INFLUENCE OF AN EXTERNAL ACOUSTIC FIELD ON THE TEMPERATURE OF AN ARC-DISCHARGE PLASMA

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The influence of an external acoustic field on the temperature of an air-discharge plasma in the channel of a sectional plasmatron is investigated.

Acoustic oscillations of a gaseous medium at high temperatures are utilized in metallurgy [1], for the intensification of combustion processes [2], and more recently in the laser hardening of metal surface layers [3]. Their application in plasma technology, on the other hand, has been limited by a lack of information on how the acoustic field affects the local characteristics of the plasma flow, primarily its temperature. It has been shown [4] that the superposition of high-intensity acoustic oscillations ($P \gtrsim 150$ dB, $f = 10$-14 kHz) on a heterogeneous jet ($T_0 = 15{,}000$ K) improves the performance characteristics of the plasma spraying of powdered materials, increasing the coefficients of powder utilization and the power of the plasma jet, while simultaneously enlarging the diameter of the deposition spot on the substrate. This result is evidently a consequence of broadening of the plasma jet and, hence, a variation of the radial temperature distribution in it.

Here we report an investigation of the influence of an acoustic field on the temperature profile in the channel of a plasmatron with the sound waves directed perpendicular to the flow axis. The investigated working conditions included: current 60-180 A; arc voltage 80-110 V; mass flow of air $(2$-$2.5)\cdot 10^{-3}$ kg/sec. The arc burned between a water-cooled hafnium cathode and an annular copper anode, which was fitted with a projection to stabilize the arc in the plasmatron. The diameter of the stabilizing sectional channel was $0.8\cdot 10^{-2}$ m, and its length was $1\cdot 10^{-1}$ m. The measurement arrangement is shown schematically in Fig. 1.

The sound generator was a stem-jet generator (SJG) 1 with a power rating of 200 W and a frequency of 10-14 Hz. The sound beam was focused by the parabolic mirror 2; the conical "concentrator" 3, whose inner surface coincided with the acoustic wave surface of the sound beam reflected from the parabolic mirror, was used to decouple the SJG from the plasma, to concentrate acoustic energy at the entry to the channel, and to match the geometrical dimensions of the generator with those of the plasmatron channel. The calculated sound pressure level in the plasmatron channel was 180 dB, and the experimental value (estimated from the time to heat and ignite a sound-absorbing material [5] placed in the focal spot) was ~150 dB. This discrepancy is attributed to the active losses of acoustic energy in friction between the gas and the concentrator wall, since the calculated diameter of the principal diffraction maximum of the acoustic mirror 2 was $3\cdot 10^{-2}$ m and the exit diameter of the concentrator was $0.8\cdot 10^{-2}$ m. To ensure invariance of the operating regime of the plasmatron with the SJG turned on, the parabolic mirror was equipped with a row of radial ports for escape of the working gas (air), albeit this also decreased the useful acoustic power.

The proposed acoustical system permitted the effective input of energy into the discharge channel only in the traveling-wave regime, i.e., without any appreciable influence of reflected waves on the SJG. The minor influence of plasma-reflected waves under our conditions was confirmed experimentally. The acoustic concentrator 3 of the system operated as a particle-velocity transformer with a gain of ~24 dB. The investigations were carried out under conditions such that the air flow from the SJG into the discharge channel was negligible, and so its action on the characteristics of the plasma flow could be disregarded. The air flow through the channel was monitored by means of a special stroboscopic flowmeter during cold-flow through the plasmatron.

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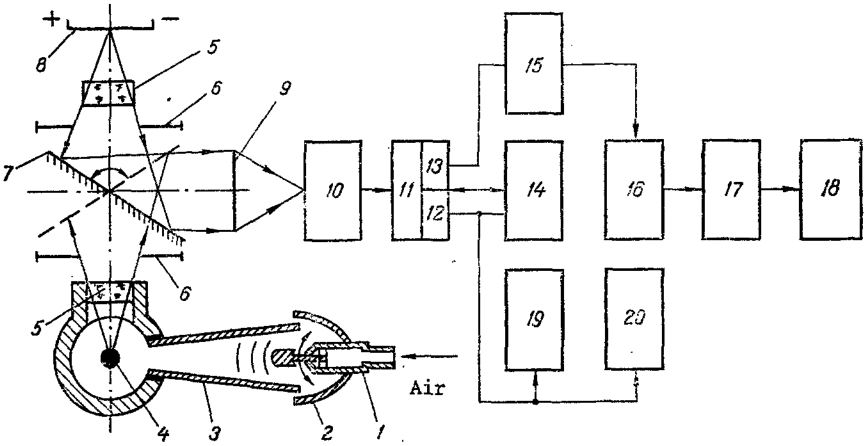

Fig. 1. Schematic diagram of the experimental arrangement. 6) Optical diaphragm; 8) SI 10-300 lamp; 17) type 15-21 interface unit. The remaining elements are explained in the text.

The radial temperature field T(r) in the channel was determined by means of an ASK-3 automated spectrometric system [6]. The temperature was determined by the method of absolute intensities at the atomic line NI744.23 nm on the assumption of the existence of local thermodynamic equilibrium (LTE). The validity of this assumption follows from the results of [7, 8], in which it is shown that LTE is present in nitrogen and air discharges under similar conditions. The radiation energy in the lines was computed with the use of an equilibrium composition [9], transition probabilities, and partition functions [10, 11]. The losses in the wings of the line due to the finite width of the monochromator exit slit were corrected by means of data from [12, 13], and the line was assumed to have a dispersion contour.

The radiation from the investigated zone of the arc 4 (Fig. 1) was extracted through the quartz window 5 and converged by means of the long-focus lens 9 onto the entrance slit of the spectral unit 11. The discharge axis was oriented parallel to the slit. The radiation intensity $I(x_j)$ from different spatial zones x_j ($j = 1, \ldots, 64$) of the arc was recorded by means of the specular scanning unit 10, which was used to shift the image of the arc. The selected aperture and the magnification of the optical system were such that $I(x_j)$ could be measured with a spatial resolution smaller than or equal to $3 \cdot 10^{-5}$ m. The investigated part of the spectrum was brought into the exit slit of the monochromator 11 by rotation of the diffraction grating (1200 lines/mm), and the width $\Delta\lambda$ of the extracted spectral interval was determined by the geometrical width d of the exit slit and the reciprocal linear dispersion L_λ of the monochromator. The radiation detector was an FÉU-112 photomultiplier (PM) mounted at the exit slit. The electrical output signal of the PM was sent to the transistorized dc matching amplifier 12, whose output was then sent to the analog-to-digital converter (ADC) 14 and from there through the special digital processor 13 and the type 15-10 interface device 15 for entry into internal storage of the supervisory computer in the 15 VSM-5 computer system 16.

Next, the experimental data were either processed or stored on magnetic tape in the 15 VSM-5 computer system. The data were entered into internal storage of the 15 VSM-5 in batches of six transverse contours $I(x_j)$ with a temporal resolution $\tau \sim 10^{-4}$ sec per single reading j. The time to record an individual contour was $8 \cdot 10^{-2}$ sec, and the total number of contours recorded on magnetic tape for an individual operating mode of the apparatus was made as high as 200. The operating conditions of the experimental apparatus were monitored by means of the S8-13 oscilloscope 19 and the SK4-58 spectrum analyzer 20.

Energy calibration of the measurement system at the investigated wavelength was carried out by means of the SI 10-300 tungsten ribbon-filament lamp 8, which was mounted symmetrically with the plasmatron relative to the axis of the mirror 7, and the results were read out on the Konsul 254 typewriter 18. The total calibration error did not exceed 4%. Data on the temperature and spectral dependences of the emittance of tungsten were taken from [14].

Stochastic and regular displacements of the arc and variations of the plasma luminance take place in the plasmatron channel as a result of shunting of the arc, fluctuations of the electrical characteristics of the power supply, and application of the acoustic field. In

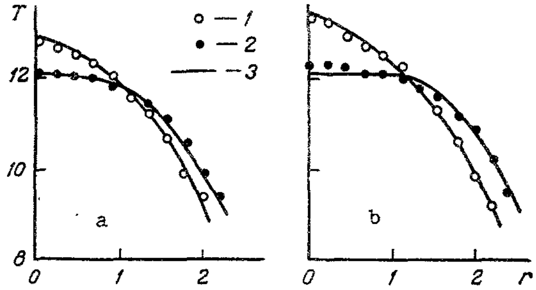

Fig. 2. Transverse temperature profiles in the channel of the sectional plasmatron. a) Discharge current i = 70 A; b) 110 A; 1) without acoustic oscillations; 2) with the application of acoustic oscillations; 3) approximation of the experimental distributions T(r); T in 10^3 K; r in 10^{-3} m.

accordance with the above-cited characteristics of the measurement system and the plasmatron, the time to record the contour $I(x_j)$ is much greater than the characteristic luminance fluctuation time τ_F, but τ_F is comparable here with the measurement time in the individual spatial zone x_j. To diminish the influence of fluctuations on the accuracy of the temperature determinations in the present study we recorded a large number of contours $I(x_j)$, which were then subjected to statistical processing by means of an automated system [15] based on an SM-3 computer. The system software made it possible to estimate the degree of symmetry of each of the intensity contours, to group the latter in separate arrays, and after appropriate identification to enter the information onto disk storage int the SM-3. The comprehensive processing of the resultant data [averaging, smoothing, numerical solving of the Abel integral equation, and computation of the hemispherical emittances $\varepsilon(r_j)$ for different radial zones r_j of the arc] was analogous to [16].

Figure 2 shows the resulting temperature distributions T(r) along the radius of the discharge channel. The role of resorption was analyzed on the basis of numerical estimates, according to T(r), of the optical thickness $\tau_\lambda(x_j)$ of the arc in the vicinity of the center of the pyrometric line ($\lambda \in \lambda_0 \pm 0.2$ nm), using the data of [17]. The maximum value of $\tau_\lambda(x_j)$ did not exceed 0.18 for the investigated operating conditions. According to [17], the absorption of the emission line in the arc can be neglected for this value of the optical thickness.

The maximum temperature T_0 of the plasma on the channel axis in the absence of an acoustic field is 12,600 K at i = 70 A and 13,200 K at i = 110 A. The application of the acoustic field lowers T_0 by ΔT = 600 and 1200 K at i = 70 and 110 A, respectively. The radial temperature profile of the plasma without the acoustic field corresponds to a parabolic distribution function $T(r) = T_0 - \xi r^2$, where $\xi = 94\cdot10^7$ and $87\cdot10^7$ K/m² at i = 70 and 110 A, respectively. In the acoustic field the following approximation relations are valid:

$$T(r) = \begin{cases} T_0 - \Delta T, & 0 \leqslant r \leqslant \Delta r, \\ (T_0 - \Delta T) - \xi (r - \Delta r)^2, & r > \Delta r, \end{cases}$$

where $\Delta r = 0.5\cdot10^{-3}$ m, $\xi = 105\cdot10^7$ K/m² for i = 70 A, and $\Delta r = 1.0\cdot10^{-3}$ m, $\xi = 140\cdot10^7$ K/m² for i = 110 A.

Ultrasound has the most appreciable effect on the temperature gradient (Fig. 3). Two characteristic zones are observed: the axial zone, where the temperature variation is small, $|\mathrm{grad}\ T| \approx 0$; and the peripheral zone, where $|\mathrm{grad}\ T| \geqq (3.2\text{-}3.6)\cdot10^6$ K/m, for a distance from the axis $r \geqq 2.5\cdot10^{-3}$ m. With an increase in the current, the zone with $|\mathrm{grad}\ T| \approx 0$ grows: Its radius is equal to $2\cdot10^{-3}$ m for i = 110 A, i.e., is twice the value for i = 70 A. This situation is typified by the fact that the zone with $|\mathrm{grad}\ T| \approx 0$ is absent when the acoustic field is absent, and practically $|\mathrm{grad}\ T|$ = const over the entire investigated part of the radius.

The distributions and radial gradients of the temperature can be used to interpret the behavior of the arc in an acoustic field as follows. The high sensitivity of the axial flow to low-intensity transverse perturbations is widely exploited in practice [2] and causes the arc to oscillate in an acoustic field, so that the plasma flow in the channel is unsteady.

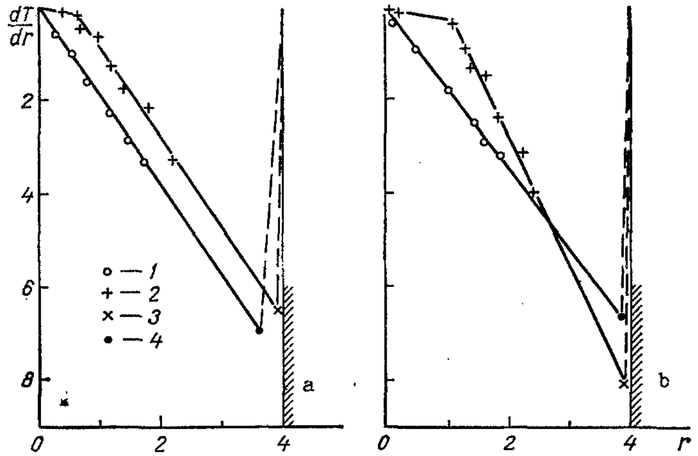

Fig. 3. Radial temperature gradients of the plasma in the channel of the sectional plasmatron. a) i = 70 A; b) 110 A; 1) without an acoustic field; 2) with the application of the acoustic field; 3, 4) approximation of T(r) up to a temperature of 300 K; dT/dr in 10^6 K/m.

This kind of mechanism has been noted previously in a study [18] of the influence of acoustic waves (P = 120 dB) on an arc fired in a submerged jet. The effective cross section of the arc becomes greater than in the absence of the field, and the recorded contour $I(x_j)$, which is mainly the result of time averaging of the intensity fluctuations of the plasma radiation in the individual zones of the channel, broadens. This transformation of the contour $I(x_j)$ lowers the temperature T_0 of the arc plasma in comparison with the zero-field case. The distributions T(r) shown in Fig. 2 for the application of an acoustic field must therefore be referred to the temperature obtained on the basis of time averaging of the radiation intensity for the individual spatial zones of the channel.

The mean-temperature gradient of the arc plasma is significantly smaller for i = 70 A than for i = 110 A. Inasmuch as the differences in the temperature T_0 are insignificant, the foregoing result is clearly associated with the influence of the channel wall on T(r) at high currents. Confiramtion may be found in the growth of |grad T| in the acoustic field for i = 110 A, in contrast with the case i = 70 A, where the value of |grad T| in the absence of an external acoustic field is observed to coincide with the value in the peripheral zone when a field is applied. This situation also indicates that the acoustic field does not yet induce appreciable interaction of the arc with the channel wall in this regime. The temperature distribution in the arc plasma can also be affected by the oscillations induced in it by the action of turbulence of the air flow around the arc.

It can be concluded that, in addition to acoustic oscillations, the channel walls and air flow can also influence the value of the recorded temperature gradient. The amplitude S of the oscillations of the arc have been estimated from the temperature distribution T(r) for the investigated operating conditions. It follows from Figs. 2 and 3 that $S \sim 0.5 \cdot 10^{-3}$ and $1 \cdot 10^{-3}$ m at i = 70 and 110 A, respectively.

An analysis of the experimental data enabled us to determine the amplitude of the luminance fluctuations in the various spatial zones. The standard deviations σ_ε of the local intensities from their mean value as a result of the unsteadiness of the arc in the acoustic field could then be estimated on the basis of the foregoing results in accordance with [19]. It was established that the relative random error σ_T/T of determination of the mean temperature for the central zones of the arc, being associated mainly with σ_ε, amounts to 1% for i = 70 A and 1.5% for i = 110 A. The values of σ_T/T do not exceed the methodological error of determination of the temperature (3%).

The experimental results indicate that the transverse action of acoustic waves on an arc induces a considerable variation of the radial distribution of the mean plasma temperature and its gradients in the plasmatron channel.

The proposed device for the transmittion of acoustic waves into the plasmatron channel is capable of generating very high-level acoustic fields in the channel. This consideration has important bearing on investigations in arc-discharge physics and should be useful in the organization of high-temperature technological processes.

NOTATION

P, sound pressure level; f, acoustic frequency; T, plasma temperature; r, radial coordinate in arc; I, line-of-sight integral intensity of plasma radiation; x, transverse coordinate of arc in scanning direction; $\Delta\lambda$, recorded spectral interval; d, geometrical width of monochromator axit slit; L_λ, reciprocal linear dispersion of monochromator; λ, radiation wavelength; τ, temporal resolution; τ_F, period of arc liminance fluctuations; ε, local emittance of plasma; τ_λ, optical thickness of arc in the direction of observation at wavelength λ; λ_0, wavelength corresponding to center of pyrometric line; T_0, axial temperature of arc; i, current; ξ, an approximation parameter; σ_ε, standard deviation of local emittances; σ_T/T, relative standard deviation of measured temperature; j, index enumerating transverse zone of channel.

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