Influence of chemical composition on radiations of microwave discharge lamp

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Abstract: This paper study the influence of chemical composition on the photometric properties of a conventional metal halide (MH) plasma lamp containing Hg doped with TlI sustained by a microwave (mw) electromagnetic field. The plasma is assumed to be fully mixed, implying a constant mercury/thallium ratio throughout the discharge tube. Plasma composition, radial gas temperature, luminous efficacy and CCT have been computed.

Keywords: plasma lamps, ray tracing, plasma chemical composition

1. General

The development of new, efficient electrodeless HID light sources, based on the “resonant cavity” [1] concept (so-called plasma lamps) has aroused considerable interest in recent years. When electrical power in the lamp is sufficiently high, these lamps can achieve higher luminous efficacies than conventional HID lamps [1], with photometric properties comparable to or exceeding those of the current generation of LED lamps. Further, plasma lamps are considerably smaller than either the equivalent LED arrays or conventional HID lamps, and therefore provide excellent optical control. Theoretical analysis of plasma lamps has to date been limited to pure Hg discharges [1, 2]. This paper provides an initial approach to understanding the performance of the photometric properties of MH plasma lamps once the chemical composition of the plasma changes. Gas temperature profile of a microwave sustained HgTlI discharges has been calculated using a simple numerical model [1]. A ray tracing model [3] has been used later to compute the radiation flux emitted by all visible spectral lines. The influence of the variation of the chemical composition on the photometric properties of a conventional metal halide is therefore discussed.

2. Chemical composition calculation

The radiation transport in HID lamp clearly depends on the chemical composition of the discharge. For pure Hg discharges, the plasma composition is relatively simple to be calculated compared to other Hg doped discharges. The discharge studied here contains mercury doped with thallium iodide, and a low pressure (a few Torr) of argon as a buffer gas. The chemical composition of the plasma depends on the quantities of each material present in the lamp, as well as the temperature profile. In the temperature range between 1000 K to 6000 K, the chemical species present in the plasma are the monatomic species (Hg, Tl and I), the molecular species (Hgl, HgI2, TlI and I2) and the charged species (Hg+, Tl+, I− and e).

To determine the profiles of densities and partial pressures of the eleven chemical species present in the discharge, it is necessary to have eleven independent equations. These relationships are derived from the laws governing the state of the plasma in local thermodynamic equilibrium. Thus, chemical equilibrium and ionic equations lead to seven equations. In addition four equations expressing the charge conservation, conservation of total pressure, and also the two atomic ratios: the mercury to thallium ratio (R1) and the thallium to iodine ratio (R2).

The atomic ratio $R_1 = \text{mercury/thallium}$ is expressed by:

$$R_1 = \frac{Hg}{Tl} = \frac{P_{Hg} + P_{Hg^+} + P_{HgI} + P_{HgI^+}}{P_{Tl} + P_{Tl^+} + P_{TlI}} = \text{constant} \quad (1)$$

The atomic ratio $R_2 = \text{thallium/iodine}$ is expressed by:

$$R_2 = \frac{Tl}{I} = \frac{P_{Tl} + P_{Tl^+} + P_{TlI}}{P_{Hgl} + 2P_{HgI} + P_I + 2P_{I^+} + P_{TlI} + P_I} = 1 \quad (2)$$

The chemical species present in the plasma are shown in Fig. 1 for $R_1 = 148$.
3. Temperature profile calculation

In the calculations described here, a simple “skin depth” numerical model [1] was used to compute the radial temperature profile in a microwave generated discharge at frequency 2.45 GHz. The lamp’s parameters (radius \( R = 3.9 \) mm, inter-electrode distance \( L = 7.2 \) cm) and the net emission coefficient are obtained from Bouaoun [4]. The discharge was assumed to be in LTE in the T_{010} mode and the gas temperature was computed from the simplified Elenbaas- Heller equation

\[
\nabla \cdot \kappa_g \nabla T_g + \sigma_{e} E_z^2 - U_{rad} = 0
\]

where \( T_g \) is the gas temperature, \( \kappa_g \) is the coefficient of thermal conductivity of the gas, \( \sigma_e \) is the electrical conductivity, \( E_z(r) \) is the axial electric field at radius \( r \), computed from the “skin depth” equation [1] and \( U_{rad} \) represents the net energy transported by radiation from each point in the discharge. In the calculations, \( \kappa_g \) and \( \sigma_e \) were calculated self consistently and values of \( U_{rad} (T_g) \) were taken Bouaoun [4]. The total electrical power in the discharge is

\[
W_{elec} = 2\pi RL \int_0^R n_e \sigma_e E_z^2 (r) rdr = W_{rad} + W_{therm}
\]

where \( n_e \) is the electron density and \( W_{rad} \) and \( W_{therm} \) represent the electrical power dissipated as radiation and heat respectively.

4. Results

The obtained temperature profile is consistent with operation of plasma lamps at low power, where the short skin depth prevents the microwave power from penetrating into the discharge [1] as shown in Fig. 2.

![Fig. 2. Temperature profile of the discharge.](image)

The calculated gas temperature profile was then used as input into a 3D radiation model [3] to compute the radiation flux from the visible spectra of Hg and Tl. The obtained results of luminous efficacy and CCT for different atomic ratios \( R1 \) are summarised in Table 1.

<table>
<thead>
<tr>
<th>Discharge</th>
<th>( W_{elec} ) (W)</th>
<th>( \eta ) (lm/W)</th>
<th>CCT (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R1 = 100 )</td>
<td>214</td>
<td>101</td>
<td>5613</td>
</tr>
<tr>
<td>( R1 = 150 )</td>
<td>214</td>
<td>93</td>
<td>5580</td>
</tr>
<tr>
<td>( R1 = 200 )</td>
<td>214</td>
<td>86</td>
<td>5376</td>
</tr>
</tbody>
</table>

5. Discussion

The influence of changing the chemical composition of the plasma was presented. The density of Hg seems to be dominant in the discharge as shown in Fig. 1 and stay relatively unchanged for different atomic ratio \( R1 \). However, the density of thallium increases once the atomic ratio \( R1 \) decrease (Fig. 3) and play an important role in improving the photometric properties of the lamp as shown in Table 1. This is a direct consequence of the difference between the ionization energies where the energy of ionization Tl is relatively low compared to that of Hg (\( E_{Tl} = 6.11 \) eV and \( E_{Hg} = 10.43 eV \)).

![Fig. 3. Density of Tl for different atomic ratio.](image)
6. References


