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Operating Characteristics of DC Arc Plasma Torch*

(I. Operation at Atmospheric Pressure Using Argon Gas)

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In adopting the DC arc plasma torch as a heat source of plasma tunnel, it is, first of all, important to know the nature of non-uniformity of the plasma flame in interpreting the data obtained in the test section. In this experiment, the authors pointed out that the non-uniformity occurred even in the domain equivalent to static arc, and that it seemed, therefore, doubtful to use the anode nozzle as a supersonic nozzle. Next, it is observed that, in the domain in which cyclic voltage fluctuation is present, the nature of the fluctuation is analogous to the vibration of string with both end being fixed, and from the energy equilibrium consideration, the desirable operating condition of torch is proposed. Some comments are made on the electrode failure.

1. Introduction

For verifying theories or clarifying problems associated with the supersonic flow of gases at very high temperature and low density, the experimental researches are indispensable. As the means of producing high temperature gases, for this purpose, we may indicate two possible ways, namely of heating gases by strong shock wave⁽¹⁾ or electric discharge. As for the low density plasma tunnel, in which the operations are continuous and steady, it is customary to adopt the method of heating gases by electric discharge. There are, however, many variations and improvements even in this method, and the authors, from the standpoint of using plasma as a working gas of the wind tunnel, conducted researches on the plasma tunnel making use of the gas vortex stabilized plasma generator and reported some interim results⁽²⁾ about that tunnel.

When the DC arc plasma torch (for brevity, the authors call it simply "torch" hereafter) is used as the plasma generator for plasma tunnel, the plasma conditions at the test section seem to fluctuate periodically. (As an example, we may verify this by observing time-resolved radiation from the plasma.) This fact has already been pointed out by some investigators⁽³⁾, and it is presumed that it

would be connected with the mechanism of gas heating at the arc column. For the present, details have not been studied yet, and it is usual to obtain the temperature and the other values from the average results measured over some time interval neglecting these time-resolved fluctuations. To know the temperature of plasma, the authors, too, from the abovementioned viewpoints, analyzed the spectroscopic plates which were exposed longer than one cycle of the fluctuation, and detected the electron heating by the shock wave⁽²⁾.

But to do more detailed studies and get more quantitative data, it becomes indispensable to clarify the nature of these fluctuations.

As the mechanism of gas heating within the torch is connected with the complex interactions between the arc column and the gas flow, it is very difficult to investigate the fundamental mechanism of the phenomena. And the experimental studies^{(4) (5)} of very preliminary nature have just been started out in relation to the electrode mechanisms of MHD power generation and propulsion.

The authors, in this paper, aimed at obtaining the data of torch as a heat source for plasma tunnel, but the experimental results will be useful for operating the torch for various objects such as the material processing.

2. Experimental apparatus

Block diagram of the experimental apparatus is shown in Fig. 1.

The argon gas of which the pressure is reduced

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to 3 atg by the pressure reduction valve, passes the flow meter (orificemeter or floating flow meter) and is supplied to the torch. In passing the DC arc discharge column, argon gas is heated by Joulean heating to plasma state and is exhausted to the atmosphere. (Hereafter, the part which is exhausted from the torch in the state of plasma is called "plasma flame".) Fig. 2 is a picture of the torch.

The compositions of the argon gas used in this experiment are as follows:

Ar > 99.99 %, $N_2 < 0.005$ %, $H_2 = 0.000$ %

At the normal operating condition, no impurity was found spectroscopically. (Electrode contamination was carefully checked especially.)

To avoid the overheating, the torch was sufficiently water-cooled, and from the flow rate and the

temperature rise of the cooling water, the heat losses may be calculated. To measure the temperature rise correctly, the thermister thermometers of high sensitivity were used, and special care was taken to maintain the water flow rate constant.

By the plane grating spectrograph and the ultra-high speed streak camera, whose arrangement is shown in Fig. 1, the time- and space-resolved conditions of the plasma flame have been observed in detail.

The electrode arrangement of the torch and the symbols used in this paper are shown in Fig. 3; 2 % thoriated tungsten and copper are used as the cathode and the anode respectively. Argon gas is given a swirling component flowing around the cathode and exhausted into the atmosphere from the nozzle.

When the torch is operated as a heat source for low density plasma tunnel (test section pressure is about 1 torr), the plenum chamber pressure ranges between 300 and 800 torr, and therefore, the meaningful data may be expected from the results of the present observation.

3. Disturbance and exhaust velocity of plasma flame

The uniformity of the plasma flow from the torch is closely connected with the problem of possibility of using the electrode nozzle as a supersonic nozzle as well, when the torch is used as a heat source of plasma tunnel⁽⁶⁾.

In spite of the fact that the temperature of plasma flame obtained spectroscopically ranges from 12000°K to 13000°K on the average and reaches 17000°K as maximum, the average temperature under the same condition, which is estimated using the chart by Bosnjakovic⁽⁷⁾, depending on the argon gas flow rate and the electric power input, is about, 8000°K. Therefore, there is large discrepancy between them. Same tendency may be found also by varying the electric current and the gas flow rate.

V: Voltmeter
A: Ammeter
HFS: High-frequency starter
SS: Synchroscope
GC: Gas container
PRV: Pressure reduction valve
PG: Pressure gauge
q: Gas flow meter
Q: Water flow meter
T₁: Water inlet temperature
T₂: Water outlet temperature

Fig. 1 Block diagram of the experimental apparatus

Fig. 2 Plasma torch

Fig. 3 Electrodes arrangement

This fact has recently been pointed out by several investigators^{(8) (9)}, and the authors regarding it to be attributable to the non-uniformity of gas heating at the arc column, observed the plasma flame using the ultra-high speed streak camera. Two examples of these streak pictures are shown in Fig. 4 (a) and (b). As shown in these pictures, the plasma flame, though stable apparently, fluctuates periodically and it comprises high temperature parts (which parts) and low temperature parts (dark parts). The temperature measured spectroscopically by the radiation from the high temperature part may give the average value of the high temperature part only, and the temperature estimated from energy balance may do the average one of the compound plasma flame treated as the uniformly heated condition. Such reasoning will explain satisfactorily the above-mentioned discrepancy between two different temperatures of the flame.

As is evident from Fig. 4 (a) and (b), there are two kinds of flame fluctuations of about 2.5 kc/sec and higher frequencies. The former fluctuation will be mentioned in detail in the following section. The latter fluctuation of higher frequencies may be regarded as owing to the non-uniformity of the gas heating at the arc column. The gases which pass through the arc column are exhausted into the atmosphere without uniformly mixing.

The average exhaust velocity of the plasma flame will be estimated from the degree of inclination of the figure of flame by the streak camera. Fig. 5 is the relation of the exhaust velocity vs. the flow rate of argon gas obtained by such procedure.

It will be presumed that the plasma flow in the test section fluctuates considerably when the torch is used as the heat source of the tunnel, especially the electrode nozzle is used as a supersonic nozzle. Consequently, in order to get the uniform plasma flow, it would be necessary to provide the plenum chamber between the plasma torch and the test section in spite of a considerable heat loss.

Fig. 4 Streak camera picture of the plasma flame

4. The nature of the voltage fluctuation

On account of the heat transfer in the gas within the torch being associated with the complex interaction between the gas flow and the arc column, it is difficult to treat the heat transfer quantitatively. But some preliminary studies have just been started^{(4) (5) (10)}. Consequently, the authors, from the viewpoint of energy balance, tried to explain the interaction between the gas flow and the arc column by means of the voltage fluctuation and to find the adequate operating condition of the torch. For this purpose, accurate observations of the influence of the various parameters on the voltage fluctuation have been made.

Firstly, we explain the domain in which cyclic voltage fluctuation is present. The operating domains of the torch for varying gas flow rate (q) vs. electric current (I) at fixed electrode arrangement are shown, as an example, in Fig. 6. Boundaries between domains have considerable width, but at the fixed electrode configuration and arrangement, the operating domains have been fairly distinctly divided.

Next, the reasons for the presence of voltage fluctuations in the B and C domains (the distinction between these two domains will be discussed later)

Fig. 5 Average exhaust velocity of the plasma jet

Fig. 6 Operating domains of the torch

Fig. 7 I - f curve

are explained.

The frequency of voltage fluctuation (hereafter it is expressed in " f " for brevity) changes complicatedly with the variation of average electric current density $i=4I/\pi D$ (D : diameter of the arc column), gas flow rate q and effective arc length L (defined later). Then, to find the influence on f of only one parameter, the rest of parameters should be fixed.

(1) Influence of I

An example of the relation between I and f with q as a parameter is shown in Fig. 7; f increases with an

Fig. 8 q - f curve

increasing I at fixed q .

(2) Influence of q

The relation between q and f with I as a parameter is shown in Fig. 8 for $d=3, 4$ and 5 mm. In this case, a peak appears on the curves when i becomes greater than about 29 A/min^2 . (i is shown in the parentheses of the same figure). The same tendency is observed for all other results of different d .

(3) Influence of L

The relations between x (defined in Fig. 3) and f at fixed q and I for $d=3$ mm are shown in Figs. 9 (a) ~ (d). As shown in these figures, the x - f curves have such forms as to coincide with each other by the parallel displacement in x direction. This fact shows that f depends only on the arc length at fixed I and q . The effective anode point is said to be substantially fixed physically even if x is varied. The position of the anode point has not been specified from these results, but it is apparent that the position is on the parallel part of

the electrode nozzle. And an appreciable error will not be caused by assuming that for the minimum $l=2.2$ mm, the anode point is at the center of the parallel part of the nozzle. Then, the position of the effective anode point for each nozzle is readily obtained by the parallel movement of each x - f curve in x direction to the point where it will coincide with that of $l=2.2$ mm. S values (defined in Fig. 3) in Table 1 were found by such method for each nozzle. (In that Table, for comparison, the values of half of l are shown for each nozzle). Now, we define "the effective arc length" L by the following expression,

$$x - S = L$$

Fig. 10 was obtained from Figs. 9 (a) ~ (d) by the parallel displacements in x direction.

Now, from the above descriptions, it becomes clear that the behaviour of f by the various parameters resembles that of the frequency of string with

Table 1

l mm	2.2	5.4	9.4	12.5
$l/2$ mm	1.1	2.7	4.7	6.25
S mm	1.1	2.7	5.4	8.1

Fig. 9 x - f curve

both ends being fixed. Namely, parameters specifying each frequency may correspond mutually as follows:

fluctuation frequency of arc column f	vibrating frequency of string ν
average current density i	tension σ
effective arc length L	length of string l

Following such conception, the aforementioned influence of three parameters (I , q , x) on f may be referred to the influence of i and L . In other words, it is supposed that the arc column which is substantially fixed at its cathode and anode point, begins to vibrate under some conditions, like the string with both ends being fixed, and the frequencies of vibration may be specified by the arc length and the average current density. This vibration of the arc column causes the fluctuation of the arc length, which is observed as the periodical variation of the arc voltage. Sufficient gas flow rate is needed to cause the fluctuation of the arc column and such conditions are indicated as the domains B and C of Fig. 6. The distinction between B and C is due to the following consideration. In the domain C, splits are not found in the picture of streak camera [Fig. 4 (a)] in spite of the voltage fluctuation being present, but in the domain B, distinct splits are observed in the picture [Fig. 4 (b)]. Namely, in the domain C, the arc column seems to vibrate periodically but does not come to break down. But in the domain B the break-down occurs and there are portions which do not cross the arc column, and are observed as dark bands in Fig. 4 (b). As it is difficult to distinguish the two domains clearly, the boundary between the domains B and C shown in Fig. 6 is not distinct. By increasing the gas flow rate further beyond the domain B, the arc which is once broken, will be extinguished without regrowth.

Fig. 10 L - f curve

Such phenomena occur in the domain A.

Considering the above-mentioned correlation between the voltage fluctuation and the vibration of string, the influences of each parameter on f would be clarified as follows:

- (1) In the case of increasing I ,
 - (i) i increases (in this case, as a first approximation, we put $D=d$),
 - (ii) there is a possibility of L being slightly reduced by the interaction between the gas flow and the arc column.
- Both these factors have effects to increase f and this fact is clearly indicated in Fig. 7.
- (2) In the case of increasing q ,
 - (i) f increases by reducing the diameter of the arc column,
 - (ii) f decreases by reducing L as the result of interaction between the gas flow and the arc column.

These two factors have a mutually contradicting effect regarding the influence on f . As a result, as shown in Fig. 8, the q - f curves on which the peak values exist have been affected by these factors dominantly. Namely, when i becomes approximately 29 A/mm², there appears a peak value on the q - f curve by the influences of these factors.

(3) In the case of decreasing x , f increases as shown in Fig. 9. This effect would be more properly understood by changing variables x to L as shown in Fig. 10. (There is an approximate functional relation between f and L , i.e., $f \propto 1/L^3$, which is different from the relation of the vibration of string, $\nu \propto 1/l$. This difference may be caused by the fact that a complete analogy between these two phenomena can not be expected and by the assumption of the anode point being fixed.)

As has been shown above, the interaction between the arc column and the gas flow can be expressed by the two parameters i and L which have the influences on f . As will be mentioned in the next section, the energy efficiency in the torch will be discussed based on the voltage fluctuation, since the vibration of the arc column has a direct connection to the energy transfer processes to the arc column.

Recently, Pfender et al.⁽⁴⁾ detected a kind of vibration called "take-over mode" in a very simplified arrangement of electrodes. For the time being, however, it has not been verified yet that the authors' result and the "take-over mode" physically coincide. Moreover, there would be some possibility of Pfender's "fluctuating mode" being comprised in the domain B of Fig. 6. Further details about them will be discussed in the second report in which nitrogen and helium gases have been used as the

working fluids of the torch.

5. Energy transfer process to gas

The energy transfer processes to the gas in the torch have been examined in connection with f , for the purpose of making use of the torch as the gas heating device. Here, the torch efficiency η as a gas heating device and the energy density to gas I_{uM} may be defined as follows:

$$\eta = \frac{I_p - L_s}{I_p}$$

$$\text{and } I_{uM} = \frac{I_p - L_s}{q}$$

where $I_p = IV$ (the electric power input), L_s is the heat loss to the cooling water. The above expressions are calculated from the energy balance in the control surface surrounded with a dotted line in Fig. 3. Here we neglected the radiation loss from the plasma within the torch passing through the nozzle hole and radiation heating to the torch by the plasma flame exhausted to outside of the control surface, but both of these radiations cancel the effects with each other in evaluating η and I_{uM} . And as the heat loss to the cathode is below 10% of all losses, the heat losses in the cathode and the anode are expressed by summarizing in L_s .

To clarify the connection between the operating domain of Fig. 6 with η and I_{uM} , η - q and η - I_{uM} curves shown in Figs. 11 and 12 are available. As shown in Fig. 11, η - q curves consist of curves with different slopes adjoining at X. This point approximately coincides with the boundary between the domains C and D in Fig. 6. Fig. 12 further shows clear distinction between two domains C and D, namely, at the fixed electrode arrangement and the current, the increasing of q causes an abrupt increase in the domain D but η gradually increases in the domains B and C and the energy density rather decreases in these domains.

The examples of x - η relations at the fixed I

Fig. 11 q - η curve

and q for $l=2.2, 5.4, 9.4, 12.5$ mm are shown in Fig. 13. If the same result has been arranged using L as a variable instead of x as shown in Fig. 14, the effect practically vanishes. In the same figure, the L - f curve is shown. Similarly, Fig. 15 shows L - I_{uM} relation, too. As known from these figures, L is considered to be a useful parameter specifying the operating characteristics of the torch. The qualitatively same results can be obtained for different I and q .

For increasing η and I_{uM} at fixed q , l and I , it is necessary to increase the heat transfer of the electric power to heat so long as the increase of energy loss to the nozzle remains small. For this purpose, it is sometimes effective that the axial magnetic field is applied to rotate the anode spot⁽¹¹⁾ (this rotating action broadens the effective anode spot area, too) and the voltage drop at the arc column is increased to increase the plasma resistance. In this experiment, argon gas has been supplied tangentially around the cathode and a similar effect to the above-mentioned has been expected on the axial magnetic field to increase the arc stability. When the arc vibrates, a higher energy transfer may occur for the same reason as that of the magnetic field being applied. In Figs. 14 and 15, are shown the relations between L and f and the values of $(\eta)_{\max}$ and $(I_{uM})_{\max}$ may be

Fig. 12 I_{uM} - η curve

Fig. 13 x - η curve

obtained at $(f)_{\max}$ as expected.

In making use of the torch, it becomes necessary to know the adequate length of the parallel part of the electrode nozzle. It depends on the electrode configuration and arrangement. But generally speaking, there must be some optimum values of l , because an excessively long l will cause greater heat loss to the wall and an excessively short l will cause an increase of the anode point heat transfer and eventually lead to an anode failure. To investigate this circumstance, the relations between η and I_{uM} in which l are parameters, are shown in Fig. 16. From this figure, the length of $l=5.4$ mm gives the best property in this case but the same results have been obtained for the other values of l and q .

Further, the relations between η and I_{uM} for the optimum value of $l=5.4$ mm are shown in Fig. 17 for various x values. As is seen from this figure, the effective arc length of L corresponding to $(\eta)_{\max}$ (in this case $x=10$ mm) gives the best property and this fact proves the authors' considerations about the energy transfer process being valid.

6. Electrode erosion

Argon gas is a very stable working fluid for the

Fig. 14 $L-\eta, f$ curve

Fig. 15 $L-I_{uM}, f$ curve

electric discharge⁽¹²⁾ but adequate considerations are necessary to minimize the electrode erosion. Here, the authors express their interpretations about the electrode erosion. As the result of various experiments about the electrodes, for the anode and the cathode, copper and 2% thoriated tungsten respectively are found most adequate as generally accepted. Therefore, the experiments which are mentioned in this paper have been carried out with these electrode materials.

(1) Anode

An excessively small electrode spacing and an excessively large I at fixed gas flow will cause the electrode failure. But in the domains B and C of Fig. 6 in which the cyclic voltage fluctuations are present, the anode erosion may be slight. And because $(\eta)_{\max}$ and $(I_{uM})_{\max}$ exist in these B and C domains, no anode erosion will arise if the operation of the torch is conducted in the B and C domains.

(2) Cathode

Unlike the erosion of the anode, that of the cathode occurs even in the B and C domains of Fig.

Fig. 16 $I_{uM}-\eta$ curve

Fig. 17 $I_{uM}-\eta$ curve

6, and it seems to depend on the average current density on the cathode surface. In the experiment using the nozzle for $d=3$ mm, the erosion of the cathode may be caused, if the value of i increases beyond 55 A/mm^2 . To reduce the erosion, it would be necessary to make the diameter of the cathode greater than that corresponding to the case of $i=55 \text{ A/mm}^2$. In addition, at the normal operating condition (in the B and C domains of Fig. 6), very gradual erosion of the cathode has been observed. This phenomenon may be similar to that which is found with the static arc⁽¹²⁾.

7. Conclusions

By performing an experiment of the operating characteristics of the torch which is used as a heating device of gases, the following results have been obtained for argon gas as a working fluid.

(1) There are great discrepancies between two temperatures which are measured and spectroscopically estimated from the energy balance.

(2) The relations between the frequencies of voltage fluctuation and the various parameters were obtained.

(3) The correlation between the frequencies of voltage fluctuation and energy transfer was clarified and the operations of the torch within the B and C domains of Fig. 6 were found desirable.

(4) Some considerations about the electrode erosion were given.

Even under the normal operating conditions of the torch, the time-resolved fluctuations are observed in the plasma flame. In making use of the torch as a heating device of gas of the plasma tunnel, it would be necessary to check the possibility of the influence of the perturbation of the flame on the measured values. And if the fluctuations are not favorable, some considerations should be made to absorb them.

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