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HYDRODYNAMIC STRUCTURE AND HEAT TRANSFER IN THE INITIAL REGION OF AN ARGON PLASMA JET

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The relationship between the hydrodynamic structure of a turbulent argon plasma jet and the intensity of heat transfer between the flow and the wall normal to it is analyzed.

The initial segment (the potential-core region of the jet) of a plasma jet is the operating region in many industrial applications of plasma and, therefore, considerable attention has been devoted to its investigation. The hydrodynamics and the thermal structure of the jet and also the intensity of heat transfer between plasma jet and the wall normal to it were investigated in the course of a complex investigation of free plasma jets at the Institute of Thermal Mechanics of the Academy of Sciences of the Czechoslovak SSR using a segmented plasmotron of type 100 V [3] with different geometrical dimensions of the discharge chamber with tangential as well as axial supply of argon [4]. The hydrodynamic structure of the jet with rotational arc stabilization gets complicated. In certain operating regimes there is tangential component of the flow at the exit from the plasmotron [5]; therefore the effect of the hydrodynamic structure on the intensity of heat transfer q was investigated on the variant of the plasmotron with axial feed. The anode diameter D_a was 8 mm, the distance between the electrodes was 127 mm, the diameter of the discharge chamber was 15 mm, and the argon was fed along the front part of the cathode. The ranges of the operating parameters of the plasmotron were: $I = 50\text{-}180$ A, $U = 78\text{-}144$ V, $G_A = 0.3\text{-}3.8$ g•sec^{-1}.

Characteristics of the Structure of the Plasma Jet

The determination of the plasma-jet structure is made difficult by the fact that the basic hydrodynamic and thermal quantities, i.e., the velocity, the dynamic pressure, and the temperature in the exit section of the plasmotron nozzle, depend on the operating parameters of the plasmotron in different ways [6].

The magnitude of the maximum dynamic pressure at the exit aperture of the plasmotron with a relatively long discharge chamber ($l' > 8$) depends on $h_s G_A^2$, while in the range 0–3000

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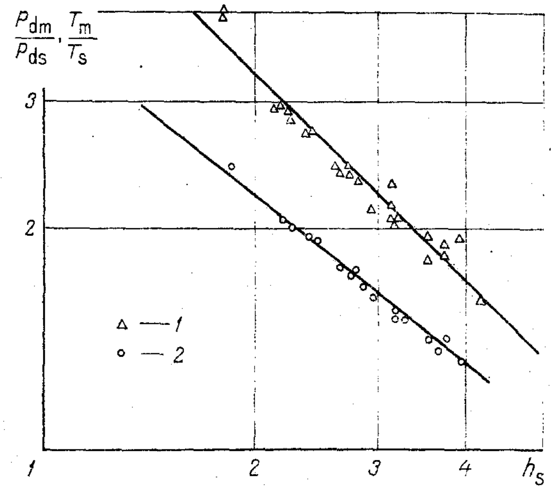

Fig. 1. The ratio of maximum and mean dynamic pressures in a plasma jet [1) P_{dm}/P_{ds}; 2) T_m/T_s].

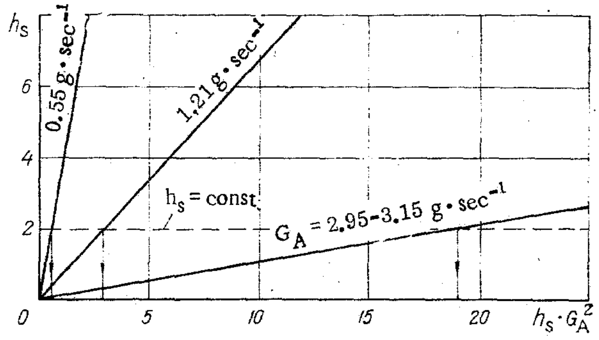

Fig. 2. The dependence $h_s = f(h_s G_A^2)$ for a plasmotron with axial argon supply.

$kgf \cdot m^{-2}$ it is given by the expression* [7]

$$P_{dm} = \left[\frac{0.68 \cdot 10^{-3}}{D_a^2}(h_s \cdot G_A^2)^{0.44}\right]^2. \tag{1}$$

On the other hand, the maximum temperature can be regarded as constant in the first approximation. In all measurements (different dimensions of the discharge chamber, different methods of gas feed) the temperature was varied in the range T_m = 10,500 (±14%). The ratio of the maximum and mean values of the dynamic pressure, which qualitatively characterizes the shape of the pressure profile according to Fig. 1, depends only on the mean enthalpy of plasma h_s [8]. The ratio T_m/T_s also has a similar form of the dependence on h_s. A comparison of the radial profiles of the temperature and the dynamic pressure shows that the temperature profile for h_s = const will be more flat than the pressure profile. On decreasing the flow rate of the gas (Fig. 2) for h_s = const the ratios T_m/T_s and P_{dm}/P_{ds} remain constant. On changing G_A the magnitude of the pressure P_{dm} changes appreciably (approximately in ratios corresponding to the magnitude of $h_s G_A^2$). On the basis of Fig. 1 for a plasmotron with axial argon feed the temperature T_m can be expressed by the equation

$$T_m = 3.83 \frac{T_s}{h_s^{0.77}} \quad \text{for} \quad h_s \lesssim 5 \text{ kJ} \cdot \text{g}^{-1} \tag{2}$$

(for $h_s \gtrsim 5$ kJ·g⁻¹, $T_M = 1.05 T_s$, approximately).

The investigations carried out here show that for h_s = const the maximum temperature and the radial temperature profile do not change, while the maximum dynamic pressure changes significantly. On the contrary, for regimes $h_s G_A^2$ = const the radial temperature profile will

*For a plasmotron with a sharp discharge chamber the following expression holds:

$$P_{dm} = \left[\frac{0.38 \cdot 10^{-3}}{D_a^2}(h_s G_A)^{0.9}\right]^2.$$

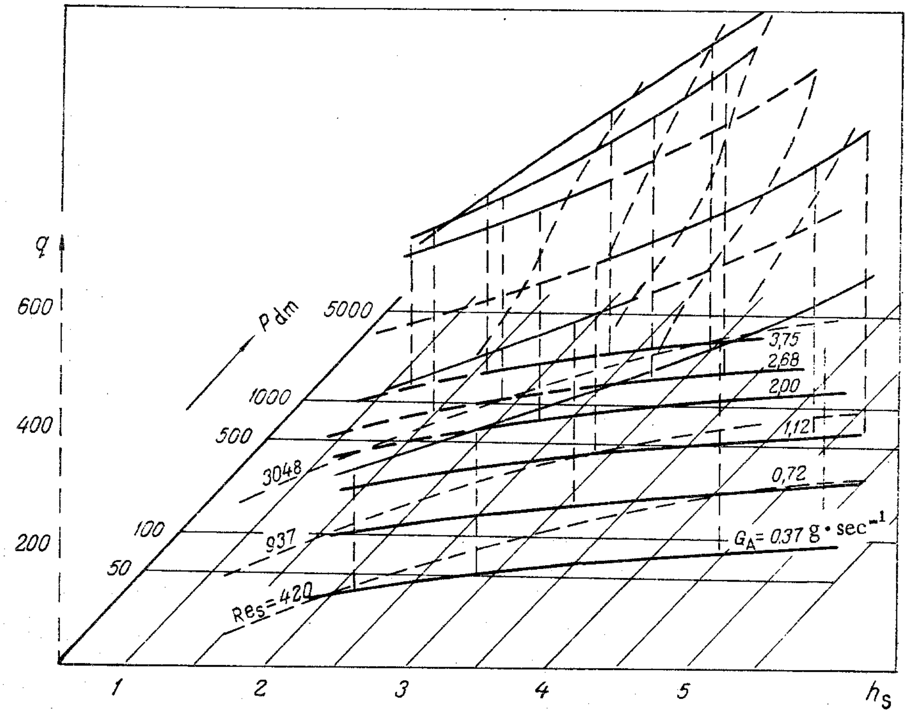

Fig. 3. The intensity of heat transfer q as a function of h_s and P_{dm}.

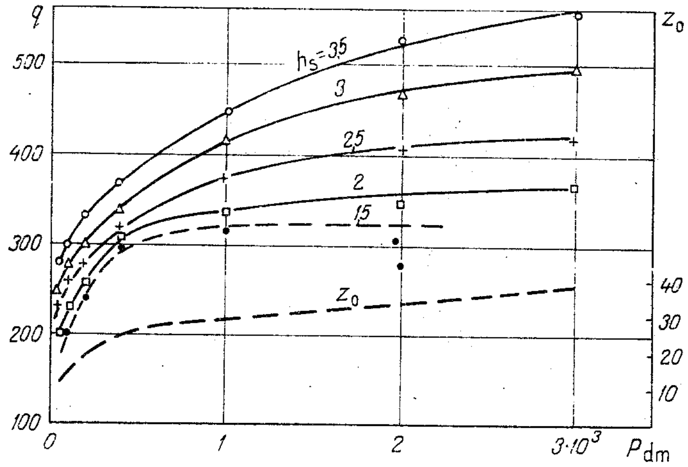

Fig. 4. The dependence of $q = f(P_{dm})$.

also change quite significantly, which is accompanied by a small change in temperature T_m. The radial profile of the dynamic pressures changes more rapidly than the temperature profile; however, the maximum value of P_{dm} remains constant.

Experimental Results

In some investigations of the heat transfer in a free plasma jet (for example [9, 10] and others) the heat-transfer coefficient or heat flux is expressed by the dependence on the Reynolds number computed from the average values of v_s, ν_s at the exit from the plasmotron. In these cases the characteristic dimension is the diameter of the exit nozzle D_a. However the variable conditions at the exit of the plasmotron nozzle, which were mentioned above, do not depend on Re_s alone. Therefore, we began to search for a direct dependence of q on parameters P_{dm} (or v_m) and T_m.

The use of mathematical methods of determining the dependence did not produce the desired result; therefore, we carried out a graphic analysis, whose results are presented below.

It was assumed that $q = f(h_s, P_{dm})$, where the dependent variables h_s, P_{dm} include the effect of other quantities on q [for example $T_m = f'(h_s)$, $z_0 = f''(P_{dm})$, $P_{dm}/P_{ds} = f'''(h_s)$ and

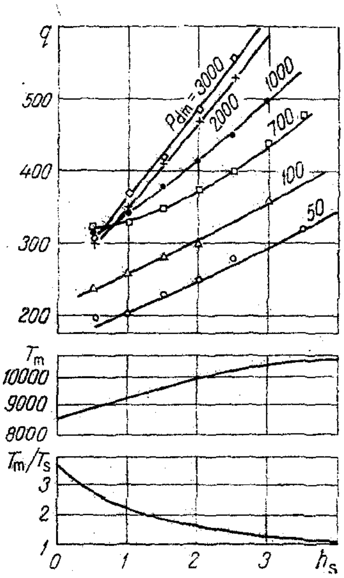

Fig. 5. The dependence $q = f(h_s)$. P_{dm}, $kgf \cdot m^{-2}$

so forth]. In the spatial coordinate systems h_s, P_{dm}, q the lines G_A = const were drawn in the h_s, P_{dm} plane and the corresponding measured values of the intensity of the thermal flux, taken from [1, 2], were plotted along the q axis. Certain anomalies are observed in the obtained dependence in the region $h_s < 1.5\ kJ \cdot g^{-1}$ at large flow rates of argon.

The dependence $q = f(P_{dm})$ is shown in Fig. 4 for the case h_s = const (section with the plane parallel to the P_{dm}, q plane). It is evident from the figure that at first the heat flux for q increases very rapidly with the increase of P_{dm} for all lines h_s = const. In the range $P_{dm} \sim 300$–$400\ kgf \cdot m^{-2}$ its growth slows down. For small values of h_s the effect of P_{dm} is insignificant in the next segment (for example line $h_s = 2\ kJ \cdot g^{-1}$); with the increase of the enthalpy the nature of variation of $q(P_{dm})$ is distinguished by a large slope. This tendency can be explained by the increase of the plasma velocity ($v_m = [9.81(2P_{dm}/\rho_m)]^{1/2}$; ρ_m increases with the increase of T_m). Also, with the increase of the average temperature T_s, the temperature profile, as well as the pressure profile, is gradually equalized (see Fig. 1).

The sharp increase in the dependence $q(P_{dm})$ in the region of small values of P_{dm} can also be caused by the change in the range of action of the plasma jet, i.e., by elongation of its potential core which is most intense in the range of small values of P_{dm}. In Fig. 4 this characteristic dependence is shown by dashes. The following empirical formula for z_0 was given in [4]:

$$z_0 = 4.5\ P_{dm}^{0.27}. \tag{3}$$

The dependence shown in Fig. 5 was also determined in the same way. In this figure the effect of the mean maximum temperature on the intensity of heat transfer is shown for the system of lines P_{dm} = const. In the lower part of the figure the corresponding values of T_m and T_m/T_s are shown for $h_s = 1$–$5\ kJ \cdot g^{-1}$. In most cases the dependence $q(h_s)$ is approximately linear and the rate of increase of q becomes large with the increase of P_{dm}.

Analysis of the Possibility of Using the Reynolds Number Re_s

In the investigation of heat transfer the obtained experimental results are most often expressed by similarity relations of the type

$$Nu = k Re^m Pr^n. \tag{4}$$

In the general case parameter h and the exponents m, n are functions of temperature, flow velocity, and the arrangement of the heat exchange planes. For laminar flow m varies in the range 0.4–0.6, while for turbulent flow $m \approx 0.8$; the exponent n is the same for both cases and most often it equals 1/3.

Whereas the Prandtl number expresses the property of the material (strictly speaking, the ratio of the characteristics of two types of molecular transport: momentum transfer by

TABLE 1. Values of the Basic Hydrodynamic Quantities in the Measurement during the Variation of the Operating Regimes of Plasmotron Using Argon

h_s, kJ·g^{-1}	$\dot{G}_A$, g·sec^{-1}	Re_s (9)	P_{dm} (1), kgf	v_m, m·sec^{-1}	T_m (2) °K	v_m/v'_m	T_m/T_s	Re_s/Re'_s
h_s = const = 2 kJ·g^{-1} (T_s = 4140°K)								
2	0,55	Re_s = 592	72	v_m = 138	9300	1	2.25	1
	1,21	1002	290	303		2,20		2,20
	3,05	3280	714	756		5,50		5,53
GA = const = 1.21 g·sec^{-1}								
2	1,21	Re_s = 1302	290	v_m = 303	9300	1	2,25	1
4		776	535	485	10400	1,60	1,32	0,59
6		635	763	590	11040	1,95	1,05	0,49

friction and heat transfer by conduction), the Reynolds number includes the effect of the hydrodynamic structure of the specific investigated phenomena. For longitudinal flow past a plane sheet usually the distance from the leading edge or the thickness of the boundary layer is taken as the characteristic dimension in the Reynolds number [11]; in the flow perpendicular to the plane, for example, in the Fay–Ridell expression which is valid for ionized gases [12], the characteristic dimension is the boundary-layer thickness.

The use of the Reynolds number, referred to the mean values of the plasma, was analyzed for the case of the plasmotron with axial argon feed. The Reynolds number is given by the formula

$$Re_s = \frac{v_s D_a}{\nu_s}. \tag{5}$$

For argon plasma, in Eq. (5) we can put

$$\nu_s = 4 \cdot 10^{-10}\, T_s \quad (T = 3000\text{-}11{,}000°K), \tag{6}$$

$$\rho_s = \frac{474}{T_s} \quad \text{or precisely} \quad \rho_s = \frac{474}{T} + 273, \tag{7}$$

$$v_s = \frac{G_A}{F\rho_s} \cdot 10^{-3}. \tag{8}$$

For anode diameter D_a = 8 mm the Reynolds number will be

$$Re_s = k\,\frac{G_A}{T_s^{0,8}}, \tag{9}$$

where $k = 8.4 \cdot 10^5$ and Re_s is directly proportional to the flow rate of argon and inversely proportional to the mean temperature with a power index of 0.8. However, the mean temperature is a function of the mean enthalpy; for argon the following approximate formulas hold:

$$T_s = 2.04 \cdot 10^3 h_s \quad \text{for} \quad T < 6000\ °K,$$
$$T_s = 1.29 \cdot 10^4 \log h_s \quad \text{for} \quad T = 6000\text{-}11{,}000°K. \tag{10}$$

According to Fig. 3 the quantity q also increases with the increase of h_s; however, according to Eq. (9) the Reynolds number decreases for G_A = const. Therefore, the power index m in (4) must be negative and the intensity of heat transfer would decrease with the increase of Re_s (for the case G_A = const).

The relationship between the individual quantities is shown in Table 1. For constant mean enthalpy h_s, Re_s also increases proportionally to v_m as G_A increases (see the ratio v_m/v'_m). On the other hand, for G_A = const the Reynolds number decreases with the increase of h_s (almost by half for the quantities shown in the table); also P_{dm} and v_m as well as T_m increase. The impossibility of using the Reynolds number as a criterion for estimating heat transfer is seen still more clearly from Fig. 3, where the lines Re_s = const show that the

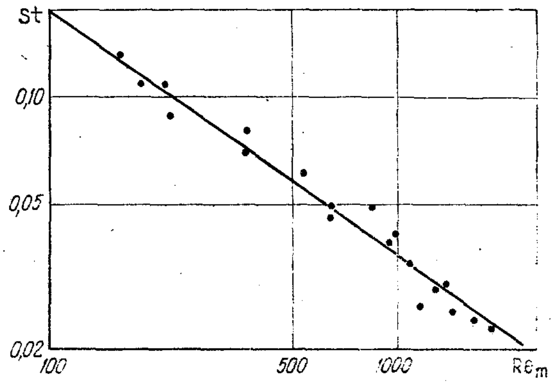

Fig. 6. The dependence St = f(Re_m).

intensity of heat transfer in the plasma jet is not a unique function of the Reynolds number Re_s.

In the initial region of the free isothermal jet there is no similarity of the aerodynamic quantities [13]; therefore, this segment is often called the non-self-similar region; the condition of self-conservation, i.e., conservation of the form of the dependence for the radial variations of the aerodynamic quantities, is not fulfilled [14].

It is shown experimentally in [5, 8] that in a plasma jet the change of $P_d(r)$ along the radius in the initial segment will not be self-similar. However, it should be noted that P_{dm} and T_m, as well as their ratios P_{dm}/P_{ds} and T_m/T_s, depend on h_s or on $h_s G_A^2$ at the edge of the plasmotron nozzle. It follows from Eq. (5) that in the general case Re = f($h_s G_A$). The Reynolds number computed from the actual measured quantities could thus characterize the phenomena at the exit section of the plasmotron and the quantities q measured at a distance of 15 mm from the exit aperture could be referred to the Reynolds number. The above analysis confirms this idea.

In view of the fact that for an axial type plasmotron Eq. (2) enables calculation of T_m and, according to [5], for D_a = 8 mm the maximum velocity v_m is given by the formula

$$v_m = 493\ G_A \log(1.6 h_s), \tag{11}$$

Re_m can be expressed as a function of h_s or T_s. For $h_s > 3$ kJ•g^{-1}

$$Re_m = 35 G_A \frac{h_s^{1.385} \log(1.6 h_s)}{(\log h_s)^{1.8}}\ ; \tag{12}$$

for $h_s \lesssim 3$ kJ•g^{-1}

$$Re_m = 970\, G_A \frac{\log(1.6 h_s)}{h_s^{0.415}}. \tag{13}$$

The dependence St = f(Re_m) is shown in Fig. 6. The Stanton number is given by the formula St = $Fq/h_s G_A$, whereas in (14)-(16) q is in kW/m^2. As seen from this figure, in the entire range of variation of the quantities this dependence can be expressed by the equation

$$St = 4.6\, Re_m^{-0.7}. \tag{14}$$

The root-mean-square deviation is ±0.02.

From the known relationship for the Stanton number St = Nu(RePr)$^{-1}$ the dependence for the Nusselt number Nu can be found from Eq. (14):

$$Nu \sim Re_m^{0.3}, \tag{15}$$

determining the intensity of heat transfer in this case. For computing the heat flux it is convenient to use the following formula:

$$q = 9.15 \cdot 10^4 \frac{G_A h_s}{Re_m^{0.7}}. \tag{16}$$

NOTATION

D_a, anode diameter in m; F, cross-sectional area of the anode (nose), m^2; G_A, flow rate of argon, g•sec^{-1}; h, enthalpy of the plasma, kJ•g^{-1}; I, the current, A; k_1, k_2, k, k', constants; l', relative length of the discharge chamber; $l' = L_{obl}/D_{vk}$; L_{obl}, the distance between the electrodes; D_{vk} = 0.015 m, the diameter of the discharge chamber; Nu, Nusselt number; Nu = $\alpha D_a/\lambda$; P_d, dynamic pressure of the flowing plasma, $kgf \cdot m^{-2}$; Pr = ν/a, Prandtl number; q, intensity of heat transfer measured by a 6-mm-diameter calorimetric probe at a distance of 15 mm from the exit aperture of the plasmotron, $W \cdot cm^{-2}$; Re = vD_a/ν, Reynolds number; St = Nu/RePr, Stanton number; T, plasma temperature, °K; U, voltage between the plasmotron electrodes, V; v, plasma velocity; ν, kinematic, viscosity $m \cdot sec^{-2}$; ρ, density $kg \cdot m^{-3}$; z_0, length of flow core, mm. Indices: m, maximum; s, average.

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