INSTITUTE OF PHYSICS PUBLISHING PLASMA SOURCES SCIENCE AND TECHNOLOGY

Plasma Sources Sci. Technol. **14** (2005) 219–225 doi:10.1088/0963-0252/14/2/002

Application of similarity theory to the characterization of non-transferred laminar plasma jet generation

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Received 26 June 2003
Published 11 February 2005
Online at stacks.iop.org/PSST/14/219

Abstract
Laminar-flow non-transferred DC plasma jets were generated by a torch with an inter-electrode insert by which the arc column was limited to a length of about 20 mm. Current–voltage characteristics, thermal efficiency and jet length, a parameter which changes greatly with the generating parameters in contrast with the almost unchangeable jet length of the turbulent plasma, were investigated systematically, by using similarity theory combined with the corresponding experimental examination. Formulae in non-dimensional forms were derived for predicting the characteristics of the laminar plasma jet generation, within the parameter ranges where no transfer to turbulent flow occurs. The mean arc temperature in the torch channel and mean jet-flow temperature at the torch exit were obtained, and the results indicate that the thermal conductivity feature of the working gas seems to be an important factor affecting thermal efficiency of laminar plasma generation.

Nomenclature

B	magnetic induction (T)
D	inside diameter of anode nozzle (m)
E	electric field (V m^{-1})
G	gas flow rate (kg s^{-1})
h	specific enthalpy (J kg^{-1})
I	arc current (A)
j	current density (A m^{-2})
L	jet length (m)
P	pressure (Pa)
Q	total volumetric radiation energy (W m^{-3})
T	temperature (K)
U	arc voltage (V)
v	velocity (m s^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
μ	viscosity (Pa s)
ξ_0	permeability of vacuum (H m^{-1})
ρ	density (kg m^{-3})
σ	electrical conductivity (S m^{-1})
η	thermal efficiency
Subscript 0	scale value

1. Introduction

The atmospheric pressure DC plasma jet with a concentrated energy flux is widely used to heat materials difficult to melt by ordinary heating sources [1]. According to the flow status, it can be classified as a laminar or turbulent plasma jet. Up to now, the turbulent plasma jet has been widely used and much discussed. The laminar plasma jet has stable flow, low noise and favourable temperature and velocity distributions for material processing [2, 3], but is seldom used because of insufficient study and understanding of this kind of jet. Systematic research and comprehensive understanding of the laminar plasma jet are needed for its broad and effective application.

There are two methods generally used to study plasma jet characteristics. One is the mathematical method, which is numerical simulation. Since plasma jet generation is a very complicated process, involving factors such as unsteadiness, non-equilibrium and non-axial symmetry, many simplifying assumptions are usually introduced. This causes the calculated solutions to be generally only a qualitative approximation of some specific situation. Another is the experimental method, by which sets of experimental data are obtained for a complete

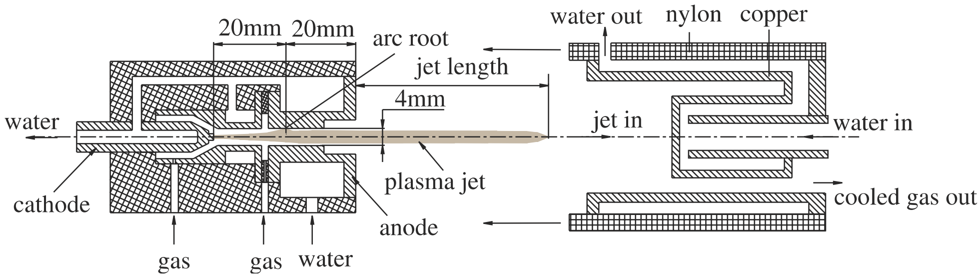

Figure 1. Schematic drawings of the experimental set-up. Left: laminar plasma torch. Right: thermal efficiency measuring method.

description of the jet characteristics. Shortcomings of the experimental method are the required cost, heavy workload and long period for the study. Accordingly, use of similarity theory could be one way to reduce the experimental workload, i.e. deriving generalized relationships involving different generating parameters and plasma conditions for given types of plasma generators from a partial set of experimental data, and then using them to predict plasma characteristics in the corresponding range of parameters.

Similarity theory was introduced for the characterization of DC plasma generation by Yas'ko [4, 5]. By means of this, Brilhac *et al* [6, 7] generalized the relationship of DC vortex plasma torches with well and button type cathodes; Paingankar *et al* [8] studied the characteristics of a non-transferred arc plasma spray torch; Hur *et al* [9] reported the characteristics of a plasma torch with hollow electrodes. Until now, all the relevant work has dealt with the generation of turbulent plasma jets, and it appears that laminar plasma generation has never been studied systematically. And among those studies, there has been no discussion on the jet length change under different generating conditions, because the jet length remains almost unchanged for turbulent plasma. The jet length of laminar plasma can change greatly with arc currents and gas flow rates [3]. Since different jet length means different flow field distribution, a generalized relationship about the jet length change of laminar-flow plasma would be helpful for a better understanding of the flow field characteristics and for effectively developing its utilization.

The relationships reported in the above-listed literature were tried on characterization of the laminar-flow plasma generation. The results show that they are entirely inapplicable (sections 4.1.2 and 4.2.3).

In this paper, argon laminar plasma jets were generated at different gas flow rates and arc currents. Dependence of arc voltage, thermal efficiency and jet length on working parameters was experimentally measured. Formulae for the characterization of laminar plasma jet generation were obtained according to experimental results and similarity theory. These formulae were then used to predict the plasma generating and jet conditions within a certain range of working parameters.

2. Experimental details

A plasma generator with an inter-electrode insert, principally similar to the one in our previous work [2], was used to generate laminar plasma jets (figure 1 (left)). A stick cathode with a taper was used. The inside diameter of the inter-electrode insert and the anode was 4 mm. The distance from the tip of the cathode to the arc root on the anode surface was about 20 mm. The operating pressure of plasma generating was 1 atm. Argon was used as the working gas at flow rates of 1.5×10^{-4}–3.4×10^{-4} kg s^{-1}, and arc current was in the range of 100–200 A.

Jet length was measured by a photograph taken by a camera without any filter. Jet power was measured as in the former work [3] (figure 1 (right)). The measurment set-up was carefully designed to ensure complete cooling of the jet flow to room temperature and little disturbance of the plasma jet. The temperature change of the cooling water was measured with a thermocouple, and the enthalpy increase of the cooling water was considered to be equal to the jet power. Thus, thermal efficiency could be obtained as the ratio of the jet power to the input power.

3. Non-dimensional numbers for characterization of laminar plasma jet generation

A laminar plasma jet could be described as a compressible, viscous, steady flow. Some of the main equations for obtaining the non-dimensional numbers are [4,8]:

Conservation of momentum

$$\rho(\vec{v}\cdot\nabla)\,\vec{v} = -\nabla P + \mu\Delta\,\vec{v} + \vec{j}\times\vec{B}. \qquad (1)$$

Conservation of energy

$$\rho\,\vec{v}\cdot\nabla(h+\tfrac{1}{2}v^2) = \nabla\cdot(\lambda\nabla T) + \vec{j}\cdot\vec{E} - Q. \qquad (2)$$

Maxwell's equation

$$\nabla\times\vec{B} = \xi_0\vec{j}. \qquad (3)$$

Ohm's law

$$\vec{j} = \sigma\,\vec{E}. \qquad (4)$$

In these equations, gravity, diffusion, viscous energy dissipation and other parameters are not included, because they are negligible for the thermal plasma jet description [4].

The following non-dimensional numbers, which are similar to those used and explained in [4], could be obtained from the above equations:

Euler number: $\Pi_{Eu} = \dfrac{P_0}{\rho_0 v_0^2}$.

Reynolds number: $\Pi_{Re} = \dfrac{\rho_0 v_0 D}{\mu_0}$.

Electromagnetic field number: $\Pi_{Em} = \dfrac{j_0 B_0 D}{\rho_0 v_0^2}$.

Enthalpy number: $\Pi_h = \dfrac{\rho_0 v_0 h_0}{j_0 E_0 D}$.

Acceleration number: $\Pi_a = \dfrac{\rho_0 v_0^3}{j_0 E_0 D}$.

Thermal conductivity number: $\Pi_\lambda = \dfrac{\lambda_0 T_0}{j_0 E_0 D^2}$.

Radiation number: $\Pi_Q = \dfrac{Q_0}{j_0 E_0}$.

Magnetic field number: $\Pi_m = \dfrac{\xi_0 j_0 D}{B_0}$.

Electric field number: $\Pi_E = \dfrac{\sigma_0 E_0}{j_0}$.

Symbols with subscript 0 represent reference values which will be discussed in a later paragraph. The above nine numbers could not be immediately used. One reason is that these numbers include parameters that vary widely under operating conditions. For example, current density, electric field and flow velocity, all have complicated distributions in the arc column. Another reason is that some measurable parameters of practical importance have not been included, such as arc voltage, arc current and gas flow rate. Hence, useful non-dimensional numbers, which contain the important parameters and eliminate the unknown ones, should be derived.

Three non-dimensional parameters, $\Pi_I = j_0 D^2/I$, $\Pi_U = E_0 D/U$, $\Pi_G = \rho_0 v_0 D^2/G$ can be obtained from boundary conditions $I = \int_s \vec{j} \cdot \mathrm{d}\vec{s}$, $U = \int_l \vec{E} \cdot \mathrm{d}\vec{l}$, $G = \int_s \rho \vec{v} \cdot \mathrm{d}\vec{s}$ [4, 8]. Then eight non-dimensional numbers could be obtained:

$$\Pi'_{Eu} = \Pi_{Eu} \cdot \Pi_G^2 = \frac{\rho_0 P_0 D^4}{G^2}, \quad \Pi'_{Re} = \frac{\Pi_{Re}}{\Pi_G} = \frac{G}{\mu_0 D},$$

$$\Pi'_{Em} = \frac{\Pi_{\mathrm{Em}} \Pi_G^2 \Pi_m}{\Pi_I^2} = \frac{\xi_0 \rho_0 I^2 D^2}{G^2},$$

$$\Pi'_h = \frac{\Pi_h \Pi_E \Pi_I^2}{\Pi_G} = \frac{\sigma_0 h_0 G D}{I^2}, \quad \Pi'_a = \frac{\Pi_a \Pi_E \Pi_I^2}{\Pi_G^3} = \frac{\sigma_0 G^3}{\rho_0^2 I^2 D^3},$$

$$\Pi'_\lambda = \Pi_\lambda \Pi_E \Pi_I^2 = \frac{\lambda_0 T_0 \sigma_0 D^2}{I^2},$$

$$\Pi'_Q = \Pi_Q \Pi_E \Pi_I^2 = \frac{\sigma_0 Q_0 D^4}{I^2}, \quad \Pi'_U = \frac{\Pi_E \Pi_I}{\Pi_U} = \frac{\sigma_0 U D}{I}.$$

When describing the plasma jet generation, 13 parameters are used, and five dimensions are involved. Thus, eight independent criteria could describe the whole process according to Buckingham theory.

As to the reference values, physical properties at a certain fixed temperature are generally selected. Yas'ko [10] selected the fixed temperature corresponding to the point of inflection of the curve $\sigma = f(h)$, where the channel arc temperature sets up. Brilhac [6] selected the fixed temperature corresponding to an electron concentration of 1% in the plasma. Actually, the two selecting methods would lead to nearly the same results [8]. Furthermore, calculation at temperatures corresponding to different electron concentrations is made in the next section, and it also shows that the selection of reference values have little effect on the calculated results. Accordingly, argon plasma reference values in table 1, selected by Brilhac's method, were adopted in this paper. The reference value for length, represented by D, was taken as the inside diameter of the inter-electrode insert.

Table 1. Reference values of Ar plasma [6].

Physical variables	Reference values of Ar plasma
Temperature T_0 (K)	9.4×10^3
Electrical conductivity σ_0 (S m^{-1})	2.35×10^3
Viscosity μ_0 (Pa s)	2.61×10^{-4}
Thermal conductivity λ_0 (W m^{-1} K^{-1})	0.487
Enthalpy h_0 (J kg^{-1})	5.1×10^6
Density ρ_0 (kg m^{-3})	5.1244×10^{-2}

4. Results and discussion

4.1. Current–voltage characteristics

4.1.1. Experimental results Figure 2 shows the experimental results of current–voltage characteristics of the laminar plasma generation at gas flow rates of 2.2×10^{-4}, 2.6×10^{-4} and 2.9×10^{-4} kg s^{-1}. The arc voltage increases with arc current at a fixed gas flow rate, and increases with gas flow rate at a fixed arc current. The reason for the tendency could arise from the relationship $E = j/\sigma$, that is, electric field E (representing arc voltage) is decided by the ratio of current density j to electrical conductivity σ. In the arc column, current density j increases simply with arc current I, and electrical conductivity σ increases with arc temperature T, which increases with the arc current non-linearly in the plasma working range. The increase of gas flow rate cools the arc column fringes and thus results in its constriction, which increases the current density, very slightly the temperature T and thus the electrical conductivity. Due to the non-linear relationship between current density and electrical conductivity, the net effect may cause an increase in the electric filed. At the same time, the arc root could be pushed more downstream at a higher gas flow rate, resulting in the lengthening of the arc column and increasing of arc voltage.

4.1.2. Evaluation of voltage character of laminar plasma jet with relationship in the literature. Turbulent plasma generators whose structures are similar to the one in our experiment have been studied by Yas'ko and Paingankar. In Yas'ko's work, the current–voltage formula [10] is

$$\frac{U D \sigma_0}{I} = 1290 \left(\frac{\sigma_0 h_0 G D}{I^2}\right)^{0.654} \left(\frac{G}{\mu_0 D}\right)^{0.205} \times \left(\frac{\lambda_0 T_0 \sigma_0 D^2}{I^2}\right)^{0.25}.$$

However, arc voltage calculated by this formula under our experimental conditions was nearly 0, which is very different from the experimental results and is not suitable for the

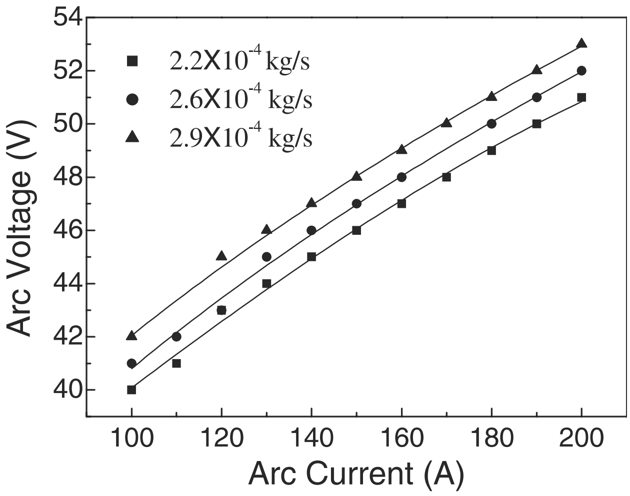

Figure 2. Experimental current–voltage characteristics of laminar plasma generation at different gas flow rates.

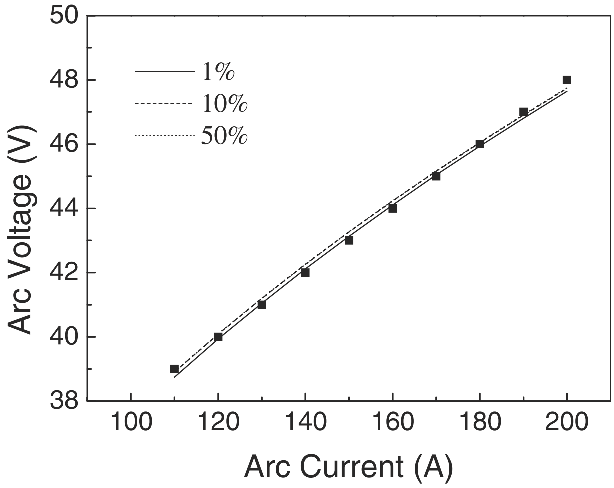

Figure 3. Calculated curves using reference values at different ionization ratios and experimental points of current–voltage at the gas flow rate of 1.5×10^{-4} kg s^{-1}.

description of the laminar plasma generation. The result using the formula in Paingankar's work is also nearly 0. That is, these formulae are not suitable for laminar plasma characterization, and it is necessary to establish current–voltage formulae anew.

4.1.3. Application of the similarity theory. It has been described in section 3 that eight criteria could fully describe the process, and then we have:

$$\Pi'_U = f(\Pi'_h, \Pi'_{Re}, \Pi'_\lambda, \Pi'_{Em}, \Pi'_{Eu}, \Pi'_a, \Pi'_Q).$$

Actually, not all eight criteria are of equal importance in the process. For plasma generators operating at atmospheric pressure, Π'_{Eu} could be omitted, because the pressure in the flow scarcely varies compared with other parameters. Experiments of additional magnetic fields show little effect on current–voltage characteristics [11], so Π'_{Em} could also be omitted. Radiation power is nearly unchanged from 140 00 to 180 00 K, which is calculated to be the temperature range of the arc column in our work indicated in a later paragraph, and thus Π'_Q could also be neglected. Then the correlation can be simplified to:

$$\Pi'_U = f(\Pi'_h, \Pi'_{Re}, \Pi'_\lambda, \Pi'_a).$$

According to the power law approximation, it could be expressed as:

$$\Pi'_U = C\Pi'^{a_1}_h \Pi'^{a_2}_{Re} \Pi'^{a_3}_\lambda \Pi'^{a_4}_a.$$

Making the formula fit the experimental data in figure 2, we can obtain:

$C = 1.38,\quad a_1 = -0.86,\quad a_2 = 1.09,$
$a_3 = 1.21,\quad a_4 = -0.024.$

Since a_4 is very small, for practical calculations, Π'_a can be omitted, and then the formula becomes:

$$\frac{UD\sigma_0}{I} = 1.38\left(\frac{\sigma_0 h_0 G D}{I^2}\right)^{-0.86}\left(\frac{G}{\mu_0 D}\right)^{1.09} \times \left(\frac{\lambda_0 T_0 \sigma_0 D^2}{I^2}\right)^{1.21}.$$

According to this formula, the current–voltage characteristics of the laminar plasma generation at a given gas flow rate could be predicted, which shows that the three dimensionless numbers Π'_h, Π'_{Re} and Π'_λ are almost equally important to the current–voltage characteristics. Figure 3 shows the calculated curves and experimental points at the gas flow rate of 1.5×10^{-4} kg s^{-1}. They agree pretty well. Three calculated curves in figure 3 correspond to reference values at different ionization ratio of 1%, 10% and 50% of the argon gas. There is no apparent difference in the three curves. This makes it clear that the reference value selection has little effect on the calculated results with the similarity fitting. Thus, only the reference values in table 1 were used for the analysis of thermal efficiency and plasma jet length in later sections.

4.2. Thermal efficiency

Thermal efficiency is an important parameter describing energy utilization. Laminar plasma, once considered as having low thermal efficiency, is thus seldom studied and applied. In our experiments, thermal efficiency of laminar plasma generation could reach 40%. Additionally, the long stable laminar jet would increase heating time and improve the heating effect on the powder particles when used in a process such as plasma spraying. Thus the actual energy utility ratio might be higher in comparison with the turbulent plasma jet.

4.2.1. Experimental results. Figure 4 is the diagram of thermal efficiency versus arc current at gas flow rates of 2.6×10^{-4} and 2.9×10^{-4} kg s^{-1}. Thermal efficiency increases with gas flow rate at a fixed arc current. This is because the increase of gas flow rate constricts the arc column, reduces the losses to the anode by heat transfer, and hence increases thermal efficiency. The dependence of thermal efficiency on arc current in figure 4 is rather complex at a fixed gas flow rate. At first, thermal efficiency decreases with arc current, but 160 A appears to be a point of change, after which thermal efficiency begins to increase slightly with arc current. It might be necessary to estimate the temperature change of the arc column with the change of arc current in the torch channel

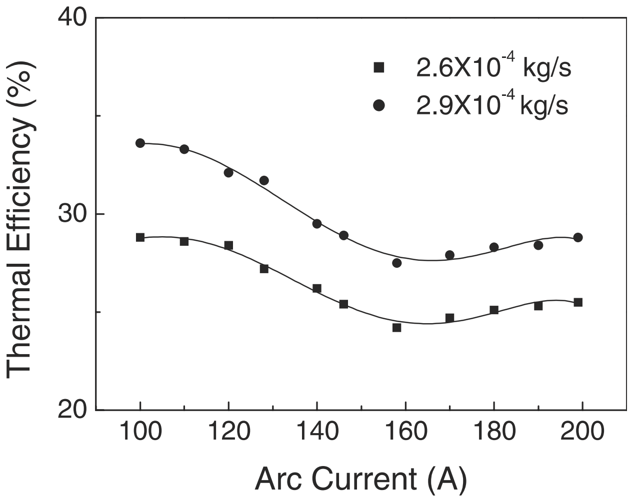

Figure 4. Experimental dependence of thermal efficiency on arc current of the laminar plasma at different gas flow rates.

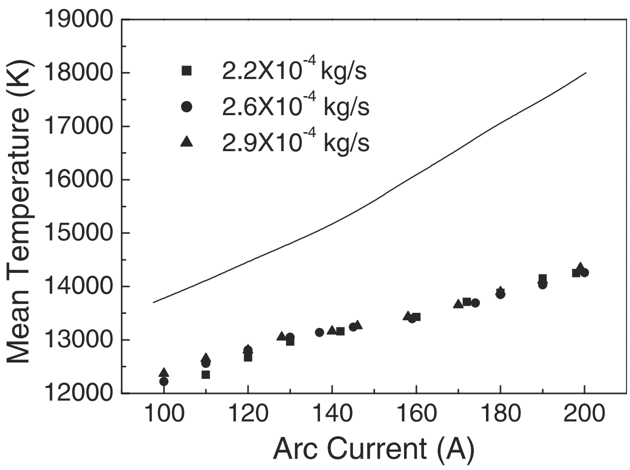

Figure 5. Dependence on arc current of mean arc temperature calculated by Steenbeck's channel model and mean jet-flow temperature at the torch exit at different gas flow rates.

to explain the characteristics of thermal efficiency shown in figure 4.

4.2.2. Arc temperature estimation. Steenbeck's channel model [12] was used to approximately estimate the arc column temperature. With this method, the arc column is assumed to be stable and fully developed, without velocity, arc temperature and enthalpy changes along the column axial direction. That is:

(1) All the current passes through the arc column, and there is a mean temperature, which leads to a mean electric conductivity and a mean current density.
(2) In the non-electric conducting area of the channel, both electric conductivity and current density are equal to zero.

By Steenbeck's channel model, arc column diameters at different arc currents were calculated, which were all nearly 3.2 mm. The curve in figure 5 shows the dependence of mean arc temperature on arc current calculated by Steenbeck's channel model. The mean arc temperature rises from 13 600 to 18 000 K as arc current changes from 100 to 200 A. The points in figure 5 shows dependence of mean jet-flow temperature on the arc current at the torch exit at gas flow rates of 2.2×10^{-4}, 2.6×10^{-4} and 2.9×10^{-4} kg s^{-1}, estimated according to the plasma jet power and gas flow rate and thus specific enthalpy and temperature [13]. The mean gas flow temperature at the torch nozzle exit is over 12 000 K at arc currents from 100 to 200 A. Considering the temperature gradient between the arc column and the torch nozzle exit, a mean gas flow temperature lower than that of the arc column is reasonable. Thus the mean temperature of the arc column calculated by the channel model may be a reasonable estimate corresponding to the laminar plasma generating condition.

It is found that only thermal conductivity shows a maximum value at about 15 000 K, by making a comprehensive survey of the related properties of argon gas in the temperature range from 13 600 to 18 000 K. That is, the thermal conductivity of argon gas increases in the temperature region of 13 600–15 000 K and then decreases until 18 000 K [13]. Hence, the thermal conductivity increases with arc current until the mean arc temperature reaches about 15 000 K, leading to the increase of heat transfer loss to the arc channel wall, and thus the decrease of the thermal efficiency with increasing arc current at the low arc current side as shown in figure 4. The thermal efficiency passes its minimum as the thermal conductivity of the arc gas passes its maximum. Thus thermal conductivity feature of the plasma working gas could be an important factor that affects the thermal efficiency characteristic of the laminar plasma generation.

4.2.3. Evaluation of thermal efficiency of the laminar jet with the formula in the literature. Among the studies discussing the thermal efficiency, Paingankar studied a plasma generator similar to ours, and obtained [8]

$$\frac{1-\eta}{\eta} = 0.824\left(\frac{\sigma_0 h_0 G D}{I^2}\right)^{0.0273}\left(\frac{\sigma_0 U D}{I}\right)^{-0.502} \times \left(\frac{\lambda_0 T_0 \sigma_0 D^2}{I^2}\right)^{-0.589}.$$

However, thermal efficiency calculated by this formula under our experimental conditions is about 0, which is also vastly different from the experimental results. Therefore, a new thermal efficiency formula needs to be established for describing the laminar plasma generation.

4.2.4. Similarity formula about thermal efficiency. According to the results and discussion in sections 4.2.1 and 4.2.2, thermal conductivity should also be taken into account, when the similarity formula of thermal efficiency is considered. Similar to current–voltage correlation, we can obtain:

$$\eta = f\left(\Pi'_h, \Pi'_U, \Pi'_\lambda, \Pi'_{Re}, \Pi'_a, \frac{\lambda}{\lambda_0}\right).$$

Replacing η with $(1-\eta)/\eta$, and again according to the power law approximation, the formula becomes

$$\frac{1-\eta}{\eta} = C\Pi_h^{\prime a_1}\Pi_U^{\prime a_2}\Pi_\lambda^{\prime a_3}\Pi_{Re}^{\prime a_4}\Pi_a^{\prime a_5}\left(\frac{\lambda}{\lambda_0}\right)^{a_6},$$

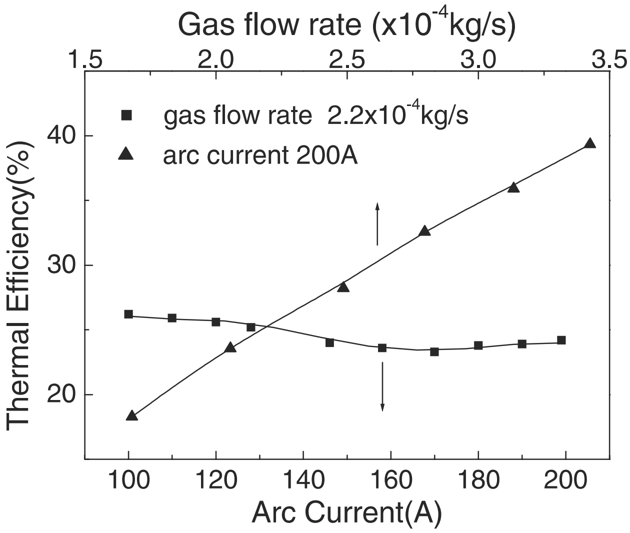

Figure 6. Calculated curve and experimental points of thermal efficiency at the gas flow rate of 2.2×10^{-4} kg s^{-1} and at arc current 200 A.

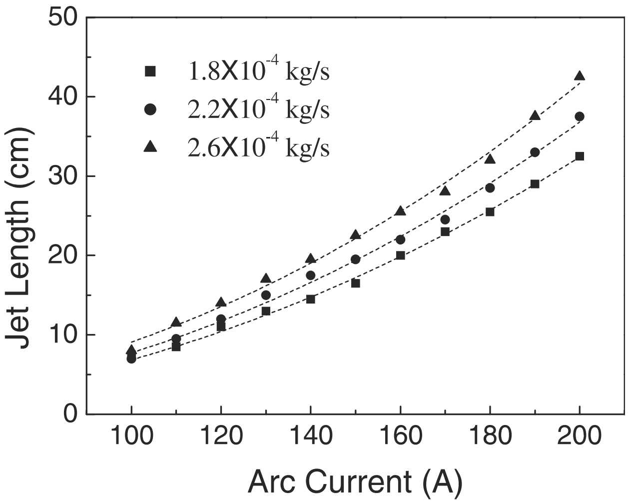

Figure 7. Experimental dependence of jet length on arc current of the laminar plasma at different gas flow rates.

where λ is the thermal conductivity at the corresponding temperature [13] of different arc current as in figure 5. Making the formula fit the experimental data in figure 4, we can obtain:

$$C = 0.032,\quad a_1 = -1.92,\quad a_2 = 3.55,\quad a_3 = 0.59,$$
$$a_4 = 0.21,\quad a_5 = 0.05,\quad a_6 = 0.91.$$

Since a_5 is very small, Π_a could be omitted, and then the formula becomes

$$\frac{1-\eta}{\eta} = 0.032\left(\frac{\sigma_0 h_0 G D}{I^2}\right)^{-1.92}\left(\frac{\sigma_0 U D}{I}\right)^{3.55} \times\left(\frac{\lambda_0 T_0 \sigma_0 D^2}{I^2}\right)^{0.59}\left(\frac{G}{\mu_0 D}\right)^{0.21}\left(\frac{\lambda}{\lambda_0}\right)^{0.91},$$

where Π'_U is the most important parameter for the thermal efficiency characteristics, followed by thermal conductivity. This formula was used to predict the thermal efficiency of the laminar plasma generation. Figure 6 shows the calculated curves and experimental points of thermal efficiency at the fixed gas flow rate of 2.2×10^{-4} kg s^{-1} and at fixed arc current of 200 A. The calculated curves agree pretty well with the experimental results. This indicates that the formula can predict the thermal efficiency of the laminar plasma generation sufficiently well.

4.3. Jet length

Jet length change of turbulent plasma has not been discussed because it is very short and the change is not obvious under different working conditions. However, in the case of laminar plasma, jet length may reach a very large magnitude and vary widely with the working conditions. Since different jet length means different flow field distribution, it is meaningful to have a study on the jet length change of the laminar plasma.

Figure 7 shows the experiment results of laminar jet length versus arc current at gas flow rates of 1.8×10^{-4}, 2.2×10^{-4} and 2.6×10^{-4} kg s^{-1}. The jet length increases with arc current and gas flow rate. Similar to the previous sections, the correlation of jet length can be expressed as:

$$\frac{L}{D} = C\Pi_h'^{a_1}\Pi_U'^{a_2}\Pi_\lambda'^{a_3}\Pi_{Re}'^{a_4}\Pi_a'^{a_5}.$$

Making the formula fit the experimental data in figure 7, we can obtain:

$$C = 54.84,\quad a_1 = -2.09,\quad a_2 = -0.94,$$
$$a_3 = 0.65,\quad a_4 = 1.06,\quad a_5 = 0.64.$$

Thus the formula for calculating jet length is

$$\frac{L}{D} = 54.84\left(\frac{\sigma_0 h_0 G D}{I^2}\right)^{-2.09}\left(\frac{\sigma_0 U D}{I}\right)^{-0.94} \times\left(\frac{\lambda_0 T_0 \sigma_0 D^2}{I^2}\right)^{0.65}\left(\frac{G}{\mu_0 D}\right)^{1.06}\left(\frac{\sigma_0 G^3}{\rho_0^2 I^2 D^3}\right)^{0.64}.$$

Using this formula, jet length of the laminar plasma under given generating conditions can be predicted, which shows Π'_h is the main parameter for the jet length change. Figure 8 shows the calculated curves and experimental points at the gas

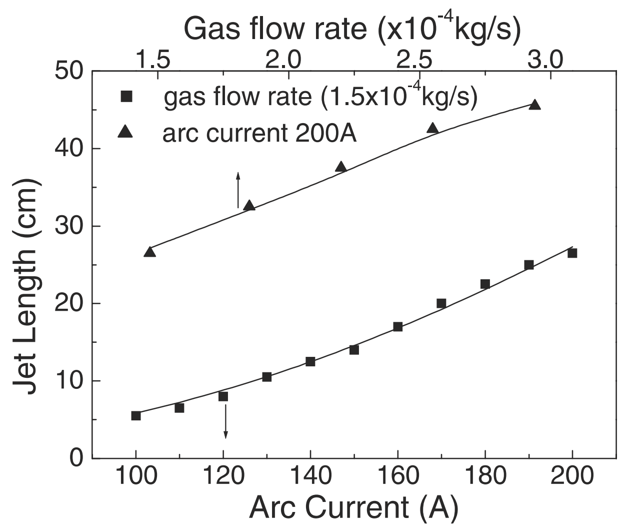

Figure 8. Calculated curve and experimental points of jet length at the gas flow rate of 1.5×10^{-4} kg s^{-1} and at arc current 200 A.

flow rate of $1.5 \times 10^{-4}\,\mathrm{kg\,s^{-1}}$ and at an arc current of 200 A. The calculated results agree well with the experimental data. Thus, this formula could be suitable for predicting jet length of laminar plasma generated with the similar structure torch within the parameter range where no transfer to the turbulent flow state occurs.

5. Conclusions

Arc voltage, thermal efficiency and jet length at atmospheric pressure were experimentally examined under different working conditions. According to experimental results and similarity theory, formulae for calculating arc voltage, thermal efficiency and jet length were obtained for the characterization of laminar plasma. The following conclusions are drawn:

(1) Similarity theory is applicable to the characterization of non-transferred laminar plasma jet generation, and the formulae are useful for the prediction of arc voltage, thermal efficiency and jet length for the given type of laminar plasma generator.
(2) Thermal conductivity feature of the plasma working gas could affect essentially the thermal efficiency characteristics of the laminar plasma generator with relatively long arc channel.
(3) Steenbeck's channel model may be an applicable approximation method for the estimation of the mean arc temperature of laminar plasma generation, in which the gas flow rate is relatively low and the arc channel is relatively long.

It should be noted that the experimental parameters are in the working range of laminar plasma generation, and thus the correlations are also in the same range. Furthermore, anode nozzle diameter (generator size) is an important structure parameter. However, such a parameter change has not been carried out and the discussion is within this limitation, due to difficulties in performing such experiments.

Acknowledgments

This work was supported by the National Natural Science Foundation of China, Project Nos 59836220, 19975064, 50276065 and 50336010.

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