TEMPERATURE AND RADIANT POWER EMITTED FROM DC HORIZONTAL SHORT FREE ARC DISCHARGE CONTAMINATED WITH TUNGSTEN VAPOR NEAR 50A

T. Iwao (JSPS Research Fellow), Y. Inoue, Y. Yamaguchi, T. Inaba (Chuo University)

ABSTRACT

The mass densities of the tungsten spectral line W I and W II are calculated. The temperature of the arc discharge in air was measured by the spectrometer and the radiant power of DC horizontal free arc between tungsten electrodes was measured with a spectroscope and a power-meter at 20-50A of the arc current, 0.1MPa in pressure. The mass density of W I is more than about $5 \times 10^{22}$ m$^{-3}$ at 6,000 K. But it decreases with temperature, and it is cross with W II around 7,500 K. After this, W II is bigger than W I. The temperature of free arc contaminated tungsten is estimated about 5,500 K ~ 5,600 K at 30 A, 50 A, 70 A. These temperature are almost same value even if the current changes.

INTRODUCTION

The characteristics of the arc discharge have the high temperature and highly intense radiation. Therefore, the arc discharge is used to a lot of application[1] such as plasma torches[2], lighting, so far. When a reduction of the waste and dissolution of the iron are carried out by using a plasma arc discharge, the radiant power emitted from the plasma arc should be suppressed. In those cases it has to be precisely controlled.

In this paper, the mass densities of the tungsten spectral line WI and WII are calculated. The temperature of the arc discharge in air was measured by the spectrometer and the radiant power of the DC horizontal free arc between tungsten electrodes was measured with a spectroscope and a power meter at 20-50A of the arc current, 0.1MPa in pressure.

MASS DENSITY OF HIGH TEMPERATURE GAS CONTAMINATED WITH TUNGSTEN

The mass density of high temperature gases contaminated with tungsten was calculated to know the radiant power density. In this paper, the ten species such as WI, WII, NII, NII, OII, OII, OII, OII, OII, OII, OII, OII, and NII are calculated. And, it is assumed that the temperature region of this calculation is 6,000-10,000 K which is generated by a free arc at 50 A[3]. Then, the mass contaminated ratio of high temperature gases contaminated with tungsten is assumed as a free arc at 2,380 W[3][current:70A, voltage:34V, distance between electrodes:1cm, radius:0.2cm]. And the 80%[3], 1,904 W/cm$^3$ ($\simeq 1.2 \times 10^6$W/m$^3$. sr), of it is assumed the radiant power density. It is assumed that the contaminated ratio is W I: 5%, N II: 76%, O II: 19% in this case.

Table 1 Dissociated and ionized voltages.

<table>
<thead>
<tr>
<th>Status</th>
<th>Voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td>WI $\rightarrow$ WII (W$^+$)</td>
<td>7.98 eV</td>
</tr>
<tr>
<td>WII $\rightarrow$ WIII (W$^{2+}$)</td>
<td>17.7 eV</td>
</tr>
<tr>
<td>N$_2$ $\rightarrow$ NI (N)</td>
<td>9.8 eV</td>
</tr>
<tr>
<td>NI $\rightarrow$ NII (N$^+$)</td>
<td>14.54 eV</td>
</tr>
<tr>
<td>O$_2$ $\rightarrow$ OI (O$^-$)</td>
<td>8.00 eV</td>
</tr>
<tr>
<td>OI $\rightarrow$ OII (O$^{2-}$)</td>
<td>13.614 eV</td>
</tr>
</tbody>
</table>

Each of dissociated and ionized voltage of species are shown in Table 1. Subscript Z is describe as ionized status.(Z=I:base).

Simultaneous equations

The equation used in this paper is shown below. The simultaneous equations such as dissociation equation, Saha equation, equation of state, natural equation of electron, equation of mass contaminated ratio of nitrogen, oxygen, is calculated by using the Newton-Raphson method. This program is written by C language, and the compiler is Microsoft C/C++., and the program is run on Windows XP.

Dissociated equation[4]

$$\frac{n_{i}n_{j}}{n_{ij}} = \frac{Q_{ij}}{Q_{ij}} \left( \frac{2\pi m_{i} m_{j} kT}{m_{ij}} \right)^{\frac{3}{2}} \exp \left(-\frac{E_{Dij}}{kT} \right)$$

(1)

where the species of elements : i, j, ij, the particle function:Q, Qij, Qij, the elemental weight:mi, mj, mij (kg), the temperature : T(K), the dissociation energy : $E_{Dij}$ (J), the mass density : n (1/m$^3$), the Boltzmann constant : k = 1.38 $\times$ 10$^{-23}$ J.K$^{-1}$, the Planck's constant : h = 6.67 $\times$ 10$^{-34}$ J.s.

Saha equation

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

(2)

where the species of elements : i, the mass density : n$_{iZ}$ (1/m$^3$), the electron density : n$_{e}$ (1/m$^3$), the mass of electron : $m_{e}$ = 9.11 $\times$ 10$^{-31}$ kg, the ionized energy : $E_{iZ+1}$ (J)
Particle function

\( Q_e = 2 \)

\[ Q_{IZ} = \sum g_{sIZ} \exp \left( -\frac{E_{sIZ}}{kT} \right) \]

(3)

where the statistical weight \( g_{sIZ} \), the energy of upper and lower level \( E_{sIZ} \), the energy of upper level \( m \), the energy of lower level \( n \) at subscript \( s \). In this paper, the particle function of vibration, rotation, translation, electron was considered.

Equation of state

\[ P = \left( \sum n_{IZ} + n_e \right) kT \]

\[ = (n_{WI} + n_{WII} + n_{WIII} + n_{O_2} + n_{O_1} + n_{O_H}) \]

\[ + n_{N_2} + n_{N_1} + n_{N_II} + n_e) kT \]

(4)

where the pressure is \( P = 0.1 \) MPa.

Natural conservative equation of electron

\[ n_e = \sum (Z - 1) n_{IZ} \]

\[ = n_{WI} + 2 \cdot n_{WII} + n_{WIII} + n_{O_2} \]

(5)

Equation of mass contaminated ratio of nitrogen, oxygen

\[ X_{N_2} = \frac{M_{N_2}}{M_W + M_{N_2} + M_{O_2}} \times 100 \]

(6)

\[ X_{O_2} = \frac{M_{O_2}}{M_W + M_{N_2} + M_{O_2}} \times 100 \]

(7)

where in case of mass contaminated ratio

\[ M'_W = (n_{WI} + n_{WII} + n_{WIII}) \times m_W \]

\[ M'_N = (2 \cdot n_{N_2} + n_{N_1} + n_{N_II}) \times m_N \]

\[ M'_O = (2 \cdot n_{O_2} + n_{O_1} + n_{O_H}) \times m_O \]

where the mass contaminated ratio of nitrogen: \( X_{N_2} \) (%), the mass contaminated ratio of oxygen: \( X_{O_2} \) (%), \( m_i \) : the atomic weight (g/mol).

Result of Mass Density

The mass density of high temperature gases contaminated with tungsten is shown in Fig. 1. The mass density of W I is more than about \( 5 \times 10^{22} \) m\(^{-3}\) at 6,000 K. But it decreases with temperature, and it is cross with W II around 7,500 K. After this, W II is bigger than W I. O\(_2\) of about 90 % has already dissociated to O I at 6,000 K. But N\(_2\) doesn’t dissociate such as O\(_2\) at 6,000 K, and its dissociation is about 20%. As the temperature increases from 6,000 K, the dissociated ratio of N\(_2\) increases. The mass densities of N\(_II\), O \(_II\) are about \( 10^{21} \) m\(^{-3}\), \( 10^{22} \) m\(^{-3}\) at 10,000 K, respectively. They barely exert an influence on total electron density at 10,000 K. Therefore, the mass density of electron is almost same as W II, and the ionization from W I is dominant. It can be confirmed by Fig.1. This phenomenon is explained because the increment of dissociated and ionized voltage is W I < O\(_2\) < N\(_2\) as shown in Table 1.

![Graph](image)

**Fig. 1** Mass Density of High Temperature Gases Contaminated with Tungsten in atmospheric air.

**RADIANT POWER DENSITY OF HIGH TEMPERATURE GASES CONTAMINATED WITH TUNGSTEN**

Method of calculation for radiation

The radiant power density of high temperature gases contaminated with tungsten, \( u \) (W/m\(^3\)-sr), is calculated by the result of the mass density of high temperature gases contaminated with tungsten and below equation[5]. In this paper, It is assumed that the region of wavelength is \( 38 \) nm ~ \( 998 \) nm[6][7][8].

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

(8)

\[ u_{cont} = \frac{1}{(4\pi e_0)^2} \frac{16\pi e^2 n_e^2}{3c^2(6\pi m^2 kT)^{1/2}} \frac{4kT}{h} \]

(9)

\[ u_{line} = \frac{n_{IZ} \cdot h c}{4\pi Q_{IZ} \lambda_{miz} g_{miz}} A_{miz} \exp \left( -\frac{E_{miz}}{kT} \right) \]

(10)
where $u_{cont}$: the continuous spectrum, $u_{line}$: the line spectrum, the dielectric constant of vacuum $\varepsilon_0 = 8.854 \times 10^{-12} \text{F/m}$, the light speed $c=2.998 \times 10^8 \text{m/s}$, the wavelength $\lambda_{mz}$, the transition probability from upper level $m$ to lower level $n : A_{nmz}$ (s$^{-1}$), the statistical weight of upper level : $g_{mz}$, upper level $E_{mz}$ is substituted into the values of species [WI, WII, WIII, NI, NII, OI, OII][6][7][8] at $38 \text{nm} \sim 998 \text{nm}$.

**Result of Radiant Power Density**

The radiant power density ($38 \sim 998 \text{nm}$) of high temperature gases contaminated with tungsten is shown in Fig. 2. The total radiant power density is estimated to be about $10^{13} \text{W/(m}^2\text{sr)}$ at $6,000 \sim 10,000 \text{K}$, $38 \sim 998 \text{nm}$ in wavelength region. The radiant power density emitted from WI is higher than NI, NII, OI, OII. The line spectrum is dominant in this wavelength. The line spectrum emitted from each particle, especially WI, is dominant in the radiant power density, even if the temperature changes. While the WII approaches to WI at $10,000 \text{K}$, WI is still bigger than WII in this calculation region. Because the electron is generated by ionization from WI, the continuous radiant power density is generated by WI. While the radiant power density emitted from the NI and OI increases with the temperature, the radiant power density emitted from WI is still dominant, because the NI is less than 1/10 of WI, and OI is less than 1/10 of WI at $10,000 \text{K}$. It is confirmed that the sum of radiant power density, the sum of line spectrum and the radiant power density emitted from WI are almost same value about $10^{13} \text{W/(m}^2\text{sr)}$ as shown in Fig. 2. And the electron from WI is dominant. As the continuous spectrum is calculated by electron density, it from WII is dominant. There is no term at which $\lambda_{mz}$ is substituted in the process of calculation for the continuous spectrum as shown in Equation (9). So, the continuous spectrum of each wavelength can’t be calculated. In this paper, it is assumed that the continuous spectrum indicate from ultraviolet to infrared rays. After this, it is same way in figures. In other words, while it can’t be compared between the line spectrum and continuous spectrum in each wavelength, it is indicated as reference.

**EXPERIMENT OF RADIANT ENERGY AND TEMPERATURE EMITTED FROM FREE ARC**

**Experimental arrangement**

The experimental arrangement is shown in Fig. 3. The free arc is generated by DC Power supply. And it is measured by spectroscope to estimate the temperature and by power meter to know the radiant power emitted from the free arc. The experiment of the radiant power, radiant energy, radiant efficiency and temperature emitted from the free arc was held to know the characteristics of DC horizontal short free arc contaminated with tungsten vapor near 50A. In this experiment, the radiant power, voltage and measurement of spectroscope was held in case of the tungsten electrodes, the distance $L$ between electrodes at 1cm, the current $I$ at 30, 50, 70A. The radiant power emitted from the DC horizontal short free arc contaminated with tungsten vapor near 50A between tungsten electrodes in an atmospheric air was measured by using power meter. The power meter can measure the wavelength from $300 \text{nm} \sim 30 \mu\text{m}$, and the sensitive of it is flat. The radiant power emitted from the free arc is not constant. But this power meter can measure the wide wavelength. So, there is few effect due to wavelength. While the radiant power emitted from WI and WII exists from $200 \sim 400 \text{nm}$[8], this experimental result is from $300 \text{nm} \sim 30 \mu\text{m}$, because the power meter can measure from $300 \text{nm} \sim 30 \mu\text{m}$.

**Radiant power**

Figure 4 shows the radiant power $\Phi (\text{W}) (300 \text{nm} \sim 30 \mu\text{m})$ in case of the point light source of radiant power emitted from DC horizontal short free arc discharge contaminated with tungsten vapor as functions of current. The radiant power is $860 \text{W (30A)}$, $1,480 \text{W (50A)}$, $2,100 \text{W (70A)}$, and increase in proportion to the $1.068\text{th}$ power of the current. The temperature was same value in different currents, even if the radius of free arc at 50A could be bigger than it at 30A. The logarithmic power of the current for the radiant
power was lower than it in case of the wall-stabilized model and torch plasma, because the radiant power depended on the bigger radius and lower temperature of the free arc.

\begin{align}
\Phi &= 16 \left( \frac{X}{d_p} \right)^2 \cdot \phi \\
\Phi(W) &= 23.4 I(A)^{1.06} \quad (12)
\end{align}

According to calculation of radiant power emitted from the wall-stabilized arc model fixed by the arc radius\cite{6}, the radiant power increases in proportion to the 2.0th power of the several tens of the current, to the 1.7th power of the several hundreds of the current, to the 1.2nd power of the several thousands of the current, in other words fully ionized region. And these calculated value is close to measured value. But in this free arc, the radiant power increases in proportion to the 1.06th power of the several tens of the current. This value is almost half of the wall-stabilized arc. Therefore, the radiant power of the free arc doesn’t increase with current. This is different between the free arc and the wall-stabilized arc.

The measurement waveform at 50 A of the current was shown in Fig. 5. The radiant power and voltage gradually increases from the discharge start point, \( t = 0 \), and they are level off at \( t = 12 \) s, because the free arc discharge starts at \( t = 0 \) by using the electrodes touch start, and after start, the distance between the electrodes is constantly changed to 1 cm at \( t = 12 \) s. It is same characteristics at 30, 70 A of the current. Therefore, they converge after \( t = 12 \) s. In this paper, the radiant power and voltage is indicated at \( t = 30 \) s.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{waveform.png}
\caption{Waveform of measured radiant power and voltage (50 A)}
\end{figure}

\section*{Radiant power as functions of current and in-put energy}

The input energy, \( Q_{in}(kJ) \), and radiant power, \( \Phi_E(kJ) \), \( (t_1=0\ s, \ t_2=30\ s) \), is calculated by below equation such as the time integral of voltage and measured radiant power as shown in Fig.6.

\begin{equation}
Q_{in}(kJ) = \frac{1}{1,000} \int_{t_1}^{t_2} IV(t) \ dt \quad (13)
\end{equation}

\begin{equation}
\Phi_E(kJ) = \frac{1}{1,000} \int_{t_1}^{t_2} \Phi(t) \ dt \quad (14)
\end{equation}

The radiant energy increases in proportion to the 1.06th power of the in-put energy. This value is almost same when the current changes, because the voltage between the electrodes is almost constant.

\begin{equation}
\Phi_E(kJ) = 0.62Q_{in}(kJ)^{1.06} \quad (15)
\end{equation}

The radiant energy \( \Phi_E(kJ) \) (300 nm~30 \( \mu \)m) in case of the point light source of radiant power emitted from DC horizontal short free arc discharge contaminated tungsten vapor as functions of current and in-put energy is
27 kJ (35 kJ), 35 kJ (45 kJ), 43 kJ (55 kJ), and increase in proportion to the 1.66th power of the input power.

Therefore, the radiant efficiency, $\eta$, is expressed as below:

$$\eta(\%) = \frac{\Phi_E}{Q_{in}} \times 100 = 61.9Q_{in}^{0.06}$$ (16)

The radiant efficiency was extremely high level, about 80% as white light as shown in Fig. 6. While, so far, it is considered about 40-50% [6][7][8]. This value is considered as champion date. It is double than gases only. The reasons of this high value of radiant efficiency are the contaminated with tungsten vapor from electrodes and radiation emitted from the electrodes. The contaminated gases should be chosen to increase the radiant power.

![Radiant energy and efficiency as function of input energy](image)

**Fig. 6** Radiant energy and efficiency as function of input energy.

**TEMPERATURE OF FREE ARC**

**Estimated Temperature by using Line Pair Method**

The temperature of DC horizontal free arc between the tungsten electrodes was measured with a spectroscopy at 30~70 A of the current in atmospheric air. The arc discharge in case of LTE status consists of Boltzmann distribution between excited atoms. The temperature was measured at the middle point between electrodes, and then calculated according to Line Pair Method under a condition of LTE as follows:

$$\ln \left( \frac{I_{mN} \lambda_{mN}}{A_{mN} g_{mN}} \right) = -\frac{1}{kT} E_{mN} + \ln \left( \frac{nhc}{Z_{mN}} \right)$$ (17)

where the species: $i, j, ij$, the subscript $m, n$ represents the upper and lower energy levels, respectively. $I_{mN}$ is the measured intensity of the line radiation, $\lambda_{mN}$ (nm) is the wavelength. $A_{mN}$ (s$^{-1}$) is the Einstein transition probability, $g_{mN}$ is a constant for the upper energy level, and $E_{mN}$ (eV) is the energy of the upper energy level. To erase the influence of the continuous spectrum, the area method was used to deal with the data.

When the x-axis is energy $E_{mN}$, the y-axis is the intensity of spectrum area, the slope of this plots becomes the straight line. The temperature, $T$, is derived from the slope.

The distribution of spectrum of free arc was measured by spectroscopy at center point between electrodes [9]. According to this distribution and the radiant power density [9], the radiant power emitted from WI is dominant. Therefore, the temperature is calculated by line spectrum from WI.

The WI was dominant in this wavelength. Figure 7 shows the temperature of the free arc. The line spectra were decided at 5 points (455.184 nm, 457.067 nm, 458.875 nm, 465.744 nm, 469.373 nm, 475.764 nm), because it was clear to recognize WI line.

The temperature was measured to be about 5,500 K at 30~50 A in current, 0.01 m in plasma length by the line pair method [9]. The temperature was same value in different currents, even if the radius of the free arc at 50 A could be bigger than that at 30 A [3]. Therefore, the temperature for the erosion would be almost same value. It is assumed that this temperature is the average temperature in the arc column.

![Temperature of Free Arc](image)

**Fig. 7** Temperature of Free Arc.

**RELATION BETWEEN RADIANT POWER AND TEMPERATURE OF FREE ARC CONSIDERED BY ARC RADIUS**

The result between the mass density of high temperature gases contaminated with tungsten, measured radiant power, temperature from the line spectrum method is compared to know relation between the radiant power and temperature of free arc considered by arc radius.

**Relation between arc radius and temperature of free arc**
The temperature of free arc contaminated tungsten is estimated about 5,500 K ~ 5,600 K at 30 A, 50 A, 70 A as shown in Fig.7. These temperatures are almost same value even if the current changes. In case of the wall-stabilized arc, the temperature increases with the current. The arc radius can’t expand because the wall exists even if the current increases. So, the temperature increases because the current density or current/radius ratio increases. But, in case of free arc, the arc radius can increases when the current increases. So, the current density doesn’t increase, and the temperature also doesn’t increase. The current density doesn’t increase and the temperature also doesn’t increase. The current density doesn’t increase and the temperature also doesn’t increase in comparison with the wall-stabilized arc. In other words, when the current increases, the effect of arc expand to radius direction is stronger than increment of temperature in case of free arc. For example, the average current density, \( J \), is expressed below equation:

\[
J = \frac{I}{\pi R^2}
\]  

where \( R \) is arc radius.

If the current density, \( J \), is constant, the arc radius is expected to increase in proportion to the square root of current.

Relation between arc radius and radiant power

According to the radiant power theory of the wall-stabilized arc in case of the same radius, the radiant power increases in proportion to the 2.0th power of the current at several ampare of the current as mentioned above. And the measured value and the theory value is almost same. But the radiant power increases in proportion to the 1.0th power of the current in this experiment. This value is half of the wall-stabilized arc. So, the radiant power doesn’t increase with the current such as wall-stabilized arc. Because the free arc doesn’t have the restriction of radius, the radius increases to expand to radius direction. So, the increment of current density is secured so much, and then the temperature also doesn’t increase. Therefore, the radiant power density doesn’t increase such as the wall-stabilized arc. In this case, the radiant power increases to expand the cross-section due to increment of arc radius. For example, the arc radius increases in proportion to the square root of the current in case of constant of current density. The radiant power is assumed that it has "radiant power \( \propto \) cross-section of arc \( \times \) radiant power density (almost constant) \( \propto \) (arc radius)^2 \( \propto \) current". Therefore, the radiant power is expressed such as \( \Phi \propto J^{1.5} \). This result is very close to the result of current parameter, 1.06, in this experiment.

SUMMARY

In this paper, the mass density and the radiant power density of the temperature and the radiant power emitted from the DC horizontal short free arc discharge contaminated tungsten vapor near 50 A is calculated, and also, the radiant power, the radiant efficiency, the radiant energy, temperature, radius of free arc is researched by using power meter and spectroscope. The result is indicated below:

1) It was calculated that the WI was bigger than the nitrogen spectral line N1 when the temperature was less than 10,000K. The total radiant power density is estimated to be about 10^{10} W/(m^2*sr) at 6,000 ~ 10,000 K, 38 ~ 998 nm in wavelength region. The radiant power density emitted from WI is higher than N1, NII, OI, OII.

2) The radiant power, \( \Phi (W) = (300 \text{ nm} ~ 30 \mu \text{m}) \), in case of the point light source of radiant power emitted from DC horizontal short free arc discharge contaminated tungsten vapor as functions of current, 860 W (30 A), 1,480 W (50 A), 2,100 W (70 A), and increase in proportion to the 1.06th power of the current. This value is more than less than wall-stabilized arc.

3) The radiant energy \( \Phi (kJ) = (300 \text{ nm} ~ 30 \mu \text{m}) \) in case of the point light source of radiant power emitted from DC horizontal short free arc discharge contaminated Tungsten Vapor as functions of current and in-put energy is 27 kJ (35 kJ), 35 kJ (45 kJ), 43 kJ (55 kJ), and increase in proportion to the 1.06th power of the in-put power.

4) The radiant efficiency is extremely high level, about 80%, as white light. This value is considered as champion date, because it is double than gases only.

5) The temperature of free arc contaminated tungsten is estimated about 5,500 K ~ 5,600 K at 30 A, 50 A, 70 A by using line pair method. These temperature are almost same value even if the current changes.

6) When the current increases, the effect of arc expand to radius direction is stronger than increment of temperature in case of free arc. It is considered that the the energy of arc becomes the increment of radius, because there is no influences of the wall and the gases for radius.

7) The radiant power increases in proportion to the 1.06th power of the current. This value is half of the wall-stabilized arc. Because the free arc doesn’t have the restriction of radius, the radius increases to expand to radius direction.

8) The arc radius increases in proportion to the square root of the current in case of constant of current density. The radiant power is expressed such as \( \Phi \propto J^{1.5} \). This result is very close to the result of current parameter, 1.06, in this experiment.

In the future, we will research the effect of the radiant power in the high current region, in various gases, and also the degradation of materials due to radiant power and the application for hazardous wastes.

Acknowledgements

The authors thank Prof. I.Miyachi of Aichi Institute of Technology, Prof. Y. Yokomizu of Nagoya University, Y. Tanaka of Kanazawa University, Dr. K. Ikeda of CRIPE, and Dr. M. Iwata of CRIPE for their fruitful suggestions and the Y. Yamaguchi, Y. Uenishi, 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


