ON GENERALIZATION OF CURRENT-VOLTAGE AND THERMAL CHARACTERISTICS OF ELECTRIC ARC.

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Abstract. Dependence of energy-transfer mechanisms on arc-burning conditions is considered. Thermal turbulence is shown to be mainly responsible for heat transfer in unstable magnetically-propelled arcs, while heat transfer rate from a longitudinally blown arc to the cylindric discharge-chamber wall is caused by conduction and radiation.

Correlations of experimental data on current-voltage characteristics (CVC) of electric arcs show appreciable dependence of dominant energy transfer mechanisms on arc-burning conditions. The conductive heat transfer is found to be mainly responsible for CVC formation in the case of long poorly blown arcs in cylindrical discharge chambers. On the other hand, strong longitudinal blowing changes the dominant transfer mechanism for convective one [1]. The attention was reentry confined to energy transfer by means of thermal turbulence which can occur in electric arcs at high electric-field strength [2]. This mode of turbulence develops at the expense of thermal energy opposite to gas dynamic one being powered from kinetic energy of a flow. In arcs with subsonic flow thermal energy can be some orders higher than kinetic one. For example in air plasma at $T=10^4$ K and M = 1 the ratio of kinetic energy to thermal one amounts only to 7.5%. Therefore, gasdynamic turbulence in subsonic arcs can be regarded negligible in comparison with thermal one.

From this point of view cross-flow arcs are the matter of special interest since they are very gasdynamically unstable. But gasdynamic instability entails temperature fluctuations which generate thermal turbulence. Therefore, both turbulence modes take part in energy transfer process in addition to convection mechanism. Their relative importance is a subject of great interest. The regression analysis can be used to treat CVC taken in generalized form. Nondimentional number $UL\sigma_o/I$ (generalized resistance) can be used as function, while $\pi_{conv}=\rho_o\sigma_o^2h_o^2L^5B/I^3$; $\pi_{turb}=\rho_o\sigma_oh_o^{1.5}L^3/I^2$ represent convective and thermal-turbulent heat transfer mechanisms respectively. On assumption that average plasma velocity and its r.m.s. pulsations are appreciably correlated the π_{conv} number takes also account of heat transfer by gasdynamic turbulence. Hence, the power expression $UL_o\sigma_o/I= =C(\rho_o\sigma_o^2h_o^2L^5B/I^3)^{\alpha}(\rho_o\sigma_oh_o^{1.5}L^3/I^2)^{\beta}$ can serve as a generalized CVC of a cross-flow arc.

CVC of unstable high-current discharges is approximately parallel to the current axis. Then at dominant π_{conv}, the effect of π_{turb} can be neglected and $\beta\approx0$, while $\alpha\approx1/3$ since I in π_{conv} takes power -3 and in function its power accounts for -1. On the contrary, at prevalent π_{turb}, $\alpha\approx0$ and $\beta\approx0.5$ because power of current in π_{turb} equals to -2. Therefore, ratios $\alpha/0.333 = 3\alpha$ and $\beta/0.5 = 2\beta$ show the relative importance of the convective and turbulent heat transfer.

In order to estimate the relative importance of thermal turbulence in energy transfer process we have analyzed some experimental data on CVC of magnetically-propelled arcs. We have used the results of our experiments with

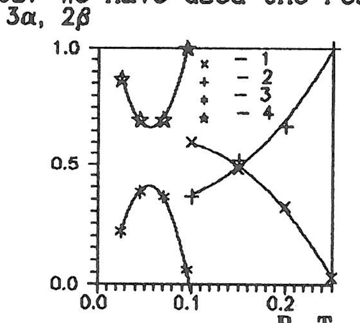

Fig. 1. Exponents α, β as function of magnetic induction. 1,3- 3α, 2,4- 2β. 1, 2- ring electrodes; 3, 4- parallel electrodes.

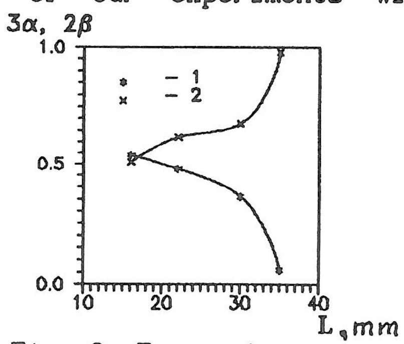

Fig. 2. Exponents α, β as functionn of interelectrode distance. Parallel electrodes: 1- 3α, 2- 2β.

arcs rotating between concentric ring electrodes and these of Adams [3] for arc propelled along parallel ones. Parameters variation of the rotating arc was: I = 100-900 A, B= 0.085-0.29 T, L = 3 and 6 mm while these of the arc between parallel electrodes changed over ranges: I = 100-1000 A, B = 0.012-0.108 T, L = 12.7 - 38.0 mm. The arcs burned in air in both cases.

The only factor stabilizing a magnetically-propelled arc is jets of electrode-material vapor forming in arc roots due to intensive heat flow rate in attachment points. Stabilizing effect of the jets decreases with interelectrode distance rise and with arc velocity enhancement owing to magnetic field augmentation. Gasdynamic destabilization of electric arc must entail the rise of heat transfer by thermal turbulence mechanism. Therefore, effect of π_{turb} should increase with interelectrode gap and magnetic induction. We can verify this assumption by correlation of the arcs CVC.

Variation of 3α and 2β with magnetic field for arcs burning between ring and parallel electrodes is shown in Fig. 1. The character of exponents behavior is seen to comply with prediction. Moreover, absolute values of exponents α and β point to predominance of turbulent similarity number; so that convective heat transfer can be neglected at high magnetic induction. The same result is obtained with interelectrode gap variation (Fig. 2). Therefore, we can conclude that thermal turbulence is of important significance for energy transfer in unstable magnetically propelled arcs. This evidence may be regarded as quite reliable since regression parameters are rather good: correlation coefficients R-sq = 0.993 - 0.996, r.m.s. deviations in natural logarithms σ = 0.0008 - 0.0043, Fisher variances ratious F= 4986 - 13931.

Generalization of longitudinally-blown arcs was done by the theoretical method enabling to obtain nondimentional expressions for CVC, heat transfer rates, temperature and geometric characteristics of an arc which were derived for asymptotic region in [4]. The model is based on power approximation of electroconductivity as a function of heat flux potential $S=\int_0^T \lambda \, dT$ with different magnitudes of exponents for the lateral and longitudinal components which product is applied at the variables separation. Reliability of the expressions obtained has been corroborated by good agreement with experiment of the calculated E-I characteristics for different working gases. Here we will determine and compare with experiment generalized functions for temperature profiles and heat transfer rate to the discharge chamber wall.

The formulae obtained in [4] are somewhat inconvenient because of radius function being written in implicit form. But one can obtain the explicit form for reciprocal function $Po(\bar{r}_*, K_Q, K_S)$ where K_Q and K_S being parameters.

$$Po = \left[10,6k\bar{r}_*^2(1+0,17K_Q\bar{r}_*^2)\right]\left(\frac{0,8K_S}{\ln(1/\bar{r}_*)}\right) ; \qquad (1)$$

Using this expression allows us to derivate compact and convinient relationships for characteristics of the arc in asymptotic region

$$\overline{\Delta S}_I(\bar{r}) = \frac{0,8\ K_S}{\ln(1/\bar{r}_*)} J_o(2,4\ \bar{r}/\bar{r}_*) ; \qquad (2)$$

$$\overline{\Delta S}_{II}(\bar{r}) = K_S \frac{\ln(\bar{r}/\bar{r}_*)}{\ln\bar{r}_*} ; \qquad (3)$$

$$\Pi_E = \frac{0,74}{k\bar{r}_*^2}\left[1,25\ \frac{\ln(1/\bar{r}_*)}{K_S}\right]^n ; \qquad (4)$$

$$\Pi_q = \frac{K_S}{\ln(\bar{r}/\bar{r}_*)} \qquad (5)$$

The formulae (1-5) represent a system of nondimentional equations where arguments $Po, \bar{r}$ and functions ΔS_I, ΔS_{II}, Π_E, Π_q are connected by radius of electroconductive zone and the given parameters K_Q, K_S.

The other parametric system of nondimentional equations can be obtained when ΔS is applied as a given parameter instead of $\bar{r}_*$. For this purpose, one may express $\bar{r}_*$ in terms of ΔS_{oo} setting $\bar{r}=0$ in (2). So that

$$\bar{r}_* = \exp\left[-\ 0,8K_S/\overline{\Delta S}_{oo}\right] . \qquad (6)$$

Substituting (6) into (1) - (5) we have

$$Po = \left\{10,6\ k\ \exp\left[-\ 1,6K_S/\overline{\Delta S}_{oo}\right] \times \right.$$
$$\left. \times \left[1+0,17K_Q\exp\left[-1,6K_S/\overline{\Delta S}_{oo}\right]\right]\right\} \overline{\Delta S}_{oo}^{\,n+1} ; \qquad (7)$$

$$\overline{\Delta S}_I(\bar{r}) = \overline{\Delta S}_{oo} J_o\left[2,4\ \bar{r}/\exp\left(-\ 0,8K_S/\overline{\Delta S}_{oo}\right)\right] . \tag{8}$$

$$\overline{\Delta S}_{II}(\bar{r}) = -\left(1,25\ \overline{\Delta S}_{oo} \ln \bar{r} + K_S\right) ; \tag{9}$$

$$\Pi_E = \left(0,74/k\right)\left(K_S/\overline{\Delta S}_{oo}\right)^n \exp\left(K_S/\overline{\Delta S}_{oo}\right) ; \tag{10}$$

$$\Pi_q = 1.25 \cdot \overline{\Delta S}_{oo} \tag{11}$$

Comparison of the theoretic profile ΔS_I (8) with the experimental one for argon [5], with ΔS_{oo} at the axis being taken as a base value for ΔS_o ($\overline{\Delta S}_{oo}$=1), is given in Fig. 3. Representation of experimental data in coordinates $\Delta \tilde{S}_I(\tilde{K}_S, \bar{r})$ is seen to give rather good correlation of temperature profiles in an argon arc at current variation, though the discrepancy at the arc column periphery amounts up to 100%. Representing experimental data in terms of temperature profiles reduses the misfit down to 13%. As can be seen from (8), a lamination is also caused by K_S variation due to different gases application. But equation (8) takes into consideration the distinction in K_S and, therefore, describes similarity of ΔS profiles.

The condition $\Delta S_o = \Delta S_{oo}$ simplifies extremely eq. (11) and we have for the heat flow-rate to the canal wall

$$\hat{\Pi}_q = 1.25 \tag{12}$$

The comparison of this relationship with experiments for argon, air, nitrogen and helium shows, that at I =20-300 A R = 2-5 mm, the theory is in satisfactory agreement with experiment.

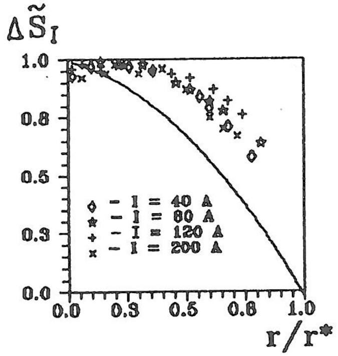

Fig. 3. Comparison of teoretical (line) and experimental generalized profiles of heat flux potential for argon [5]: P = 0.1 MPa, R = 4.0 mm.

The evidance obtained indicates that unification of formulae for approximately similar arcs still retains rather acceptable accuracy, informative capability of generalized expressions being appreciably higher than of scattered data obtained in physical or numerical experiment.

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Nomenclature

B- magnetic indication; E- electric field strength, h- enthalpy; I- current; J_o - zero order Bessel funktion; k- constant; L -interelectrode distance; Q- volumetric rate of radiation loss; R- arc canal radius; $S=\int_0^T \lambda\, dT$ - heat flux potential; $\Delta S= S-S_o$, $\overline{\Delta S} = \Delta S/\Delta S_o$; T- temperature; λ- thermal conductivity; ρ- density; σ- electroconductivity; $Po= I^2/R^2\sigma_o\Delta S_o$, $K_Q=QR^2/\Delta S_o$, $K_S=-\Delta S_1/\Delta S_o$, $\Pi_E=ER^2\sigma_o/I$, $\Pi_q=q_1 R/\Delta S_o$ - nondimentional numbers.

Subscripts

* - electroconductive zone; o - scale value; oo- axis value, I, II -electroconductive and nonconductive zones; 1- wall value.

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