

# Voltage Gradient-Current Characteristics of Ar Torch Plasma Normalized by its Experimental Photo-radius

Tsuginori INABA, Masao ENDO, Yoshimoto WATANABE  
and Masatoyo SHIBUYA\*

Department of Electrical Engineering, Chuo University

\*Central Research Institute of Electric Power Industry

For a qualitative analysis of torch plasma, the wall-stabilized arc theory is applied to the characteristic of voltage gradient versus current normalized with the photographically measured radius under the condition of the current 50 to 300 A, plasma length 1 to 9 cm and the gas flow of argon 20 NI/min. The normalized voltage gradient versus current of the present torch plasma is consistent with those found by wall-stabilized arc, suggesting that the method becomes powerful tool for analysis of free burning torch arc.

## 1. INTRODUCTION

Free burning arc plasma readily changes their modal shape, by virtue of self-exciting dynamic forces, such as convective force, electromagnetic force and viscous resistant force by external flow. Since it contains enormous energy in itself and partly radiates, in arcs accidentally generated as such in electric power plant, an immediate fault current limiting or rapid interruption techniques are highly required to avoid harmful effects on facilities itself or around.<sup>(1)</sup>

While in a use of arc plasma employing this enormous energy for heating and melting materials, or employing this enormously strong electromagnetic force for propelling space satellite, it is essential to control arc plasma behaviors well for the purpose. For any engineering application, it is basically important to understand the effects of various arc parameters for making arc plasma control better as possible.

## 2. ADVANTAGE OF TORCH PLASMA

One of the methods to make arc plasma more controllable is to use a torch in which the plasma is constricted in its radius by a small nozzle and further stabilized with axial laminar gas flow through it, and this type of torch plasma has been already developed and employed for cutting, welding and spraying materials.<sup>(2)</sup> The torch plasma is relatively easy to produce, and since it has no specific wall for stabilization, it becomes even a benefit for studying disturbances to modal shape of arc plasma by self-produced magnetic field and gas flow as well. Employing this type of torch plasma, in this study, a trial was made to understand the effects of various parameters on characteristic of arc in free space in accordance with the wall-stabilized arc theory<sup>(3)</sup> in which the voltage

gradient-current curve is shown to unify to a single one, so-called universal curve, with the normalization by arc radius.

### 3. EXPERIMENTAL EQUIPMENT OF TORCH PLASMA

Major specifications of the experimental equipment of torch plasma employing in this study are as follows: The maximum rate of the actual electric power source is DC 150 V, 400 A in current with the no load voltage of 300 V. The torch plasma is produced between the Th-W tip electrode of negative and the water-cooled stainless-steel thick disc of positive through a water-cooled nozzle. The size of the plasma chamber is 50 cm in diameter and 60 cm in length. The working gas of the torch is argon, the flow rate of which is varied from 0 to 20 Nl/min. A photographic view of the experimental equipment is shown in Fig.1 and also a detailed view of the electrode configuration in Fig.2.

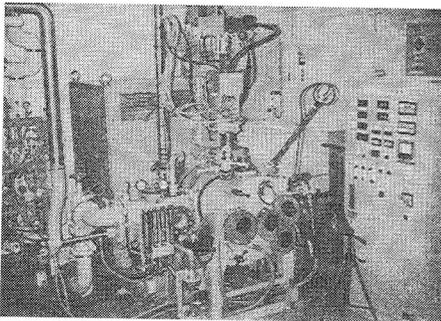


Fig.1 Experimental Equipment

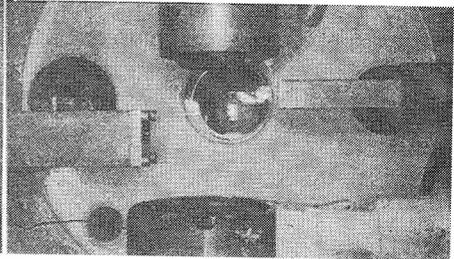


Fig.2 Electrode Arrangement

### 4. EXPERIMENTAL RESULTS OF TORCH PLASMA

#### 4-1. MODAL SHAPE OF TORCH PLASMA AND ITS PHOTO-RADIUS

Typical examples of photographic views of torch plasma, generated employing a stainless-steel (SUS) disc as an opposite electrode, are shown in Fig.3. The arc current was 100 A and the distance from the nozzle to the opposite electrode was 3 cm in (a), 5

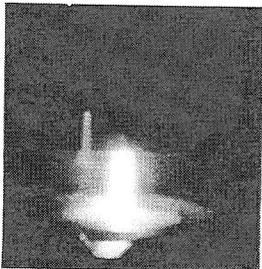


Fig.3 (a) 3 cm

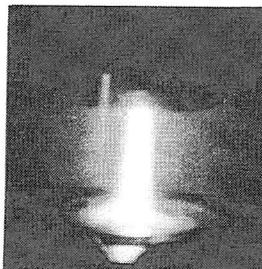


Fig.3(b) 5 cm

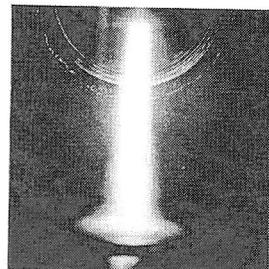


Fig.3 (c) 9 cm

cm in (b) and 9 cm in (c). As in Fig.3, the plasma column of torch is seen fairly clear, and then the arc radius can be photographically determined. The photo-radius  $R_p$  thus obtained is plotted in Fig.4, as a function of the outer plasma length out of the nozzle  $L_a$  for two electrode distances and currents. The photo-radius  $R_p$  of torch plasma becomes larger toward the opposite electrode, although it is a little bit unclear at small currents, and this may result from stagnant plasma flow in the vicinity of the disc electrode.

#### 4-2. TERMINAL VOLTAGE AND VOLTAGE GRADIENT VERSUS CURRENT CHARACTERISTICS

In Fig.5, the terminal voltage  $V_a$  between the electrodes is plotted as a function of the outer plasma length  $L_a$  with the parameter of the current. The terminal voltage increases very linearly up to the length  $L_a=9$  cm at 50 A, but at the currents more than 75 A the ter-

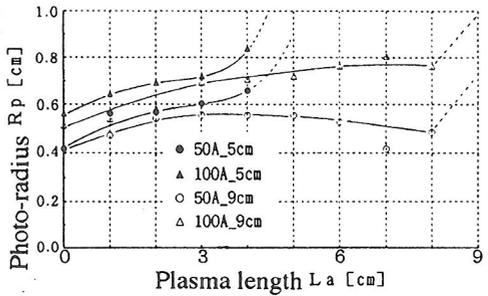


Fig.4 Photo-radius  $R_p$  in torch plasma

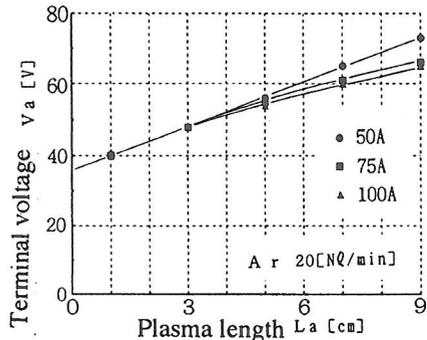


Fig.5 Terminal voltage in torch

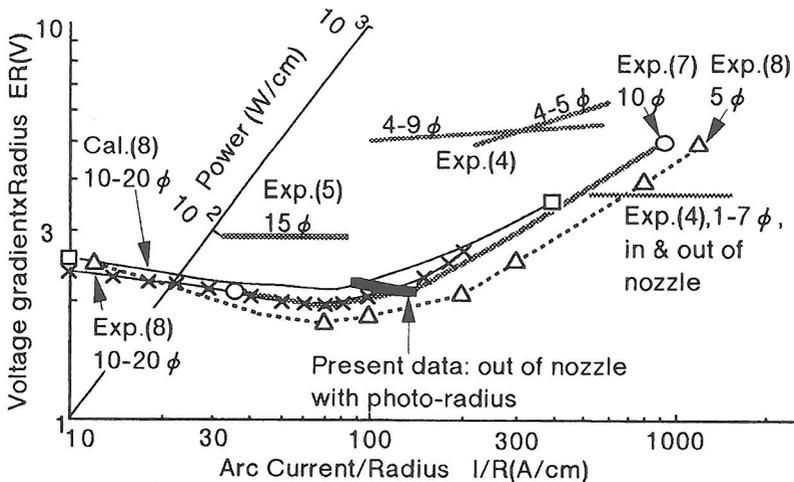


Fig.6 Normalized characteristic of voltage gradient vs current. The labels "Exp." and "Cal." respectively mean the measured and calculated with the reference number parenthesized. The number with  $\phi$  indicates the arc diameter in mm.

minimal voltage is slightly levelled off for  $L_a$  above 4 cm. The gradient of the line in Fig.5 corresponds to the electric field of the plasma, and the value thus obtained for 50 A is 4.1 V/cm as a whole data average. It is found that this value is quite consistent with that measured in a stabilized arc by water-cooled wall of the diameter 1.5 cm, in spite of unequal cooling-conditions.<sup>(5)</sup>

Employing the voltage gradient  $E$  in Fig.5 and the photo-radius  $R_p$  in Fig.4, the normalized characteristic of voltage gradient versus current was obtained in the form of  $ER_p-I/R_p$  for the present torch plasma as shown in Fig.6. It is seen, in Fig.6, that the normalized curve of the present torch plasma shows a fairly good agreement with those measured by Emmons<sup>(7)</sup>, Shindo<sup>(8)</sup> in wall-stabilized arcs and calculated with an inclusion of radial thermal conduction.<sup>(8)</sup>

## 5. ANALYSIS OF MEASURED TORCH PLASMA CHARACTERISTICS

### 5-1. AXIAL DISTRIBUTION OF AVERAGED ARC CURRENT DENSITY IN TORCH PLASMA

With the photographically determined arc radius  $R_p$  shown in Fig.4, the arc current density  $\bar{J}$  can be calculated in an averaged fashion as

$$\bar{J} = I / (\pi R_p^2) \quad (1)$$

where  $I$  is the torch plasma current. In Fig.7, the calculated  $\bar{J}$  is plotted for the outer plasma length  $L_a$ . In general, since the arc is constricted at nozzle, the current density becomes high there. However, going down to the disc electrode, the current density  $\bar{J}$  lowers, and then it reaches a steady-state value and rapidly decreases just in front of the electrode. More specifically, the arc current density reaches the steady-state value at the distance further than 1 or 2 cm from the top of nozzle at 50 A and 2 or 3 cm at 100A. As such, the current density  $\bar{J}$  at 3 cm from the top of nozzle is cited here as the steady-state value for convenience.

The steady-state value of the current density is calculated as about 51 A/cm<sup>2</sup> at 50 A and 66 A/cm<sup>2</sup> at 100 A

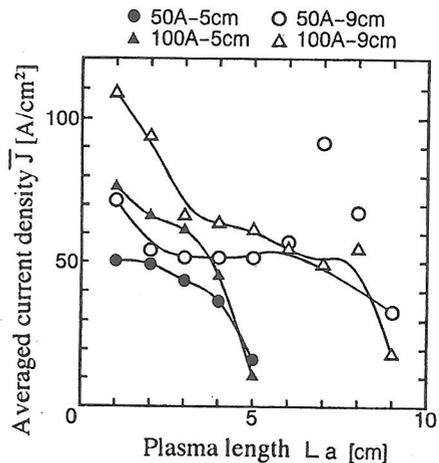


Fig.7 Axial distribution of current density

for the case of  $L_a=9$  cm, mentioning that for doubled arc current from 50 to 100 A,  $\bar{J}$  is not necessarily increased twice but rather by 1.2 to 1.5 times, about square-root of it, because the arc radius is increased thereby. For the case of  $L_a=5$  cm, due to the stagnant plasma flow as stated above, the radius  $R_p$  becomes larger and then the steady-state value of the current density is lowered by about 10 A/cm<sup>2</sup> from that for  $L_a=9$  cm for every arc current.

5-2.AVERAGED ELECTRICAL CONDUCTIVITY OF THE COLUMN

The electrical conductivity  $\bar{\sigma}$  in an averaged fashion can be calculated as

$$\bar{\sigma} = \bar{J} / E \tag{2}$$

where E is the electric field obtained in Fig.5. The electrical conductivity calculated by Eq.(2) is shown in Fig.8. Since the large data scatter was observed in the down stream,  $\bar{\sigma}$  is calculated only for  $L_a=0$  to 3 cm with the measured electric field  $E=4.0$  V/cm. The axial distribution of the electrical conductivity is equal to that of the current density itself, because the change of E by the arc current is not observed. In further down stream below 4 cm, the tendency differs from Fig.8, because the electric field is slightly lowered by increased arc radius due to stagnant plasma flow. The electrical conductivity of the steady-state value for  $L_a=9$  cm is estimated as about 12.9 S/cm at 50 A and 16.5 S/cm at 100 A. For the case of  $L_a=5$  cm,  $\bar{\sigma}$  is estimated as about 10.9 S/cm at 50 A and 15.3 S/cm at 100 A, and they are lowered by 10 to 20 % due to the stagnant plasma flow.

5-3.ESTIMATE OF A AVERAGED TEMPERATURE IN COLUMN

The electrical conductivity calculated in Fig.8 was employed to yield the arc temperature in the column through the relationship of the electrical conductivity versus temperature reported by Devoto.<sup>(10)</sup> The results of estimated temperature are plotted in

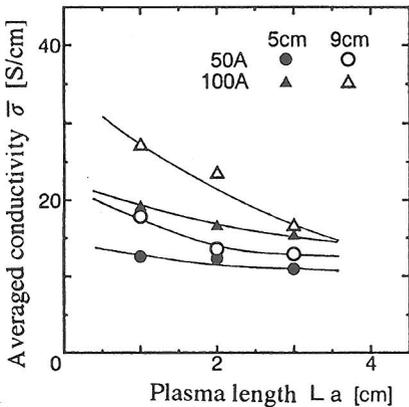


Fig.8 Electrical conductivity

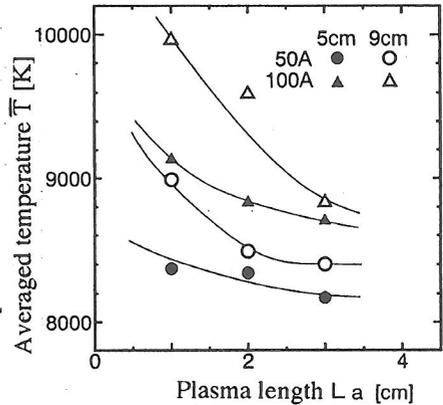


Fig.9 Arc temperature

Fig.9 for the outer plasma length  $L_a$ . It is seen, in Fig.9, that the estimated arc temperatures are ranged in 8200 to 10,000 K. In ref.(8), it is pointed out that the local thermodynamic equilibrium (LTE) is less likely established at lower arc current, larger arc radius and lower pressure in Ar. In terms of the arc temperature, the present data in Fig.9 lie in the verge of the lower limit for the establishment of LTE.

## 6.CONCLUDING REMARKS AND FUTURE PROBLEMS

The present torch plasma experiment, in which the column was stabilized with an axially cylindrical gas flow, confirmed that the wall-stabilized theory as one of analysis tools was possibly applicable to its characteristic of voltage gradient versus current normalized with the photographically determined arc radius. Some problems have been still involved in measurements of the photo-radius and its analysis, they should be future subjects to be investigated, as well as the effects of the radiation loss rate and gas flow rate.

The torch plasma can change its modal shape under the influences of the magnetic field and gas flow. In other words, this feature can be used to study the rigidity, flexibility and viscous resistivity of the torch plasma, and this kind of procedure will be able to lead an effective operation of the torch plasma in actual fields.

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## REFERENCES

- (1) H. Fukagawa and T.Inaba: Trans. I.E.E.Jpn., 111-B 937(1991) [in Japanese]
- (2) T.Inaba and M.Shibuya: Trans.I.E.E.Jpn. 107 1019(1988) [in Japanese]
- (3) T.Inaba: Trans.I.E.E.Jpn. 94-A, 83(1974) [in Japanese]
- (4) K.Ando andM.Hasegawa: Welding Arc Phenomena (Sanpou LTD, 1976)  
[in Japanese]
- (5) K.Ikeda, K.Adachi and T.Inaba: Papers of Technical Meeting on  
Switchgear and Protection, I.E.E.J., SP-94-57 (1994) [in Japanese]
- (6) M.Okada and Y.Arata: Plasma Engineering(Nikkankougyo, p352, 1965)  
[in Japanese]
- (7) H.W.Emmons: Phys. Fluids 10, 1125(1967)
- (8) H.Shindo,T.Inaba and S.Imazu: Trans.I.E.E.Jpn. 100-A, 113(1980) [in Japanese]
- (9) J.Kopainsky: Z. Physik 248, 405(1971)
- (10) R.S.Devoto: Phys. Fluids 16, 616(1973)