RADIANT POWER OF TUNGSTEN MIXED ARGON PLASMA ARCS AS FUNCTIONS OF CURRENT AT 0.1MPA IN PRESSURE

Y. Inoue, J. Mizuno (Chuo University), T. Iwao (JSFS Research Fellow), T. Inaba (Chuo University)

ABSTRACT

As treating methods of hazardous wastes, lighting and so on, a radiant power emitted from plasma arcs are of utility value. In order to treat hazardous wastes by the high temperature and the ultraviolet rays of radiant power emitted from plasma arcs, an equipment for collecting the radiant power was developed. And the mass density and the radiant power density emitted from tungsten mixed argon gas were evaluated by calculation. It is calculated under 6.15 % (50 A), 32.3 % (100 A), 51.3 % (75 A) of the contaminated ratio of tungsten at 0.1MPa more than 6,000 K[1], because the tungsten gas exists more than 6,000 K. And the calculation limit of temperature is 15,000 K, because the maximum temperature of plasma arc could be estimated about 10,000 K from 50 to 100 A in this experiment. The measured radiant power increases in proportion to the 1.8th power of the current.

INTRODUCTION

The plasma arc that has the high temperature, the highly intense light, the high energy is generated by lightning and accident of power line and so on. In this case, it is demanded to blow out. But when the working gas is blew to the plasma arc to stabilize it, the torch plasma that is higher temperature than free arc is generated. It has several ten thousand Kelvin at a central point of torch plasma, and several thousands at surface of it. So, it is expected that it can be applied to melt the substance of highly melting point, and to develop the new materials. Especially, because the radiant power emitted from the plasma arc has huger than normal light source, it is possible to do a clean treatment without combustion. So, it is applied to treat the hazardous wastes, night light source such as skiing ground, construction cite, airport, park, athletic field, farm at underground and sea and so on. In this paper, the mass density is calculated by using the Saha equation, the equation of state, the equation of contaminated ratio, and the radiant power density is calculated to know the basic theory of radiant power. Then, the radiant power increment is measured by using the highly intense radiant power equipment with the reflector as functions of current.

HIGHLY INTENSE RADIANT POWER EQUIPMENT WITH REFLECTOR

Experimental arrangement

Figure 1 shows the highly intense radiant power equipment with the reflector. The gas in chamber and the working gas is argon. It has half ellipse shape that become reflector to collect the radiant power on light spot. This reflector is made of stainless and polished. The materials can be fixed at axis of focus point to treat it. This equipment can be held until 1.0 MPa.

![Fig. 1 Highly intense radiant power equipment with reflector.](image)

Experimental method

The radiant power is measured by using such as the tungsten (W) electrodes, the distance between electrodes, L : 2 cm, the pressure : 0.1 MPa, the DC currents, I : 50, 75, 100 A. The radiant power emitted from plasma arc in argon is measured by using the power meter that is thermocouple and measured from 300 nm ~ 30 μm flatly. The accuracy is ±3%. The radiant power emitted from plasma arc is not flat from ultraviolet to infrared rays. But this power meter can measure accurately, because it can measure large region of wavelength. The tungsten and argon normally has radiant power emitted from monovalent and bivalence ions under 300 nm[2][3][4]. But it is ignored, because the relative value of radiant power is considered in this paper. The radiant power goes through the pyrex window (4.2 cm), and it is measured by using power meter sensor (incidence aperture 1.5 cm) at the point of 64 cm from window. While
this radiant power is the sum of plasma arc and reflection from reflector, its relative value is measured as functions of the current accurately.

**MASS DENSITY OF HIGH TEMPERATURE ARGON AND TUNGSTEN GASES**

**Ionized energy**

The ionized voltage, $V_i$(eV), of argon and tungsten is shown in Table 1. The $V_{e,W}$ is unknown value. In this paper, it is assumed that $V_{e,W}$ is 34.0 eV, because the $V_{e,W}$ = 17.7 eV is as twice as $V_{e,W}$ = 7.98 eV. The ionized energy, $E_i$(J), is converted by using below equation.

$$E_i = e \cdot V_i = 1.602 \times 10^{-19} \cdot V_i$$

(1)


<table>
<thead>
<tr>
<th>Ionized status</th>
<th>Ionized voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar$^+$</td>
<td>15.76 eV</td>
</tr>
<tr>
<td>Ar$^{2+}$</td>
<td>27.62 eV</td>
</tr>
<tr>
<td>Ar$^{3+}$</td>
<td>40.9 eV</td>
</tr>
<tr>
<td>W$^+$</td>
<td>7.98 eV</td>
</tr>
<tr>
<td>W$^{2+}$</td>
<td>17.7 eV</td>
</tr>
<tr>
<td>W$^{3+}$</td>
<td>34.0 eV (estimated value)</td>
</tr>
</tbody>
</table>

**Table 1. Ionized Voltage of Argon and Tungsten**

**Simultaneous equation**

The approximated electron density, $n_e$(m$^{-3}$), as functions of temperature, and the mass density, $n_i$(m$^{-3}$), of atom and ion of argon and atom of tungsten is calculated by using Newton-Raphson method. The simultaneous equation is shown in below such as the Saha equation, the equation of state, and the neutral conservative equation of electric charge.

**Particle function**

The particle functions of the electron, argon and tungsten of atom and ion are calculated by using below equation $Q_e$, $Q_{Ar}$, $Q_{W}$.

$$Q_e = \frac{2}{\sqrt{\pi n_e}} \frac{E_{iZ}}{kT} \exp \left( \frac{-E_{iZ}}{kT} \right)$$

where, $g_i$: the particle function, $E_i$(J): the energy of upper and lower. $k$: the Boltzmann's constant($=1.38 \times 10^{-23}$ J/K), $T$(K): the Temperature.

**Saha equation**

$$\frac{n_{iZ+1}n_e}{n_{iZ}} = \frac{Q_{iZ+1}Q_e}{Q_{iZ}} \left( \frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} \exp \left( -\frac{E_{iZ+1}}{kT} \right)$$

where, $m_e$: the mass of electron($=9.11 \times 10^{-31}$ kg), $h$: the Plank's constant($=6.67 \times 10^{-34}$ J·s).

**The equation of state**

$$P = \left( n_e + \sum n_{iZ} \right) kT = (n_e + n_{Ar^+} + n_{Ar^{2+}} + n_{Ar^{3+}} + n_{Ar^N} + n_{W^+} + n_{W^{2+}} + n_{W^{3+}} + n_{W^N}) kT$$

where, $P$: the pressure (0.1 MPa).

**The natural conservative equation of neutral electron**

$$n_e = \sum (Z - 1)n_{iZ} = n_{Ar^+} + 2n_{Ar^{2+}} + 3n_{Ar^{3+}} + n_{W^+} + 2n_{W^{2+}} + 3n_{W^{3+}}$$
Contaminated ratio of tungsten

\[ X_{W} = \frac{N_{W}}{N_{A} + N_{W}} \times 100 \]

\[ N_{A} = n_{Ar} + n_{ArI} + n_{ArII} + n_{ArIV} \]

\[ N_{W} = n_{WII} + n_{WIII} + n_{WIV} + n_{WV} \]

where, \( X_{W} \) (%): the contaminated ratio of tungsten.

Mass density of high temperature argon gases contaminated with tungsten

Figure 3 shows the mass density of high temperature argon gases contaminated tungsten. It is calculated under 6.15% (50 A), 32.3% (100 A), 51.3% (75 A) of the contaminated ratio of tungsten at 0.1MPa more than 6,000 K[1], because the tungsten gas exit more than 6,000 K. And the calculation limit of temperature is 15,000 K, because the maximum temperature of plasma arc could be estimated about 10,000 K from 50 to 100 A in this experiment. The C++ program and the Microsoft C/C++ compiler is used under Windows 2000 in this paper.

![Mass density of high temperature argon and tungsten contaminated gases](image)

in Table 3. And when it is compared between 32.3% (100 A) and 51.3% (75 A), 51.3% (75 A) is higher than 32.3% (100 A). The more the contaminated tungsten is high, the more boundary temperature is high.

<table>
<thead>
<tr>
<th>Dominant situation (Relative equation)</th>
<th>6.15% (50 A)</th>
<th>32.3% (100 A)</th>
<th>51.3% (75 A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completely W (( n_{eW} \geq n_{eAr} ))</td>
<td>~8,800</td>
<td>~10,400</td>
<td>~11,000</td>
</tr>
<tr>
<td>Strongly W (( n_{eW} \geq 10 \times n_{eAr} ))</td>
<td>8,800</td>
<td>10,400</td>
<td>11,000</td>
</tr>
<tr>
<td>Both equality (( n_{eW} = n_{eAr} ))</td>
<td>~9,900</td>
<td>~11,900</td>
<td>~12,700</td>
</tr>
<tr>
<td>Strongly Ar (( 10 \times n_{eW} \leq n_{eAr} ))</td>
<td>&gt;15,000</td>
<td>&gt;15,000</td>
<td>&gt;15,000</td>
</tr>
</tbody>
</table>

The mass density between the argon and the tungsten is same level at 51.3% (75 A) of contaminated ratio. In case of 32.3% (100 A), the argon is higher than the tungsten. In this paper, the total mass density as functions of contaminated ratio and current decreases, because the pressure is constant.

**RADIANT POWER OF HIGH TEMPERATURE ARGON AND TUNGSTEN MIXTURED GASES**

Calculation method of radiant power density

The radiant power, \( u(W/m^2\cdot sr) \), is calculated by using below equation[6] and results of the mass density of argon and tungsten.

\[ u = u_{cont} + \sum u_{line} \]

\[ u_{cont} = \frac{1}{(4\pi\varepsilon_{0})^3} \frac{16\pi^6 n_e^2}{3c^3} \frac{4kT}{\hbar} \]

\[ u_{line} = \frac{n_e}{4\pi Q_{line} \lambda_m \lambda_i} A_{mni} \exp \left( \frac{-E_{mi}}{kT} \right) \]

where \( u_{cont} \): the radiant power density emitted from continuous spectrum, \( u_{line} \): the radiant power density emitted from line spectrum, \( \varepsilon_{0} \): the dielectric constant of vacuum(=8.854x10^{-12} F/m), \( c \): the light speed (=2.998x10^8 m/s), \( A_{mni} \): the transition probability from \( m \) to \( n \), \( \lambda_m \): the wavelength. \( E_m \): the upper energy. The C/C++ program and the Microsoft C/C++ compiler is used on Windows 98 in this paper.

**Dominant relation of radiant power density**

Figure 4 shows the results of radiant power density as functions of the contaminated ratio of tungsten and current. The radiant power density emitted from line spectrum of tungsten (\( u_{line} \)) is larger than from argon (\( u_{lineAr} \)) at 6,000 K~15,000 K, each contaminated ratio. The relation between radiant power emitted from line spectrum at each contaminated ratio and temperature is shown in Table 4.
The magnitude of $u_c$ is determined by the electron density as shown in Equation (8). So, $u_c$ at 6.15%(50 A) of the contaminated ratio is emitted from electron generated by W I less than 10,000 K as shown in Fig.3. Ar II is gradually dominant due to effect of electron more than 11,600 K in case of the equality between Ar II and W I. And the radiant power density emitted from continuous spectrum at 6.15%(50 A) is 1/10,000 of line spectrum emitted from it at 6,000K, 1/1,000 at 8,000K, 1/100 more than 13,000K.

**Ratio of line spectrum and continuous spectrum**

The radiant power density ratio between the line spectrum and continuous spectrum as functions of the contaminated ratio, the current and the temperature are shown in Fig.5. It decrease with temperature. While 6.15%(50 A) is higher than 32.3%(100 A) and 51.3%(75 A) near 10,000 K, they reversed more than 12,000 K.

**Parameter of each contaminated ratio and current**

The parameter of each contaminated ratio and current is shown in Table 5. The more the current increase, the more the radiant power density ratio between line spectrum and continuous spectrum. And the radiant power density is minimum at 6.15%(50 A), and maximum at 51.3%(75 A). When it is 32.3%(100 A), it is about 0.6 times of 51.3%. Then, the relation between radiant power density and current is shown in Fig.6. The radiant power density is maximum such as $4.5 \times 10^{19} W/(m^3 \cdot sr)$ at 75 A. Because the maximum of contaminated ratio is 51.3% at 75 A, the tungsten species that can emit the line spectrum are larger than argon ones. So, the radiant power increases.

**Measurement of radiant power emitted from plasma arc as functions of current**

The results of highly intense plasma arc collected equipment is shown below. The measured radiant power $\Phi_m$ is functions of current at $F=121/\text{min}(\text{Normal})$ of working gas, 2 cm of distance between electrodes, at $I=50, 75, 100$ A of the current, at $P=0.1$ MPa.

**Measured radiant power as functions of current**

Figure 7 shows the radiant power as functions of current. The measured radiant power increases in proportion to the 1.8th power of the current. This parameter of current, $n_f$, is $n_f = 2.3$ in case of wall-stabilized arc, $n_f = 1.8 - 2.0$ in case of torch plasma[7][8]. Therefore, this plasma arc can be considered as a kind of wall-stabilized arc.
Table 5 Ratio of radiant power density due to line spectrum to due to continuous ray at arc temperature

<table>
<thead>
<tr>
<th>Contaminated ratio $X_W$ (Current $I$)</th>
<th>$6.15%$ (50 A)</th>
<th>$32.3%$ (100 A)</th>
<th>$51.3%$ (75 A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of Plasma arc $T(K)$</td>
<td>12,500</td>
<td>11,200</td>
<td>11,400</td>
</tr>
<tr>
<td>Radiant power density $u(W/(m^3\cdot sr))$</td>
<td>$7.9\times10^9$</td>
<td>$2.9\times10^{10}$</td>
<td>$4.5\times10^{10}$</td>
</tr>
<tr>
<td>$\Sigma u_{\text{time}}/u_c$ (times)</td>
<td>170</td>
<td>260</td>
<td>220</td>
</tr>
</tbody>
</table>

$\Phi = 3.9 \times 10^{-7}/I^{1.8}$

\[ \text{Measurement} \]

Fig. 7 Radiant power as function of the current

1. The contaminated ratio of tungsten was decided as $6 \sim 50\%$ by measurement value. The influence of argon is dominant from 11,600 K, when the electron density $X_W$ is about $6\%$. This temperature depends on the electron density. When $X_W$ increases such as $30 \sim 50\%$, the temperature increases near 15,000 K.

2. The radiant power density emitted from continuous radiation has always strong effect of electron generated by tungsten at $6.15\%$ less than 11,600 K, $32.3\%$ less than 14,600 K, $51.3\%$ less than 5,000 K.

3. The radiant power density emitted from line spectrum is dominant. The radiant power density emitted from line spectrum is more than 200 times at less than 12,000 K, and about 50 times 15,000 K in case of $X_W=6\%$, 140 to 170 times in case of $30 \sim 50\%$.

4. The radiant power as functions of the current is measured by using the highly intense radiant power equipment with reflector. The radiant power increases in proportion to 1.8th power of the current. And the radiant power density increases with the current at 50 A. But it decreases at 75 to 100 A. The increment of radiant power could be ocurred by the increment of radius.

In the future, the temperature of radiant spot will be measured, and the gases and materials on the radiant spot will be changed to treat the hazardous wastes by using the specific wavelength emitted from radiant.

Acknowledgements

The authors thank Prof. I. Miyachi of Aichi Institute of Technology, Prof. Y. Yokomizu of Nagoya University, Y. Tanaka of Kanazawa University, K. Ikeda of the CRIPE, and M. Iwata of the CRIPE for his fruitful suggestions and the Y. Yamaguchi, Y. Uemichi, and K. Kanda belonging to the High Current, Power and Energy Laboratory of...
Chuo University for their experimental efforts. This research was supported by High-Tec Project on High Temperature Plasma by The Institute of Science & Engineering of CHUO University, and Japan Society for Promotion of Science.

Reference


