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TEMPERATURE MEASUREMENT IN A REDUCED-PRESSURE SUBSONIC OXYGEN JET

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An induction plasmotron has been used to produce a stream of oxygen plasma, whose temperature distributions in the axial and radial directions have been measured at low pressure.

There are very few papers on oxygen plasmas, mainly because of difficulties in making them, as oxygen is a gas representing an explosion hazard, and when it is used at reduced pressures, one needs a mechanical pump filled with vacuum oil.

The first in which an oxygen plasma made in an induction discharge is mentioned goes back to 1961 [1]. All the measurements were made at atmospheric pressure in a plasma based on a mixture of argon with oxygen.

So far as we are aware, no experimental study has been made on induction plasmotrons with the use of oxygen plasmas at low pressures, although the topic is clearly important on account of research in gas-phase kinetics, catalysis, nonequilibrium heat transfer, and high-temperature materials science.

The present paper continues researches published in [2, 3] and relates to temperature measurements on free subsonic jets of air and nitrogen at reduced pressures produced with a VGU-2 induction plasmotron.

The VGU-2 has been used with a discharge channel 6 cm in diameter under the following conditions: anode power inputs 31.6 and 34.5 kW, oxygen flow rates 2.9-3.06 g/sec, pressure range $8 \cdot 10^3$-10^4 Pa, and flow speed at the axis near the end of the channel 90-110 m/sec.

The free jet was imaged on the slit of a DFS-452 spectrograph (dispersion 1.6 nm/mm) or that of a McPherson monochromator (dispersion 0.8 nm/mm) with photographic recording. The plasma parameters were measured along the axis and the radius near the end of the discharge channel.

The spectra were recorded at 200-800 nm. In the UV range, the spectrum is radiated in the main by the Schumann–Runge O_2 bands at 310-450 nm and the second negative system of O_2^+ at 260-310 nm, while in the visible and red regions, one gets the emission from atomic oxygen O I. Impurities were absent from the spectrum.

The plasma jet had a uniform blue emission (O_2) with 31.6 kW anode input (mode I). At 34.5 kW (mode II), the jet structure altered: a narrow core with bright emission appeared and the peripheral part acquired a yellow–green color, the extent of the core varying with the pressure, oxygen flow rate, and energy disposition. The spectral pattern was that in I, the main source was provided by oxygen molecules, with very weak emission from atomic oxygen, mainly in the two lines at 777 and 616 nm. As the power increased, the molecular spectrum weakened, and very strong lines from atomic oxygen appeared (excitation potentials over 12 eV), with the intensity there also substantially dependent on the pressure for a given power. As the pressure was reduced from 10^4 to $8 \cdot 10^3$ Pa, the intensity increased, while the lines vanished at $2 \cdot 10^4$ Pa, and the molecular emission strengthened.

A water-cooled copper holder containing the sensors or specimens was used in research on nonequilibrium heat transfer in the jet, so it was necessary to establish how the holder

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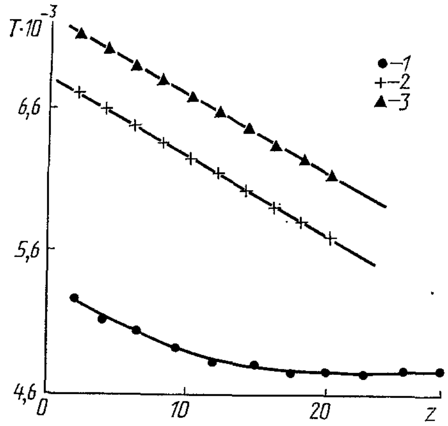

Fig. 1. Distributions of the temperature T in K along the axis z of the jet (mm): 1 and 2) 10^4 Pa, 31.6 and 34.5 kW respectively; 3) $8 \cdot 10^3$ Pa and 34.5.

affected the jet parameters. At $P \le 10^4$ Pa, a luminous layer of gas about 1 mm thick appeared at the surface, which radiated the lines of atomic oxygen and singly ionized oxygen, excitation potential over 25 eV. When the holder was inserted, the atomic lines present in the free jet extends to the end surface, and their intensities increased considerably, so a parasitic capacitative discharge arises between the plasma and the metal parts. In an air and nitrogen plasma at $P \le 10^4$ Pa, that effect is much less pronounced, which is evidently due to the higher ionization potential of the nitrogen atom. The effect became accentuated in these gases at lower pressures.

The temperature characterizing the distribution in the excited levels of the oxygen atoms was measured from the absolute and relative intensities, for which we used the atomic lines at 390-650 nm and also 777 nm. The measurement accuracy was better than 5%. The atomic oxygen concentrations were derived from calculations by S. A. Vasilevskii.

All the temperatures measured from the relative intensities were underestimated; the values need revision mainly because of the extended spectral range in the radiating pyrometric lines.

In mode I (31.6 kW) and II (34.5 kW), we examined the temperature distributions along the axis at $8 \cdot 10^3$ and 10^4 Pa. Curves 1 and 2 in Fig. 1 show the results for 10^4 Pa in a free jet near the end of the channel. Curve 1 has been derived by averaging the measurements on the 615.6 and 777.1 nm lines, while curve 2 is derived from averaging measurements on nine atomic oxygen lines.

The form is affected by the input power. At 31.6 kW, the temperature after a fall over a distance of about 12 mm becomes almost constant. At 34.5 kW (mode II), the picture is very different: the temperature at the end of the channel rises to 2000 K and the O_2 molecules are completely dissociated. The temperature variers linearly along the axis, as is characteristic for all states in air and nitrogen plasmas. A difference is that the temperature gradient along the axis in an oxygen plasma is higher by an order of magnitude than that with nitrogen or air.

The curves similar to curve 2 occur because there are interactions between thermal conduction, diffusion, and recombination in a dissociated jet [4]. From that viewpoint, curve 1 is anomalous. The explanation is that the 3 kW reduction in input involves a fall in the inductor current I_0, which reduces the temperature $T \sim c/[c - \ln(I_0 n)]$ and the conductivity $\sigma \sim (I_0 n)^2$. The reduced temperature markedly reduces the importance of thermal conduction. Under these conditions, the skin-layer thickness $\delta = c/\sqrt{\sigma f}$ increases, with $\delta \approx 2.3$ cm at about 5000 K and coinciding as regards order of magnitude with the radius of the discharge, so the skin effect vanishes. The discharge terminates at lower power.

Mode I is probably close to the threshold because of the low conductivity and the lack of skin effect, and the plasma state may be taken as unstable, as predicted by the theory [5]. The flow and discharge mechanisms differ from those in the stable state II and explain the differences in axial temperature distribution.

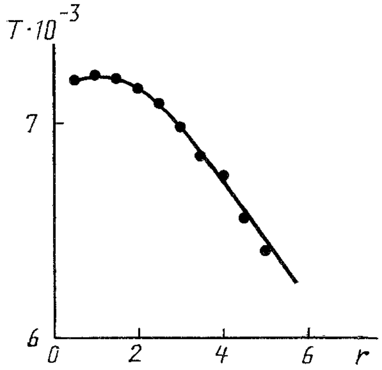

Fig. 2. Distribution of the temperature T in K along the radius r in mm near the end of the channel, 34.5 kW and $8 \cdot 10^3$ Pa.

A copper holder (z ≈ 30 mm from the end of the channel) leaves the axial T distribution unaltered, but the temperatures increase by 600 K. The holder was insulated from ground and the experiments were performed with the oxygen flowing and used with a high frequency (17 MHz) at low pressure (17 Pa). Under those conditions, the insulator between the water-cooled copper holder and the grounded body partially loses its insulating properties, and leakage currents occur because of the space-charge layer at the holder. The effects are related to the parasitic capacitative high-frequency discharge, which makes a contribution to the temperature of the main discharge. Those effects have been examined in [6].

Curve 3 in Fig. 1 shows T = f(z) for $8 \cdot 10^3$ Pa in mode II. Reducing the pressure raises the temperature by about 400 K. The dependence remains linear.

In mode II, the jet has a prominent core and a mixing layer, so we examined how the inhomogeneity in the radiating layer affected the temperature measurements via the radial intensity and temperature distributions as determined by traditional methods from the measured intensities integrated over the source depth, which were converted to local values. The procedure was applied to seven atomic oxygen lines in the range 394-645 nm. The temperature profiles for all the lines were basically the same.

The radial intensity profiles gave the effective radiating layer thickness as about 1.4 cm, which was taken as the radiating layer length.

Figure 2 shows the averaged radial temperature profile near the end of the channel. That profile in oxygen is much narrower than that in air or nitrogen. The radial intensity and temperature distributions imply that the atomic oxygen atoms radiate in a very narrow region near the axis (the core). The local temperatures at the axis coincide with those averaged along the line of sight, i.e., the radiating layer does not distort the measured temperature, and the temperature result characterizes the plasma state at the jet core.

There are thus two discharge states, one stable with linear T = f(z) and the other close to the threshold, with an anomalous axial temperature distribution. The discharge state is substantially dependent on the energy input.

Notation. P, pressure; z, axial coordinate; λ, wavelength; N_{ai}, anode input power; T, temperature; r, radial coordinate; f, frequency; δ, skin layer thickness; I_0, coil current; n, number of coil turns; σ, conductivity.

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