Experimental characterization of a hydrogen/argon cascaded
arc plasma source

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A H₂/Ar cascaded arc plasma source has been experimentally characterized by determination
of the efficiency, the electric field, and the pressure gradient of the arc. The results show that the
efficiency of a H₂/Ar cascaded arc drops when the hydrogen flow rate is increased. The electron
temperature in the argon cascaded arc has been derived to be in the range 9000–12 500 K. For
a hydrogen arc, the mass dissociation degree of hydrogen molecules has been derived to be above
60%.

I. INTRODUCTION

The cascaded arc is an example of a wall-stabilized
thermal plasma. It can be operated both as a stationary
nonflowing plasma and a flowing plasma and it has already
been widely used in nonequilibrium and nonideal plasma
effects study, flowing atmospheric plasma study, spectro-
copy and spectroscopic ellipsometry techniques, surface
modification techniques, deposition of amorphous and
crystalline thin films, and for an ionizing and dissociation
particle source.¹–³ To obtain a thorough knowledge of the
cascaded arc and to optimize the design of the arc setup, it
is helpful to characterize the cascaded arc experimentally.

II. POWER BALANCE OF A CASCADED ARC

The cascaded arc used in this work consists of a cath-
ode chamber, three cathodes, an anode plate with a nozzle,
and several copper cascaded plates. (Figure 1, only one
cathode is shown.) The total length of the arc channel in
the five plates case is 30 mm and in the ten plates case is 60
mm. The diameter of the arc channel is 4.0 mm. The cath-
ode position is chosen to be the origin of the channel axis.

Since the cascaded arc is water cooled, in the station-
ary state operation, the power loss at position (i) equals
the power obtained by the cooling water:

\[ P_{\text{water}}(i) = \rho(T)C_{pk}\phi(i)[T_{\text{out}}(i) - T_{\text{in}}(i)], \]

where \( \rho(T) \) is the water density, \( C_{pk} \) the specific heat
capacity, \( \phi(i) \) the water flow, \( T_{\text{in}}(i) \) and \( T_{\text{out}}(i) \) the water
temperatures. The local efficiency at plate (i) is then

\[ \eta(i) = 1 - \frac{2\rho(T)C_{pk}\phi(i)[T_{\text{out}}(i) - T_{\text{in}}(i)]}{I_{\text{arc}}[V(i-1) - V(i+1)]}. \]

The general efficiency of the cascaded arc is then

\[ \eta_e = 1 - \frac{\rho(T)C_{pk}[\Sigma_{\text{anode}}(\phi(i)[T_{\text{out}}(i) - T_{\text{in}}(i)]}{I_{\text{arc}}[-V_{\text{cathode}})}, \]

where \( I_{\text{arc}} \) is the total input power.

For a hydrogen arc, the power obtained by the arc
plasma can be written as

\[ P_{\text{plasma}} = \sum C_j k_j T_j + \beta_m \phi_0 E_{\text{dis}} + 2a \phi_0 E_{\text{ion}}, \]

where index \( j \) reflects the particle specimen (electron, ion,
atom, or molecule, etc.), \( C_j \) is constant, \( \beta_m \) the mass dis-
sociation degree, \( \alpha \) the ionization degree, \( \phi_j \) the particle
flow at the exit of the arc, \( \phi_0 \) the input flow at the entrance
of the arc, \( T_j \) the particle temperature, \( E_{\text{dis}} \) and \( E_{\text{ion}} \) the
dissociation energy and the ionization energy, respectively.
It is estimated that the average ionization degree of the
hydrogen plasma is at least a factor of 2–4 smaller than
that of an argon plasma under the same current conditions
due to shrinking of the plasma channel.⁴ The ionization
degree of the cascaded argon plasma (\( I_{\text{arc}} = 45 \) A) is ~5% at
the flow range of a few standard liter per minute.⁵ The
lower limit of \( \beta_m \) can thus be estimated by setting
\( \alpha = 2.5\% \), and the upper limit can be estimated by setting
\( \alpha = 0 \).

III. ELECTRIC FIELD IN A CASCADED ARC

The electric field at position (i) in the arc is defined as

\[ E(i) = \frac{j(i)}{\sigma[n_e(i), T_e(i), f(i)],} \]

FIG. 1. The cascaded arc.
where $j(i)$ is the current density, $n_e(i)$ and $T_e(i)$ the electron density and temperature, respectively, $f$ a Maxwellian velocity distribution, $\sigma [n_e(i), T_e(i), f]$ the electrical conductivity of the plasma which according to Frost mixing rule is\(^6\)

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\sigma = \frac{4\pi n_e e^2}{3k_B T_e} \int_0^{\infty} \frac{v^5 f(v)}{v_{ei} + v_{en}} dv
$$

with $v_{en}$ the e-n collision frequency, $v_{ei}$ the e-i collision frequency. The result of this integration gives a numerical relation of $T_e$ and $\sigma$.

**IV. EXPERIMENTAL RESULTS**

The general efficiency $\eta_g$ of a pure argon arc rises almost steadily with argon flow. The arc current has only a very small influence on it (Figs. 2 and 3). In the flow range from 1.0 to 10.0 slm, $\eta_g$ rises from 30% to 60%. The largest contribution to the rise of efficiency comes from the cathode region where the efficiency rises from $\sim 20\%$ to $90\%$ (Fig. 2). Although the arc current has almost no influence on $\eta_g$, it does influence the local efficiency at small current range. In the arc current range of 15–25 A, the efficiency in the cathode region rises from about 55% to 80% while in the middle region of the arc channel it drops from 70% to 35%. As a consequence, $\eta_g$ changes only slightly. The result implicates that the high efficiency part of the cascaded arc becomes shorter at higher arc currents.

When hydrogen is added into an argon arc, the energy transfer mechanism may be changed due to the large thermal conductivity of hydrogen and the association of the hydrogen atoms in the periphery of the arc channel. Both will cause a drop of $\eta_g$. The result shows that the main drop of $\eta_g$ occurs even at small hydrogen fractions (Fig. 4). Above 10% hydrogen flow component, the present hydrogen already determines the transport properties of a H$_2$/Ar mixture and $\eta_g$ remains constant about 35%. For a pure hydrogen arc with five cascaded plates, $\eta_g$ is also $\sim 35\%$ (Fig. 4, the dark circle marks, hydrogen flow range of 4–9 slm). The local efficiency in a 30 mm hydrogen arc behaves also similar as that in a 60 mm H$_2$/Ar arc (Fig. 5): it is high in the cathode region and the anode region and low in the middle region of the arc channel. This is different compared with an argon arc in which the lowest efficiency region is in the anode region.

The upstream pressure in a cascaded arc increases with increasing the gas flow or the arc current. The pressure
Gradient along the arc channel is almost constant except at the anode region (Fig. 6) where the pressure gradient is a few times larger than elsewhere in the arc since the particles must be accelerated to match the sonic exit condition. For a H₂/Ar arc mixture, the pressure and the pressure depends also strongly on the hydrogen flow component for constant current and total flow rate. Both pressure and pressure gradient in the arc drop with increasing hydrogen flow component due to the reduce of the plasma viscosity.

The electric field along a cascaded arc is rather homogeneous except at the cathode region and the anode region where the edge influence is large (Fig. 6). The electric field increases when injecting hydrogen into the arc. When the hydrogen component is large enough, the electric field in the cathode region becomes smaller than elsewhere in the arc. This is different compared with an argon arc in which the electric field in the cathode region is always higher.

Since the ion density in an argon arc over the channel cross section is almost flat, the channel cross section value can be used as the arc cross section. The average electron temperature over the cross section in the argon arc is derived to be in a range of 9000-12 500 K by Frost mixing rule (Fig. 7) at our experimental conditions. Actually, the $T_e$ is not completely homogeneous in the arc, it is slightly higher in the center and lower close to the channel wall. In the arc, $T_e$ rises slightly along the arc channel. It is higher at the anode region than at the cathode region. In a H₂/Ar mixture case, the electron density at wall is much lower than at the arc center due to the strong recombination at wall. The effective cross section of the arc is smaller than the channel cross section. This is so-called channel narrowing effect or contraction. Besides this, the homogeneous temperature assumption is also violated in a H₂/Ar mixture due to the strong cooling effect at the arc wall. In this case, it is difficult to derive $T_e$ by Frost mixing rule. Contrary, if $T_e$ is known, it is possible to study the channel narrowing effect of hydrogen plasma by deriving the effective channel width of the arc.

Figure 8 shows the derived mass dissociation degree $\beta_m$ of the hydrogen molecule at the exit of a cascaded arc. $\beta_m$ is high at low flow range. However, at the high flow range (for the same arc current) it is lower. Figure 8 also shows the atomic hydrogen flow at the exit of a cascaded arc at an arc current of 45 A.