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The turbulization of a blown electric arc discharge.

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Abstract:

The turbulization processes of blown electric arc discharges are considered. It is shown that in high-temperature media the specific turbulization can develop. The source of energy of turbulent instabilities is the enthrall of overheated region owing to formation of random thermal nozzles, when internal energy is much higher than kinetic energy of the flow. The nondimensional number for turbulent heat transfer in electric arcs is derived. Correlations of current-voltage characteristics have shown that turbulent heat transfer is essential in cross-and longitudinally-blown arcs. The measurements of radiation intensity pulsations in arcs, blown by different gases, are in fair agreement with data of correlation analysis.

1. Introduction

The flow of different media have the tendency to destabilization giving rise to turbulent fluctuations. Turbulization of cold flows has been studied rather well with the critical Reynolds numbers determined for different flows conditions. Nowadays rapid progress if closely connected with ever increasing application of high-temperature plasma flows amongst which gas flows with electric arc discharges play an essential role. Such flows are employed both in switch devices to quench electric arcs, and in the so called plasma torches or plasmatrons used for electric arc heating of a gas. The turbulization process of plasma flows differ essentially from turbulent destabilization of cold flows. First of all, as far as a temperature grows, gas viscosity increases. So the critical Reynolds number is attained at higher velocities with a given diameter of a canal. Moreover, in the case of gas, heating by an electric arc, temperature of the latter is unknown a priori since it depends in a complicated manner on arc burning conditions. Therefore the usual method to determine the onset of turbulization by the critical Reynolds number estimation encounters difficulties as Reynolds number itself becomes a function instead of an argument. However, there is one more problem concerned with the nature of turbulization.

In cold flows it is of hydrodynamics nature and turbulent instabilities develop at the expense of kinetic energy of the flow. In electric arcs, the kinetic energy of plasma flows is low as compared to internal one. The plasma heating is accomplished by Joule dissipation of the energy of an applied electric field. This process gives extra sources of destabilization which are different from hydrodynamic ones [1,2]. Therefore the electric arc turbulization will depend not only on a Reynolds number. It is quite possible that the Reynolds number is of minor importance in this case, and the main role may belong to some other number which describes the process. Therefore, this thermal turbulent number must also describe some process of heat transfer in electric arcs. This is the subject matter of the present work.

2. Derivation of the turbulent heat transfer number.

Two methods are used to derive the nondimensional numbers applied in physical modeling, namely, the dimensional analysis and the reduction equations to the nondimensional form. The both methods have their own merits and disadvantages. If the numbers are derived from equations then all physical phenomena described by the numbers, are known in advance. No any new phenomena can by found by this method, that those used in composing the equations. The method of dimensional analysis makes it possible to discover unknown phenomena, but it is easy to make mistakes. If some processes are essential, then this method can produce numbers which represent the combinations of "real" processes. In this case, it is difficult to define the real processes described by the numbers. We shall try to use the both methods simultaneously.

Using the method of dimensional analysis, we choose such technique of combining the dimensional variables that the known numbers are obtained in the same form as in the case of reducing the differential equations to the nondimensional form. In this

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case, if the adopted formalism ensures nondimensional numbers correctly describing the known phenomena, then the another obtained numbers are assumed to describe also correctly some unknown yet phenomena. But the form of these numbers offers the possibility to define the physical mechanism appropriate for this number.

The most essential processes in electric arcs are energy-transfer by conduction, convection, radiation, and turbulence. The energy conservation equations for a stationary arc may be written as follows:

$$\rho \mathbf{v}\cdot\nabla h = \nabla\cdot(\lambda\nabla T) - Q_r + J^2/\sigma + \text{correlations of pulsations} \quad (1)$$

The first three types of energy transfer are described by the terms of Eq.(1), composed of averaged quantities, while the turbulent heat transfer depends on correlations of this quantities pulsations. Eq.(1) may be reduced to the nondimensional form by choosing some scale values ρ_o, v_o, h_o, λ_o, T_o, Q_{ro}, σ_o, j_o, L for all the quantities with their subsequent division by these scales of the appropriate quantities and multiplication of a given term of the equation by them. Dividing each term of the equation by a set of scale values obtained at one of the terms, we reduce the equation to the nondimensional form. As a result, the all terms of the equation, with the exceptions of a single term, will have nondimensional factors consisting of a set of scale quantities and representing the desired numbers. This method enables us to obtain the equation:

$$\frac{\rho_o V_o h_o \sigma_o L^3}{I^2}\rho^* v^* \cdot \nabla h^* = \frac{\lambda_o T_o \sigma_o L^2}{I^2}\nabla\cdot(\lambda^*\nabla T^*) + \frac{Q_{ro}\sigma_o L^4}{I^2}Q_r^* + \frac{(J^*)^2}{\sigma^*} + \text{correlations of pulsations} \quad (1')$$

Superscripts *) denote the nondimensional values $\rho^* = \rho/\rho_o$, $v^* = v/v_o$, etc. Here, use is also made of the expressions for the total gas flow rate G and current I which are constants along the canal.

$$G = 2\pi\int_0^R \rho v r dr \quad (2)$$

$$I = 2\pi\int_0^R j r dr \quad (3)$$

Thus, three nondimensional numbers are found to describe heat transfer of Joule dissipation:

$\Pi_1 = \sigma_o h_o GL/I^2$ -convective heat transfer

$\Pi_2 = \lambda_o \sigma_o T_o L^2/I^2$-conductive heat transfer

$\Pi_3 = Q_{ro}\sigma_o L^4/I^2$ -radiative heat transfer (volume-radiation approximation)

In this case under consideration, the dimensional analysis requires nine dimensional values important for this process, i.e. I, L, σ, T, h, λ, Q_r, ρ, v. Since the electric discharge arc characteristics depend mainly on energy exchange processes, than it is expedient to use W[J], I[A], t[s], L[m], T[deg] as independent dimensions. The exponents of the independent dimensions for each subsequent variable are listed in table 1. The index u denotes dependent value, i.e. voltage across the arc; I, L, V are the independent variables; σ_o, h_o, λ_o, $Q_{\lambda o}$, ρ_o are the scale values of the plasma properties and T_0 is the scale temperature.

Table 1. Dimensions of the significant quantities.

Dimen-sions	Essential variables.									
	U	I	L	σ	T	h	λ	Q	G	ρ_r
W (J)	+1	0	0	-1	0	0	+1	+1	+1	+1
I (A)	-1	+1	0	+2	0	0	0	0	0	0
t (s)	-1	0	0	+1	0	-2	-1	-1	+1	+2
L (m)	0	0	+1	-1	0	+2	-1	-3	-2	-5
T (d)	0	0	0	0	+1	0	-1	0	0	0

Now we derive the nondimensional numbers by using the method described in ref. [3]. Representing the function U as the power-low approximation of independent variables

$$U = \alpha I^a L^b \sigma^c T^d h^e \lambda^f Q_r^l G^k \rho^m \quad (4)$$

and taking into consideration that for each dimension the exponent at U is equal to the sum of exponents at all variables, we can obtain five equations, shown in Table 2.

In the considered case, there are four extra variables, and the same number of nondimensional arguments have to be obtained. We may choose arbitrarily four exponents for these arguments and assume them to be known. Then the other five exponents can be determined in terms of these four exponents by solving the five equations from Table 2. and are evaluated from consideration. Now at the remaining exponents we have several initial variables forming the desired nondimensional numbers. We have chosen the exponents at those parameters which characterize a certain kind of energy transfer (λ- conduction; Q_r - radiation; G - convection) while the excluded exponents have been assigned to general parameters (I, h, σ, T, λ). Density ρ also refers to general properties but it has to represent the unknown desired criterion of turbulent energy transfer. The solution of the equations from Table 2. gives the values of the excluded exponents in terms of remaining exponents. These values are listed in Table 3.

Table 2. The exponents for certain dimensions

Dimensions	Exponets									
	1-	a	+b	+c	+d	+e	+f	+i	+k	+m
W	1=	0	+0	-c	+0	+0	+f	+i	+k	+m
I	-1=	a	+0	+2c	+0	+0	+0	+0	+0	+0
t	-1=	0	+0	+c	+0	-2e	+0	+0	+k	+0
L	0	0	+b	-c	+0	+2e	-f	-3i	-2k	-5m
T	0	0	+0	+0	+d	+0	-f	+0	+0	+0

Table 3. Solution of the equations from Table 2.

Variables	Exponets					
			f	i	k	m
I	a=	1	-2f	-2i	-2k	-2m
L	b=	-1	+2f	+4i	+k	+3m
σ	c=	-1	+f	+i	+k	+m
T	d=	0	+f	+0	+0	+0
h	e=	0	+0	+0	+k	+1.5m

Now we transfer the quantities with the known exponents to the left side of Eq.(4) and determine the nondimensional function as $UL\sigma_o/I$. This number is the nondimensional resistance of an arc, which is usually used to correlate of current-voltage characteristics of electric arc discharges. The nondimensional arguments in the right hand side are determined by the exponents at the variables in each column of Tables 2. and 3. Then instead of (4) we arrive at following nondimensional equation:

$$\frac{UL\sigma_o}{I} = \alpha \left(\frac{\sigma_o T_o \lambda_o L^2}{I^2}\right)^f \cdot \left(\frac{Q_{ro} \sigma_o L^4}{I^2}\right)^i \cdot$$

$$\cdot \left(\frac{\sigma_o h_o G L}{I^2}\right)^k \cdot \left(\frac{\sigma_o \rho_o h^{1.5} L^3}{I^2}\right)^m \qquad (5)$$

Since first three numbers in the r.h.s. of Eq.(5) coincide with the numbers obtained from the energy equation (1), then the adopted procedure forms the numbers displaying certain bounds of energy transfer of Joule dissipation heat. Therefore the fourth number may also represent correctly some real energy transfer mechanism. A comparison of the obtained number $\Pi_4 = \sigma_o \rho_o h_o \; L / I$ with the factor at left term of Eq.(1') $\Pi_1' = \rho_o v_o h_o \sigma_o L^3/I^2$ describing convective transfer of Joule dissipation energy, shows that they coincide provided $v_o - h_o^{0.5}$. Thus, the physical sense of Π_4 is quite evident. Gas acceleration up to $\Delta h^{0.5}$ takes place in nozzles at the expense of enthalpy. This process is widely employed in different turbines to convert heat energy into mechanical one. For this purpose nozzle must have special geometric configuration. However, it is known, that thermal and flow rate nozzles in addition to "geometric" nozzles there may be also exist under certain heat and mass transfer conditions along a jet. In the case of subsonic flow, mass and energy must be supplied to accelerate a jet, while in a supersonic situation the conditions must be reversed [4].

In an electric arc, the enthalpy necessary for development of turbulent disturbances must be mainly contributed from heat sources. It is possible when occasional thermal and flow-rate nozzles are formed with the enthalpy drop. As experiments show in unstable arc, a scale of pulsations is comparable with a radius of unstable arcs. Therefore, $\Delta h \approx h$ and, in fact, the enthalpy drop is close to its scale value. Thus, the analysis reveals that some disturbances of the flow due to the energy from the Joule dissipation sources can develop in electric arcs. In this case thermal-to-mechanical conversion takes place owing to formation of the thermal and/or flow-rate nozzles. This conclusion may be verified by experiments.

3. Correlation of current-voltage characteristics of electric arcs.

The parameters of an electric arc discharge depend on energy transfer process. This phenomenon may be used to verify the conclusion on thermal nature of turbulent pulsations in an arc made in Section 2. Depending on conditions, the Joule dissipation energy can be removed from an arc by different ways. Thus in low-flow-rate laminar arcs conductive heat transfer prevails. As far as a gas flow-rate increases heat transfer by convection becomes more important and the amount of heat removed by heat conduction decreases. With instability development, the turbulent heat transfer becomes appreciable. Such mechanism of heat transfer is described by the certain nondimensional number ($\Pi_1 - \Pi_4$).

But in a general case of influence of different energy transfer process the generalized current-voltage characteristic is described by Eq.(4). The problem is now concerned with determination of significant phenomena. For this purpose we may apply the regression analysis for experimental selection of significant numbers. However, the nondimensional numbers are not initial variables, and we need special experiments to correlate them.

Nevertheless, there is some possibility to use common experiments for revealing the important mechanism. We may correlate the experimental current-voltage characteristics in turn by using each nondimensional arguments individually and estimate the correlation parameters. The more important process, the larger correlation factor and the smaller error are. Such estimations have shown that at very small gas flow rates, for example in the water stabilized arcs, the dominant process is the heat conduction while at high flow rates the convective transfer prevails [5, 6]. But now the turbulent heat transfer is of the principal interest to us.

A comparison of the correlation parameters for different energy transfer mechanism has been made for an arc rotating in an annular gap in the presence of an external magnetic field.Experiments were conducted in different media: air, hydrogen, argon and helium. Current varied from 100 to 900 A, a distance between concentric electrodes, with an arc rotating between them, amounted to 3 and 6 mm. A gas flow rate did not exert appreciable influence on current-voltage characteristics of a rotating arc. Data of the correlation analysis are represented in Table 4.

For an arc rotating in a magnetic filled the number Π_1 is

$$\Pi_1'' = \rho_o h_o^2 \sigma_o^2 L^5 B/L^3$$

since the arc velocity depends on current interaction with the magnetic field [5]. The size of the gap was assumed as the determining dimension on the considered case. The number Π_3 was not used for correlation since at the atmospheric pressure this process is insignificant.

Table 4. Correlation parameters of rotating arcs voltage-current characteristics.

Gases	Correlation parameters for different numbers					
	Π_1		Π_2		Π_4	
	Δ	t	Δ	t	Δ	t
Hydrogen	0.12	37	0.16	27	0.13	34
Argon	0.11	44	0.23	19	0.16	29
Helium	0.08	96	0.11	66	0.09	83
Nitrogen	0.03	121	0.08	45	0.05	69

Table 4 shows that in a rotating arc all the considered numbers are significant, as 0.1% Student quantil is equal to 3.291 in all the cases. The number Π_1 is found to be the most important in all the cases. The number Π_4, i.e.turbulent heat transfer follows. The transfer by conduction (Π_2-number) is a less important process in all cases. It is interesting to compare the results of Table 4 with the absolute Π_4 values for different gases. It increases with $\rho_o \sigma_o h_o^{1.5}$, with other conditions being equal. This complex as a function of a temperature is plotted in Fig.1 According to this plot, the thermal turbulization is more characteristic for air, nitrogen and helium than for argon or hydrogen. And this agrees with the data from Table 4.

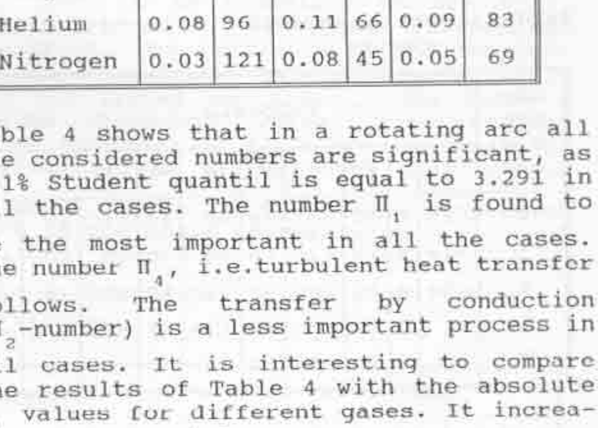

Fig. 1. Temperature dependence of Π_4 physical property part $\rho\sigma h^{1.5}$ 1- air, 2 - nitrogen, 3 - argon, 4 - hydrogen, 5 - helium.

The longitudinally blown arcs are less disturbed than cross-flow blown arcs. Besides, arc facilities with relatively short arcs, whose length in a canal is not beyond the boundaries of the initial and transient flow sections, find wider application. This limitation of the arc length is connected with heating of the near-wall gas layer insulating the arc from an electrode wall. To extend the arc into the region of developed turbulent flow, a special rather complicated plasmatron design has to be used that decreases its reliability.

However, on the other hand, the breakdown is of a random character and in the constant-section canal causes random fluctuation of the arc length, that causes flow turbulization.

Table 5 displays the correlation data on experimental current-voltage characteristics of the longitudinally blown arc whose length undergoes random fluctuations due to electrical breakdown. The canal diameter was 1,2 and 4 cm, I = 40 - 900 A. Gas flow-rates: Ar - (1 - 12)g/s, He - (0.25 - 4)g/s, N_2 - (2 - 6)g/s, H_2 - (1 - 3)g/s.

Table 5. Correlation parameters of the longitudinally blown arc with its randomly changing length.

Gases	Correlation parameters for different numbers					
	Π_1		Π_2		Π_4	
	Δ	t	Δ	t	Δ	t
Hydrogen	0.05	34	0.13	11	0.18	7
Argon	0.11	25	0.13	21	0.12	21
Helium	0.21	22	0.20	23	0.16	31
Nitrogen	0.08	39	0.12	26	0.14	23

As it was expected the thermal turbulization in longitudinally blown arcs turned to be less appreciable than in cross-flow arcs in spite of the arc length fluctuations. The turbulent heat transfer takes the last place in hydrogen and nitrogen, but nevertheless it follows after heat convection in an argon arc and even dominates in a helium arc. This phenomenon may be explained from the viewpoint of the size of the arc diameter. The arc is more constricted in molecular then in atomic gases owing to increased heat conductivity attributable to a dissociation process. The cross-flow arcs are very unstable and the heat conductivity does not exert appreciable influence on the size of its diameter, but in more stable longitudinally blown arcs this phenomenon appears to be significant. The turbulent number highly depends on the diameter size since its exponent is equal to three. Therefore the helium arc which has a high value of $\sigma_o \rho_o h_o^{1.5}$ becomes turbulent while an argon arc allows the turbulence to occupy only the second position despite of large arc column diameter.

The results, obtained by the correlation method are also in good agreement with the measurements of the radiation intensity pulsations in electric arcs.

4. The measurements of radiation intensity pulsations.

Measurements of radiation intensity pulsations were made in longitudinally blown arcs with the stabilized arc length. The length stabilization was achieved by step-like expansion of the electrode diameter or by igniting the arc between two rod electrodes. The experimental canal was made of the copper diaphragms insulated from each other and cold by water. The internal diaphragms diameter was equal to 8 and 10 mm, the canal length - 50 and 100 mm. Current varied from 60 to 250 A, and gas flow rate were (0.1 - 0.5) g/s for helium, (0.5 - 4.0) for nitrogen, (1.0 - 4.0) for air and (0.3 - 3.5) for argon. The radiation intensity was measured with a special automatic device with the time and space resolution 10^{-3} s and 10^{-5} m. The better time resolution up to $2.5 \cdot 10^{5}$ frames per second could be achieved with using a high-speed camera.

The radiation-intensity pulsations in the discharge canal are caused both by radiative pulsations inside the arc column and by oscillations of the column across the canal. It is difficult to measure the radiation pulsations inside an oscillating arc column. Therefore some approximations were used. The model "Gauss-Gauss" assumes that radiation intensity J(y) and the probability of the column position across the canal $\varphi(y)$ have normal distributions with mean-square root deviations A and σ, respectively. In this case the radiation intensity inside the column I(x) has the normal distribution too with the mean-square root deviation a. Then:

$$J(y) = J_o \exp(-y^2/2A^2) \quad (6)$$

$$\varphi(y) = \varphi_o \exp(-y^2/2\sigma^2) \quad (7)$$

$$I(x) = I_o \exp(-x^2/2a^2) \quad (8)$$

$$A^2 = a^2 + \sigma^2 \quad (9)$$

$$n = \sigma/a \quad (10)$$

$$I_o a = J_o A \quad (11)$$

Investigations of the instant and time-average radiation-intensity distributions have demonstrated that this model is valid for the central part of the arc column. In conformity with this model the distribution of the radiation intensity pulsations may be written as follows:

$$\Delta J^2(y) = J^2(y)\left[\frac{1+\Delta\bar{I}_o^2/\bar{I}_o^2}{\sqrt{1-n^2}}\cdot .\exp\left(\frac{y^2}{A^2}\cdot\frac{n}{n+1}\right)-1\right] \quad (12)$$

This relation has the maximum which, due to column oscillations, deviates from the canal axis when $0 < \sigma/a < 0.84$. This deviation is:

$$y_m = A^2\frac{n+1}{n}\ln F \quad (13)$$

Where:

$$F = \frac{(n+1)\sqrt{1-n^2}}{1+\Delta\bar{I}_o^2/\bar{I}_o^2} \quad (14)$$

The constant relative intensity of pulsations inside the column may be calculated if the pulsations are measured at two points $y = 0$ and $y = y_m$, or $y = A$. The corresponding relations are as follows:

$$\Delta J^2(0)=J^2(0)\left[\left(1+\Delta\bar{I}_o^2/\bar{I}_o^2\right)\frac{1}{\sqrt{1-n^2}} - 1\right] \quad (15)$$

$$\Delta J^2(y_m) = nJ^2(y_m) \quad (16)$$

$$\Delta J^2(A)=J^2(A)\left[\frac{1+\Delta\bar{I}_o^2/\bar{I}_o^2}{\sqrt{1-n^2}}\exp\left(\frac{n}{n+1}\right)-1\right] \quad (17)$$

The contribution of the outer parts of the column to the radiation intensity may be neglected. Then the measurements of the relative intensity of the radiation pulsations may be simplified by using the relation:

$$\frac{\sqrt{\overline{\Delta\varepsilon}^2(r)}}{\varepsilon(r)} = \sqrt{\frac{\overline{\Delta I}^2(x)}{\bar{I}(x)}} \quad (18)$$

The temperature pulsations may be estimated from the relation:

$$\frac{\sqrt{\overline{\Delta T'}^2}}{\bar{T}} = \frac{kT}{E_n}\cdot\frac{\sqrt{\overline{\Delta\varepsilon}^2}}{\bar{\varepsilon}} \quad (19)$$

Some results of the radiation intensity measurements are given below. Fig. 2 shows the temperature profiles T(y) in a discharge canal for different blowing gases. It is seen that the highest temperature is attained when helium is used for arc blowing. It is one of the reasons of thermal turbulization of the helium arc.

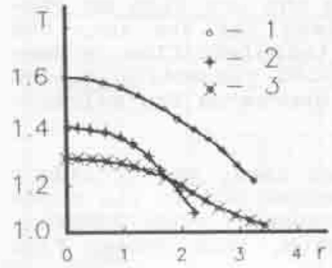

Fig. 2. Temperature profiles of the arc, blown by different gases: 1 - helium (HeI, 494.3 nm); 2 - air (NI, 742.3 nm); 3 - argon (ArII, 480.6 nm); T, K 10^4; r, mm;

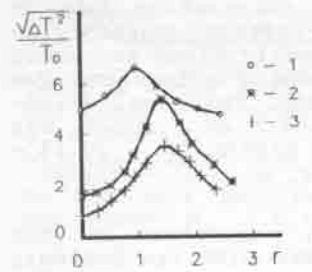

Fig. 3. Mean-square root relative temperature pulsations in the turbulent arcs: 1-argon; 2-air; 3-argon, $\sqrt{\Delta T^2/T_o}$, %

The profiles of the relative temperature pulsations of arcs in turbulent flows are plotted on Fig. 3 [8, 9]. It is seen that maxima of the profiles deviate from the axis due to the arc column oscillations. Comparison with the data from [10] shows the similarity of the profiles but the intensity of pulsations depends on a gas flow rate.

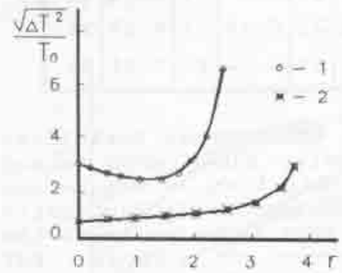

Fig. 4. Mean-square root relative temperature pulsations in the laminar arcs: 1 - helium, 2 - argon;

The profiles of relative temperature pulsations of arcs in laminar flows differ from those of turbulent arcs (Fig. 4). The arcs in laminar flows do not oscillate and the plots display the distributions of pulsation intensity inside the arc columns. It is seen that both in argon (data from [10]) and in helium there are sources of pulsations at the periphery of the arc column. The intensity of these pulsations decreases towards the axis. Such kind of pulsations in laminar flows may occur owing to a drastic increase of the flow velocity in the high temperature arc column They must decrease inside the column due to high plasma viscosity. The pulsation profile in argon arc is in good agreement with such explanation. However in a helium arc, the intensity of pulsations increases in the column center after its drastic decrease at the periphery. It means that there arc specific sources of destabilization in the helium arc. Such destabilization may be caused by thermal processes which are described by Π_4 number. This is just the helium longitudinally blown arc, where the Π_4 number is dominant. The plot in Fig 1 is also in good agreement with the experimental data.

5. Conclusion

1. The analysis shows that a peculiar mechanism of turbulization must exist at high temperatures. Acceleration of random gas jets occurs at the expense of enthalpy in this case. Accordingly, random thermal and flow rate nozzles arc formed in overheated zones which arc necessary for thermal jets acceleration.
2. The nondimensional number for this kind of turbulization is derived.
3. The correlations of current voltage characteristics of electric arcs confirm that the turbulent heat transfer is appreciable in different electric arcs.
4. Measurements of radiation intensity pulsations in electric arcs are in good agreement with the correlations.

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Nomenclature

A,a - mean-square root deviations of the radiation intensity normal distribution in the discharge canal and in the arc column respectively; E_n - energy of the radiation level; G - gas flow rate; h - enthalpy; I - current, radiation intensity in the canal; j - current density; L - scale of a length; Q_r - volume radiation; R - canal radius; T - temperature; t - Student quantil; U - voltage; v - velocity; W - energy; Δ - correlation error; ε - radiation emission; λ - heat conductivity; ρ - gas density; σ - electroconductivity; Π_1 - Π_4 - - nondimensional numbers; φ - probability of the arc column departure from the canal axis. Subscripts: $_\circ$ -scale values; $_r$ - radiation; Superscript: * - nondimensional quantify.

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