature distributions in the entire domain. In case of Kr and Ar, it can be seen that the temperature is high throughout because of the high temperature arc, the maximum temperature of the tips of both the electrodes reached the melting point of W (3680 K). Since molten electrodes cannot be actually used in the lamp, the calculations in the cases of Kr and Ar at 17 atm at 300 K are carried out as a virtual experiment.

Only in the case of Kr, the hot gas vortex shifted to the bottom (left) side of the anode comparing with the Xe case. This is because the momentum of the Kr gas flow increased with increasing the cathode jet velocity. On the other hand, although the cathode jet velocity of Ar increased furthermore, the flow distribution of the Ar was found to follow the same trend as the Xe. This is because the viscosity of the Ar in the low temperature gas occupying most of the volume in the lamp is lower than that of Xe. The low viscosity prevents the gas to flow along the edge of the anode. If the anode is designed to have a curved shape, it is unlikely to affect the flow. Therefore, it is considered that the distribution in the Ar case was similar to that in the Kr case. This indicates that the gas convection is also affected by the anode shape.

Fig. 5 shows the distributions of the deposition mass flux of the W vapour on the inner bulb wall. Equation (9) gives the deposition mass flux of the W vapour

$$J_{\text{dep}} = \gamma \rho u_{\text{th}}$$

where $u_{\text{th}}$ is the thermal velocity of the W vapour [m/s]. The evaporation rate of the W vapour increases almost exponentially with the electrode temperature [26]. The W vapour was mainly distributed around X=50 mm. The X position where the maximum appeared depends on the contacted region of the high temperature gas flow with the inner bulb wall. This is because the W vapour produced from the electrodes was mixed into the cathode jet, and was transported primarily by the convective flow rather than diffusion, despite of the small gas velocity. The half-width of the distribution peak was the widest for Ar. This is because the diffusion of the W vapour perpendicular to the gas flow increases, since the diffusion coefficient increases with the temperature. In addition, the diffusion coefficient of the W vapour in Ar is higher than that in Xe and Kr due to the smaller atomic mass of Ar.

Thus, the arc characteristics such as the arc voltage, temperature and flow field were found to be affected by the gas species. The thermodynamic and transport properties were in turn found to affect the radiative efficiency and gas convective pattern, and were thus finally reflected in the location of blackening position. This indicates that the light intensity and life time of the short arc lamp can be controlled by optimizing a mixture composition taking into account the thermodynamic and transport properties of the gas. For example, mixing of Xe, which has a larger arc volume and a smaller heat load on the electrode, with Kr or Ar is suggested to lead to a higher arc temperature and gas velocity. Moreover, it is considered that by mixing Kr or Ar having a higher gas velocity
with Xe, the blackened location can be shifted to a location that is shadowed by the anode. In these ways, it is possible to optimally design a lamp to realize high radiation efficiency and long lifetime.

4. Conclusions

In the present paper, we have used a unified numerical simulation model [15] to investigate the factors that affect the short arc lamp characteristics by changing gas species. The influence of the arc voltage, temperature and flow field, radiative efficiency and gas convective pattern and also the blackening location was compared for Xe, Kr and Ar gases and examined.

The arc voltage, temperature and flow field were found to be affected by the gas species. The thermodynamic and transport properties were in turn found to affect the radiative efficiency and gas convective pattern, and were thus finally reflected in the location of blackening position. The results indicate that the light intensity and life time of the short arc lamp can be controlled by using a gas mixture with composition determined based on the thermodynamic and transport properties of the gas. For example, mixing of Xe, which has a larger arc volume and a smaller heat load on the electrode, with Kr or Ar is suggested to lead to a higher arc temperature and gas velocity. Therefore, a detailed investigation of the influence of the thermodynamic and transport properties of the gas on gas flow is planned.

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