CURRENT-VOLTAGE CHARACTERISTICS GENERALIZATION FOR PLASMA TORCHES OPERATING WITH DIFFERENT GASES

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ABSTRACT

The possibility of current-voltage characteristics (CVC) generalization by a common expression for arcs blown with different gases is considered. Experimental data for d.c. plasma torches with rod cathode and tube anode are used. Analysis has shown that the method of scale properties determination, based on plasma properties temperature dependence enables to obtain rather good generalized relationships.

INTRODUCTION

At present, generalized CVC in dimension form, which is applicable for a given working gas, are mostly used. The difficulties of CVC correlation for different media follow from the intricate plasma properties dependence on temperature, distinctive characteristics slopes which themselves are controlled by discharge regime. Therefore, in contrast to cold flows, determination of plasma properties scale values is very difficult. At the same time, the derivation of common CVC relationships is of great importance. It would enable to evaluate arc device CVC for uninvestigated working media without performing expensive experiments and to reduce time for new equipment development.

Another difficulty is connected with the selection of dominant similarity numbers that describe some prevailing processes, which govern the arc characteristics. Such high-temperature phenomena like electric arc discharge depends mainly on energy transfer processes. The domination of particular heat-transfer mechanism is determined by discharge conditions including discharge chamber geometry, gas dynamics, and electrical parameters. For example, heat conduction prevails in long, well-constricted, weak flow-rate discharges. However, plasma torches with well-blown unstable arcs are mostly used for different scientific and manufacturing applications. The convective energy transfer has appeared to dominate in such cases. The extent of prevalence and influence of other processes on CVC depend on many factors. Together with electric and gas dynamic parameters, the break-down between arc and tube anode wall is important.

It can occur that the extent of convective heat transfer prevalence or even the dominant mechanism will be different for distinctive working gases. That hinders CVC generalization for different gases, increasing the lamination of a common relationship. But this discrepancy ought to be compared with the scatter of expressions for individual gases. The last can also be rather high due to the effect of many factors. The quantitative comparison can be made by means of regression analysis. If

the lamination caused by gases is comparable with the scatter of individual curves the generalization may be considered as acceptable. For this purpose, we consider CVC generalization possibility for widely used d.c. plasma torches with rod cathode and tube anode. Experimental data from different organizations are used for correlation.

EXPERIMENTAL

Experimental CVC of non-transferred arcs have been used for correlations. The arc burns between rod cathode and tube anode. The arc length is continuously changing owing to breakdown to anode wall. The arc is blown by swirling flows of different gases. Together with our own experiments, the CVC data have been taken from [1-5]. Plasma torches operated over the following ranges:

$d = 10$ and 20 mm; $G = 6$, 12, 18 and 24 g/s; $I = 40$ - 180 A; air [1].
$d = 5$, 10 and 20 mm; $G = 0.62$ - 31.5 g/s; $I = 10$ - 250 A; air [2].
$d = 9.2$ mm; $G = 1.27$ - 4.27 g/s; $I = 38$ - 146 A; air (own experiments).
$d = 4.8$ and 16 mm; $G = 0.44$ - 2.50 g/s; $I = 24.2$ - 167.8 A; argon [3,4].
$d = 10$ mm; $G = 0.75$, 1.0, 1.5 g/s; $I = 350$ - 900 A; hydrogen [5].

For these gases, convective heat transfer has been revealed to be the dominant process. Therefore, the convective heat transfer number have been used for CVC generalization. Characteristics of every torch were correlated separately, and then common expression for CVC of all plasma torches was obtained. Characteristic values of plasma properties must be known for each gas to perform such generalization. To determine these values, we have applied the method accounting for plasma properties dependence on temperature [6].

The temperature distribution across the column of a weakly stabilized arc is rather flat. Therefore, arc plasma properties at every given discharge regime depend on the "floating" arc mean temperature T^*. When arc behavior is governed by any dominant process, T^* is determined by this mechanism. Therefore, it may be evaluated by putting the corresponding similarity number to unity. Thus, with heat convection domination, we apply plasma properties power approximation in the vicinity of T_0: $\sigma^*/\sigma_0 = (T^*/T_0)^{n_1}$, $h^*/h_0 = (T^*/T_0)^{n_2}$, we may obtain $(Gd\sigma^*h^*/I^2) = (Gd\sigma_0 h_0/I^2)(T^*/T_0)^{n_1+n_2} = 1$. Hence, $T^*/T_0 = (Gd\sigma_0 h_0/I^2)^{-1/(n_1+n_2)}$, here T_0, σ_0, h_0 are some constant characteristic plasma properties values. As the only argument is constant at T^*, the function must be also constant: $(Vd\sigma^*/I) = (Vd\sigma_0/I)(T^*/T_0)^{n_1} = C$. As a result, CVC may be written in the form $(Vd\sigma_0/I) = C(Gd\sigma_0 h_0/I^2)^{\alpha}$, where $\alpha = n_1(n_1 + n_2)$. Exponents n_1, n_2 and α can be determined for very narrow ranges as functions of temperature. Such functions for exponents of convective, conductive, and turbulent heat transfer similarity numbers for argon plasma are shown in Fig.1 ($\Pi_{conv.} = Gd\sigma_0 h_0/I^2$; $\Pi_{cond.} = \sigma_0 \lambda_0 T_0 d^2/I^2$; $\Pi_{turb.} = \sigma_0 h_0^{1.5} d^3/I^2$).

The CVC of high-current weakly-stabilized arcs are rather flat. It implies for the mentioned numbers that $\alpha \simeq 0.5$. Hence, one may evaluate T_0 from $\alpha(T) = 0.5$ and calculate characteristic values of plasma properties. This method is proved

Table .1: Characteristic value of plasma properties at $\alpha(T) = 0.5$

	Plasma properties	Properties (characteristic values)				
		Air	Nitrogen	Argon	Hydrogen	Helium
Convec-tion	T_0, K	12300	12300	10700	12300	17500
	σ_0 ,$\Omega^{-1}m^{-1}$	5630	5220	3438	4558	5820
	h_0 ,J$\times$kg^{-1}	6.62×10^7	7.41×10^7	7.44×10^6	6.69×10^8	1.55×10^8
Conduc-tion	T_0, K	13400	12300	10300	15700	19000
	σ_0 ,$\Omega^{-1}m^{-1}$	6800	5528	3042	8014	7920
	λ_0 ,W/(mK).	2.40	3.53	0.64	6.44	8.55
Turbu-lence	T_0, K	13400	12700	10700	12900	17500
	σ_0 ,$\Omega^{-1}m^{-1}$	6800	5528	3438	5270	5820
	h_0 ,J$\times$ kg	8.28×10^7	8.00×10^7	7.44×10^6	7.61×10^8	1.55×10^8
	ρ_0 ,kg m^{-3}	1.05×10^{-2}	1.17×10^{-2}	4.37×10^{-2}	8.16×10^{-4}	2.55×10^{-3}

to be applicable at $\alpha(T_0) \neq 0.5$. Table 1 lists such characteristic values of some plasmas for convective, conductive and turbulent heat transfer mechanisms.

Lamination of the common relationship has been estimated by means of Fisher variances ratio [7]. The ratio of lamination variance S^2_{lam} to random one S^2_{rand} has been calculated ($F_{lam} = S^2_{lam}/S^2_{rand}$). All CVC scattering of each individual torch has been attributed to random processes. Random variance of the common expression S^2_{rand} has been calculated as the ratio of the total sum of squared deviations for all torches SS_{rand} to the corresponding total sum of degrees of freedom N_{rand} ($S^2_{rand} = SS_{rand}/N_{rand}$). The lamination sum of squared deviations SS_{lam} equals the difference between the sum of squared deviations for common expressions SS and the total sum of random squared deviations ($SS_{lam} = SS - SS_{rand}$). Similar calculation has been made for degrees of freedom ($N_{lam} = N - N_{rand}$).

RESULTS AND DISCUSSION

The data of own experiments and from literature [1-4] have been used to obtain generalized formulae for CVC of every individual torch. Characteristics are approximated by power nondimensional expressions. Dimensionless variables include characteristic values of plasma properties from Table 1. Obtained regression parameters are listed in Table 2. Table 2 shows that CVC of individual plasma torches are appreciably different even for the same working gas. It is caused by distinctive design features which govern torch gas dynamics. That increases the total sum of random squared deviations and reduces the sum of lamination ones improving generalization parameters. R.m.s. deviation of common CVC occurs less than the scattering of individual characteristic for the torch operating which argon. Correlation coefficient, Student quantile, and regression Fisher ratio of the common expression are higher then analogous parameters of CVC for particular torches. This is an evidence in favor of the method used for characteristic plasma properties calculation. But the shift of particular CVC distorts the common characteristic, increasing exponent α and diminishing factor C. This is illustrated by Fig.2, where

Table .2: Regression parameters of CVC d.c. vortex plasma torches with rod cathode and tube anode

Working gas	Constant C	Expoent α	Correlation coeffi-cient K	Student quantile t	r.m.s deviation	Fisher variances ratio for regression F_{reg}
air [1]	1.61	0.68	0.976	24	0.09	570
air [2]	1.16	0.68	0.978	37	0.08	1343
air	4.65	0.52	0.986	28	0.04	775
argon [3,4]	1.39	0.56	0.961	14	0.12	204
hydrogen[5]	2.38	0.51	0.923	16	0.06	252
common	0.99	0.71	0.988	86	0.11	7396

Table .3: Lamination parameters of the common CVC

Regression parameters	all gases	Air
Sum of total squared deviation from common CVC, SS	2.264763	1.124752
Total sum of individual CVC squared deviations, SS_{rand}	1.050938	0.670573
Sum of sq. dev. from common CVC caused by lam., SS_{lam}	1.213825	0.454179
Degrees of freedom for common CVC total scattering, N	181	116
Sum of degrees of freedom for individual CVC scattering, N_{rand}	173	112
Lamination degree of freedom, N_{lam}	8	4
Randon deviation variance of common CVC, S^2_{rand}	6.07×10^{-3}	5.99×10^{-3}
Lamination variance of common CVC, S^2_{lam}	1.52×10^{-1}	1.14×10^{-1}
Fisher variances ratio for lamination, F_{lam}	25	19
Ratio F_{lam}/F_{reg}	3.38×10^{-3}	9.69×10^{-3}
Table values of Fisher variance ratio (5% / 1%)	2.96 / 4.92	2.45 / 3.49

CVC domains for different gases are plotted.

Quantitative evaluation of lamination exerted by different working gases and design factors is given in the second column of Table 3. Table 3 shows that F_{lam} is higher than 5% and 1% of the table values of Fisher ratio. Hence, in spite of the high value of regression Fisher ratio for the obtained common CVC, this characteristic can't be considered as unsegregated. But separation appears to be rather small - lamination Fisher ratio amounts only to 0.34% of its regression magnitude. Therefore, the obtained common CVC may be used for rough estimation of uninvestigated plasma torches characteristics.

The lamination, considered in the second column of Table 3, is exerted by different gases and design parameters diversity. To clarify the separate influence of these factors, we have calculated F_{lam} occurred through design effect in the case of air - operated torches. The result is shown in the third column of Table 3. It is seen that the discrepancy exerted by design factors is of the same magnitude of the lamination Fisher ratio as in the common case (19 and 25). Hence, the main separation seems to be caused by design diversity, and we may conclude that the applied method of characteristic plasma properties determination allow rather good

CVC.

CONCLUSIONS

Different effect of the distinctive important processes in arcs blown with discriminative gases hinders generalization of plasma torch characteristics. Another difficulty of characteristic plasma properties determination seems to be overcome by the method accounting for properties temperature dependence. It has provided the possibility to obtain common characteristics for arcs blown with different gases. That enables rough estimation of characteristics for arcs blown with non investigated gases. The further progress in the development of common relationships depends on better accounting of plasma torch design factors and gas dynamic features.

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NOMENCLATURE

d - electrode diameter; F - Fisher variance ratio; G - gas flow-rate; I - electric current; V - voltage; n_1 - n_2 - exponents; h - enthalpy; N - degree of freedom; λ - heat conductivity; Π - non dimensional similarity number; ρ - plasma density; δ - electric conductivity; T - temperature.

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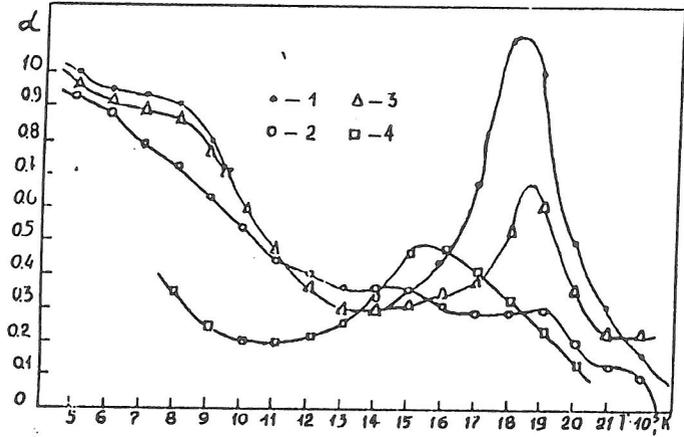[7] N.R. Draper, H. Smith, Applied Regression Analysis, John Willey & Sons Inc., New York, London, Sydney, 1966.

Fig.1 Theoretical values of exponents α for argon plasma as functions of temperature. 1 - turbulence, 2 - conduction, 3 - convection, 4 - radiation
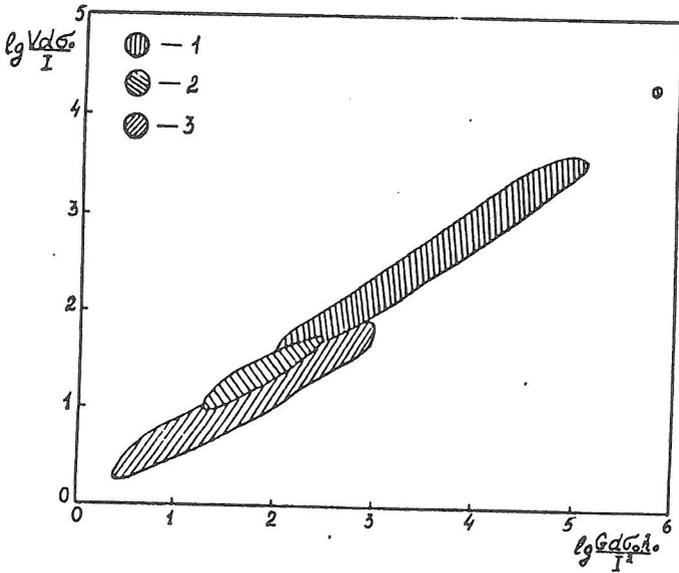

Fig.2 Different gases domains of generalized CVC for plasma torches with rod cathode and tube anode. 1 - air; 2 - hydrogen; 3 - argon.