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INTERFEROMETRIC DETERMINATION OF TEMPERATURE IN A LAMINAR JET OF ARGON OR NEON PLASMA

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A Mach-Zehnder interferometer and an He-Ne laser were used in determinations of the temperature in a laminar jet of argon or neon plasma achieved in a plasmotron. Presented here are the measuring technique, the equipment used and the numerical method of analyzing the interferograms of the jets of axial symmetry.

Introduction

Determination of the refractive index of a gas or plasma provides information on the density of the examined medium, what may constitute the basis for a determination of its temperature, degree of ionization, or velocity.

A precise measurement of the index of light refraction in a jet of gas or plasma is possible by using the interferometric technique. Recent years have brought renewed attention to this old method, developed in the seventies of the last century by E. Mach and L. Mach. This is associated with the achievement of strong monochromatic sources of light — lasers — which improve the precision of measurements pronouncedly and make possible the acquisition of high orders of interference and, hence, the observation of regions of gas or plasma with very different refractive indices.

This method is accurate enough for large and homogeneous regions of gas or plasma. In practice, however, the objects under observation are often jets of diameters from several millimeters to several centimeters, and inhomogeneous as regards temperature. In this case the interferometric technique of gas or plasma diagnosis may prove to be rather inaccurate owing to the considerable participation of the cooler external layers.

This author was interested in the low-temperature part of a laminar jet of argon or neon plasma obtained in a plasmotron [1], [2].

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Equipment and results of measurements

The applied Mach-Zehnder interferometer was an instrument of medium size, manufactured by the French firm SOPRA. It consisted of two mirrors, L_1 and L_2 (Fig. 1), of a useful diameter of 52 mm, what ensured a theoretically possible observation of an elliptic zone of the dimensions: 52 mm major axis and 36 mm minor axis. The mirrors and semitransparent platelets were set precisely at an angle of 45° with respect to the incident light. The technique of making the setting and control of the Mach-Zehnder interferometer, and its theoretical basis as well, are given in many publications such as those cited by this author [3], [4], [5].

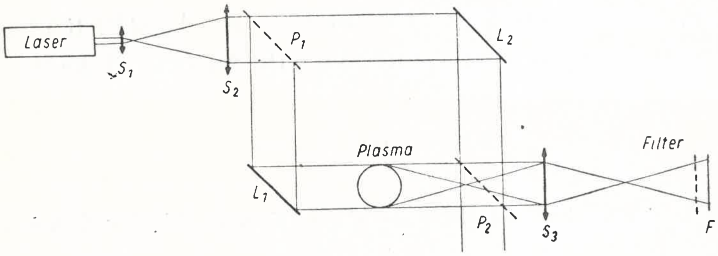

Fig. 1. Diagram of Mach-Zehnder interferometer adapted for determinations of refractive index of plasma by means of a laser

The analyzed plasma jet, perpendicular to the path of the rays in the interferometer, had a rather high brightness. It was therefore necessary to use a strong beam of laser light in order to differentiate the interference fringes from the plasma's own background. An F 9094 He—Ne laser was utilized. It gives coherent radiation corresponding to the Ne I $3s_2$—$2p_4$ 6328.17 Å line; beam diameter was $\Phi = 1.8$ mm at a power of about 25 mW.

Filling of the interferometer mirrors with laser light required the use of two lenses, S_1 and S_2, in the Kepler arrangement, *i.e.* one lens with a short focal length and the other with a long focal length, with one focus being mutual. In this way a parallel flux of laser light of diameter 32 mm was obtained. The interferometer was adjusted in such a way that with no plasma jet in its L_1P_2 arm parallel horizontal fringes were seen lying in the plane perpendicular to the direction of the laser beam. The interferometer had adjustment of the spacing between fringes and their slope with respect to the axis of the analyzed plasma. The flux of light leaving the semitransparent platelet P_2 was still parallel in the absence of the plasma, and the formed interference pattern was identical no matter what the distance of the photographic plate F was from the platelet P_2.

After inserting the plasma column perpendicularly to the path of the rays in the interferometer the fringes became curved out because of the difference in optical paths between the P_1L_2 and L_1P_2 arms of the instrument. This difference was caused by the different indices of refraction between the air and the heated argon or neon. Apart from this distortion of the fringes there also appeared a divergence of the light leaving the platelet P_2. This came about because the plasma column acted upon the previously parallel beam of light like a negative lens. The influence of this effect, not immediately evident, required the use of an additional converging lens S_3 placed at double its focal length from the plasma and also from the plate F. This allowed observation of the interference pattern in the plane of the plasma column and avoidance of a systematic error in determinations of the dimensions of this column.

Proper contrast, differentiating the interference fringes from the plasma background, was achieved by using Wratten Kodak No 29 or 92 gelatin filters. For an analysis of regions of the plasma of a higher temperature it was even necessary to use interference filters with $\Delta\lambda = 50$ Å instead of the No 29 filter. In the latter case, however, the obtained interference pattern was made more complicated by the overlapping of interferences due to the imperfect structure of the filter itself.

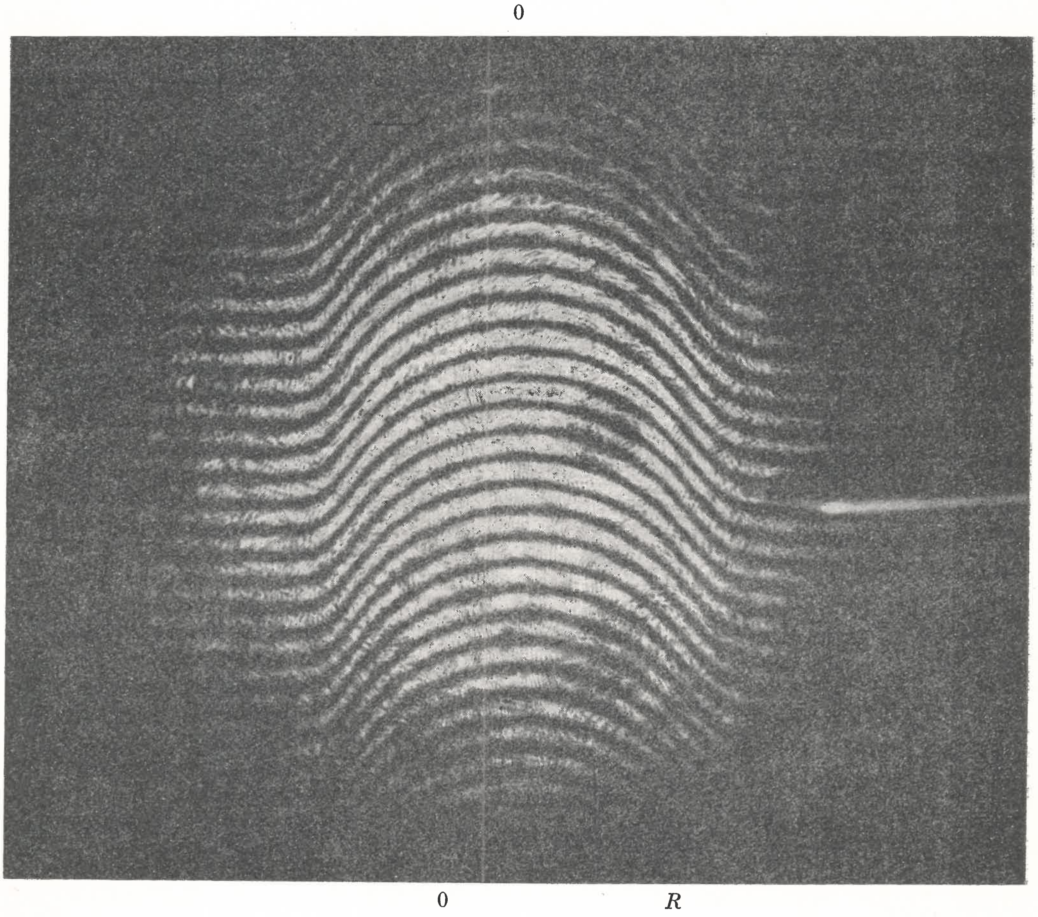

Fig. 2. Interference pattern of low-temperature argon plasma obtained with the Mach-Zehnder instrument and He-Ne laser

Figure 2 shows by way of illustration one of the obtained interference patterns. The 0—0 axis represents the direction of emergence of the plasma jet, and R is the radius of the plasma column. Figure 3 depicts the cross-section of the plasma jet (L = constant) of axial symmetry, where y is the direction of the laser beam. Such an axially symmetric jet of plasma has a variable temperature, depending on the position of the layer r. Of course, $T =$ maximum for $r = 0$ and $T = T_0$ (ambient temperature) for $r = R$. This brings about a change in the refractive index n along r. The change in optical path $\delta(x)$ at point x is, hence, given by the integral

$$\delta(x) = 2\int_0^y [n_0 - n(r)]dy = 2\int_x^R [n_0 - n(r)]\frac{r \cdot dr}{\sqrt{r^2 - x^2}} \tag{1}$$

where n_0 is the refractive index of the medium surrounding the plasma.

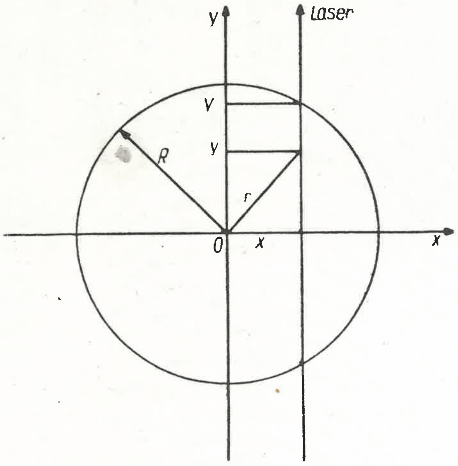

Fig. 3. Cross-section of plasma jet of axial symmetry

The change in optical path may be calculated for a given x from the phase shift $\Delta p(x)$ and wavelength λ,

$$\delta(x) = \lambda \cdot \Delta p(x) \tag{2}$$

whence

$$\Delta p(x) = \frac{2}{\lambda}\int_x^R [n_0 - n(r)]\frac{r \cdot dr}{\sqrt{r^2 - x^2}}. \tag{3}$$

If the distribution $\Delta p(x)$ is known, it is possible to find the refractive index of the plasma for each distance r from the axis. Then $[n(r) - 1]$ can be found after accounting for the refractive index of the reference medium and after application of Abel's inversion formula

$$n_0 - n(r) = -\frac{\lambda}{2}\int_r^R \frac{\frac{d[\Delta p(x)]}{dx}\, dx}{\sqrt{x^2 - r^2}}. \tag{4}$$

This equation may be easily solved by approximating $\Delta p(x)$ by a parabola, what does not always agree well with the actual run of experimental points, however. Therefore, the author solved the problem by a numerical technique, dividing the entire radius R into 25 parts and assuming that in each of these sections $T =$ constant, hence, also $n =$ constant, as was done by Pearce [6] for the case of emission of radiation from an axially symmetric medium. The use of the coefficients given by Pearce, or the somewhat modified coefficients of Bockasten [7] or Nestor [8], recommended by some authors [9], [10], proves to be unjustified, for the numerical techniques applied hitherto concern emission of light from the interior of plasma ("volume" process) and not the penetration of external radiation through a plasma column ("linear" process). This compelled the author to elaborate a numerical table. In truth, the assumptions of this numerical technique of solving problems of interferometry had been proposed earlier [11] and some calculations were even performed [12]; none the less, the numerical tables of Weyle, announced in the Physical Review [13], never appeared in this publication or any other accessible scientific publication.

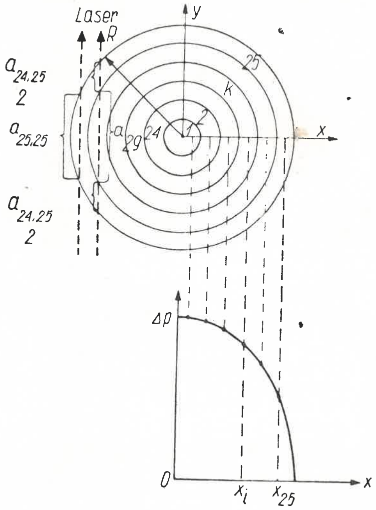

Fig. 4. Manner of dividing plasma jet into coaxial sections Δx and choosing points for numerical conversion of the dependence $\Delta p(x)$ into $\Delta p'(r)$

Let us consider the cross-section of a plasma column with $R = 25$ unit zones $\left(\Delta x = \frac{R}{25} = 1\right)$, numbered as in Fig. 4 from the center outwards 1, 2, ..., k, ..., 24, 25. Each chord led through the center of each of these zones along the direction of radiation (y) is at the same time the optical path. For example, the length of this path in the zone $k = 25$ (x_{25}), denoted as $a_{25,25}$, is

$$a_{25,25} = 2\sqrt{(25)^2-(25-\tfrac{1}{2})^2} = 9.94987.$$

At x_{24} the analyzed laser beam passes through two different media, $k = 24$ and $k = 25$, whereby

$$a_{24,25}+a_{24,24} = 2\sqrt{(25)^2-(24-\tfrac{1}{2})^2} = 17.05872$$

but

$$a_{24,24} = 2\sqrt{(24)^2-(24-\tfrac{1}{2})^2} = 9.74679,$$

and thus

$$a_{24,\,25} = 17.05872-9.74679 = 7.31193.$$

Likewise, the result of the experiment for the point x_i, where $i = 23$, is the sum of effects in the layers r_k, with $k = 23$, 24 and 25; and so on.

In order to get the numerical values of $\Delta p'$ corresponding to the individual zones k from the experimental curve $\Delta p(x)$ the procedure is as follows. The value Δp at the point x_{25} is divided by the coefficient $a_{25,\,25}$. The result ($\Delta p'_{25}$) is the phase shift per unit optical path in the zone $k = 25$. The next value, Δp_{24}, is the sum of the partial effects in the zones 24 and 25, viz.,

$$\Delta p_{24} = \Delta p'_{24}\times a_{24,\,24}+\Delta p'_{25}\times a_{24,\,25}$$

whence

$$\Delta p'_{24} = \frac{\Delta p_{24}-\Delta p'_{25}\times a_{24,25}}{a_{24,25}}.$$

Going on successively it is possible to reach right up to the center of the plasma column. The coefficients

$$a_{i,k} = 2\sqrt{k^2-(i-\tfrac{1}{2})^2}-\sum_{b=i}^{b=k-1} a_{i,b} \qquad 25 \geqslant k \geqslant i \tag{5}$$

needed for conversions, with $i = 1, 2, \ldots, 25$, were calculated by this author with the use of an Olivetti 101 computer.

The computative procedure presented here as an illustration may also be applied when the radius R is divided into less than 25 zones. Then also calculations begin with the last, external zone of the plasma.

The interference patterns of the examined plasma were photographed on panchromatic 6×9 cm Guilleminot Panchro 66 Anti-halo plates, the shutter being set at 1/30 to 1/90 second and the lens S_3 of focal length 15 cm being used. Next, the plates were magnified exactly ten times by means of an aberration-free Durst enlarger. Interference patterns which were asymmetric due to a temporary perturbation of the jet or thermal currents in its nearest neighbourhood were rejected. From the remaining ones the $\Delta p(x)$ dependences were plotted, use being made of a millimeter division (what enabled determination of Δp with an accuracy of up to 0.05 unit). Subsequently, each dependence was transformed numerically by dividing the whole into 12 to 15 zones, thus getting the $\Delta p'(r)$ values. The temperature of the surrounding air and the atmospheric pressure measured at the instant the photographs were being taken supplied information on the refractive index of the reference medium n_0 (adopted from tables). Whereby the difference made possible the calculation of n_{Ar} in the given layer r_k, and then the temperature of the layer from

$$T = T_0\,\frac{n_{\mathrm{Ar}}-1}{n_0-1}\,\frac{p_0}{p} \tag{6}$$

where n is the refractive index for argon corresponding to temperature T and pressure p.

The results of temperature determinations at the center of the jet of argon plasma ejected from the burner to the atmosphere for several L sections are depicted in Fig. 5. Attention should be turned to the fact that a jet such as this does not consist of pure argon and may contain quite large quantities of air, especially at the peripheral layers, which diffuses into the interior [14]. However, the refraction of air and argon is very similar, what ensures that there are no essential changes in the calculations. This is exhibited by

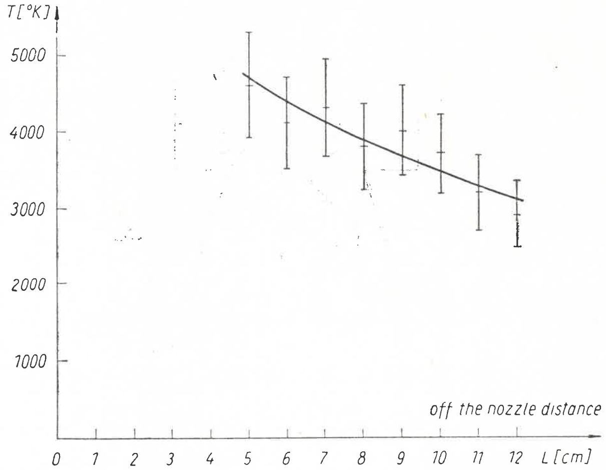

Fig. 5. Results of interferometric temperature determination at center of laminar jet of argon plasma in air

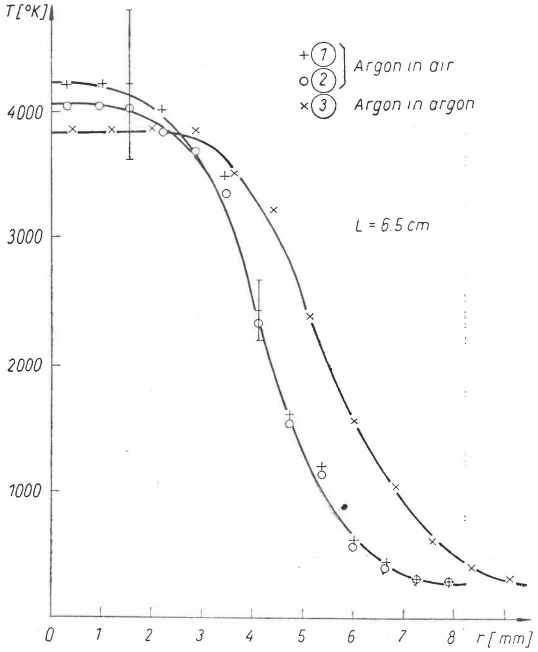

Fig. 6. Radial temperature distribution in section of laminar argon jet 6.5 cm away from nozzle mouth *1* — jet surrounded by air, *3* — jet surrounded by argon

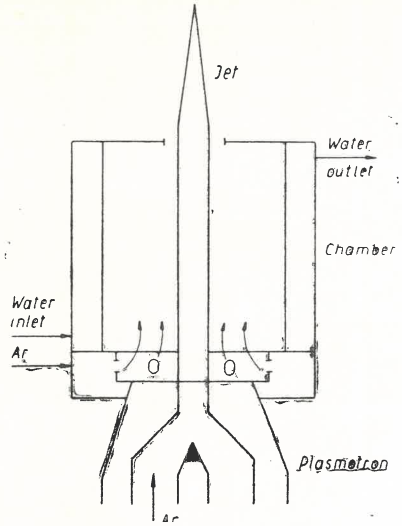

Fig. 7. Diagram of device for plasmotron preventing diffusion of air into plasma jet

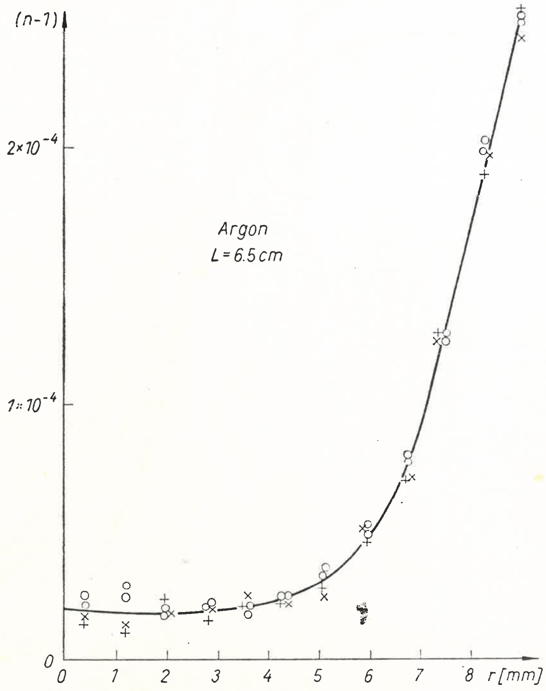

Fig. 8. Results of determinations of refractive index of argon plasma ($\lambda = 6{,}328$ Å) in section 6.5 cm away from nozzle mouth

Fig. 6, showing the radial temperture distribution in a section of the distant from the nozzle of the plasmotron by 6.5 cm. Curve *1* was plotted with the assumption that the jet consists entirely of air, whereas curve *2* is the same for a pure argon jet. It was found that the differences between these two curves are smaller than the accuracy of temperature determinations by this method.

In order to prevent any diffusion of air into the argon plasma jet a stream of cold argon (18 liters per min.) is additionally blown around the jet from the device shown schematically in Fig. 7. The region of plasma observation is just above the chamber cover, the height of which may be altered. With unchanged parameters of plasma jet generation, its features became changed enormously when the additional stream of argon was applied. Namely, the luminosity of the plasma became more intense and originated, as was proved, from the Ar I line spectrum. This brightly glowing jet of argon, and then neon, became the object of new interferometric research.

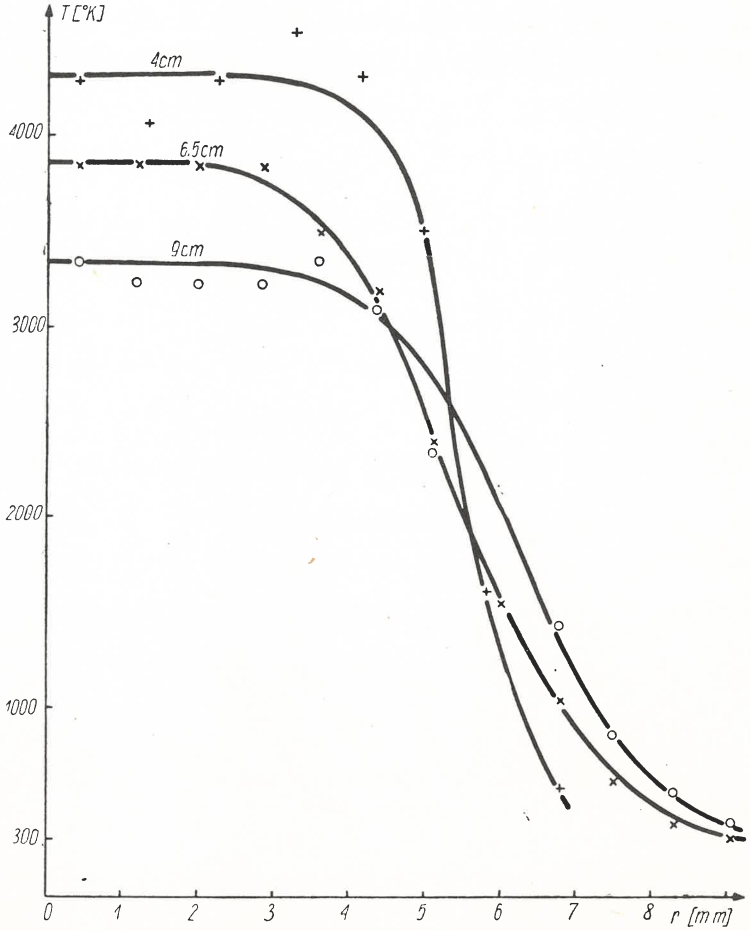

Fig. 9. Radial temperature distribution in three sections of a laminar jet of argon plasma protected by an argon envelope

It was found that the temperature at the center of the jet of such plasma remained almost unchanged, although the diameter of the jet column increased by about 30 per cent. This is substantiated by the results of refractive index ($n-1$) determinations (Fig. 8) and temperature determinations in the $L = 6.5$ cm plasma section (Fig. 6). The full results of determinations of the radial distribution of temperature in the argon plasma jet flowing into an argon atmosphere are shown in Fig. 9 for $L = 4$, 6.5 and 9 cm. The experimental points shown in Figs 5, 6, 8 and 9 represent the mean values of several or ten odd measurements.

It is seen thus that the temperature of neutral particles T_n in the analyzed 4, 6.5 and 9 cm cross-sections surely does not exceed 5000°K, although the appearance of the argon jet in an argon envelope implies an emission which is characteristic of argon heated to a temperature of the order of 10,000°K.

This author performed a similar interferometric determination of the temperature in a jet of neon plasma.

The plasmotron was fed with 99.99 per cent pure N 40 neon ("Air Liquide"). At the same time neon flowed to the chamber shielding the jet (14 liters per min.), giving in result a strongly glowing red plasma cone. To save neon gas, only the section of the jet $L = 4$ cm away from the mouth of the burner's nozzle was analyzed. At an almost constant plasmotron power (3.75 kW, 15 V, 250 A) and somewhat increased flow of neon (4 liters per min.) it was expected that temperatures similar to those for argon would be found. However, an

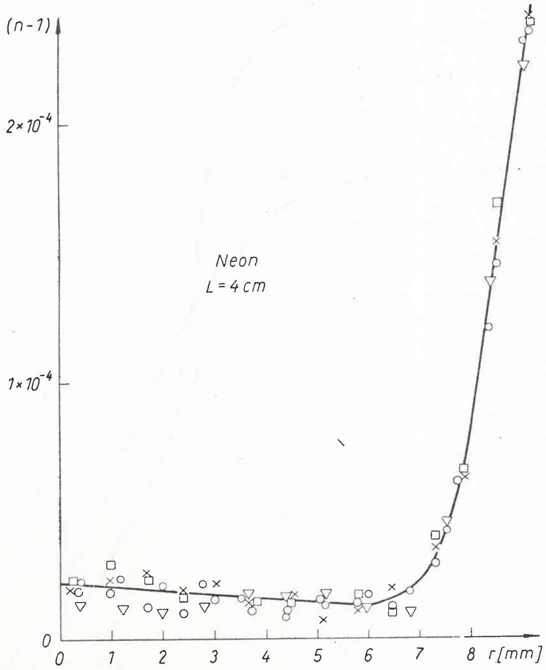

Fig. 10. Results of determinations of refractive index of neon plasma ($\lambda = 6{,}328$ Å) in section 4 cm away from nozzle mouth

elaboration of seven interference patterns showed that $(n-1)$ of the neon plasma (Fig. 10) reaches a minimum value some six millimeters away from the jet's center, after which it slowly rises. Making use of the known specific refraction of neon [15] the temperature distribution was found for the $L = 4$ cm section; it is shown in Fig. 11. Of course, the actual temperature of this neon plasma is at least 4,000°K, what implies that the measured index of light refraction $(n-1)$ is some four times larger. This may be due to absorption of the laser radiation (the $3s_2-2p_4$ line of Ne I) by the highly populated excited state $2p_4$ in the analyzed neon plasma. This would indicate lack of thermodynamic equilibrium in this plasma — and this is also supported by the luminosity of the neon jet itself, corresponding to a temperature over 10,000°K.

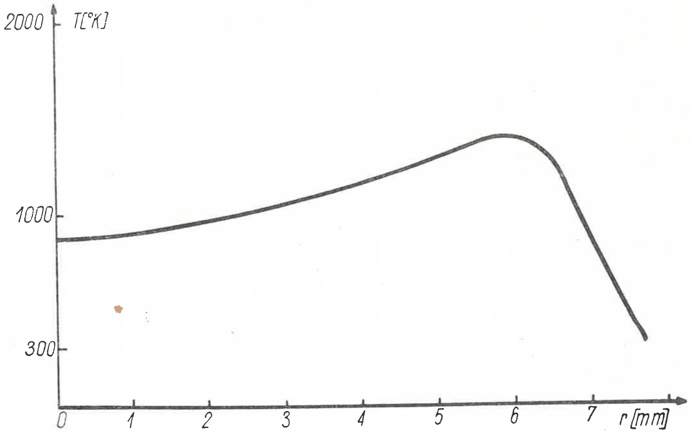

Fig. 11. Radial temperature distribution in section of laminar neon plasma jet. Distance from nozzle is 4 cm

It appears that a more exact determination of the temperature of neutral particles in the neon plasma by the interferometric method will be possible with the use of a different source of light than the He—Ne laser, what would exclude light absorption in the plasma. This problem has been recently approached at the CNRS laboratory in Orléans.

Error analysis shows that $\frac{\Delta T}{T} \sim \frac{\Delta(n-1)}{n-1}$. But the refractive index $(n-1)$ is inversely proportional to temperature T and for a fixed value of $(n-1)$ the quotient $\frac{\Delta T}{T}$ grows with temperature and may reach pronounced values at high temperatures. The error $\Delta(n-1)$ obtained after the numerical conversion $\Delta p(x) \rightarrow \Delta p'(r)$ was diminished thanks to a statistical analysis of the dispersion of a larger number of results. The error stemming from any eventual slight jet asymmetry was decreased by choosing the mean values $\Delta p(x)$. Despite this, at $T = 4{,}000$°K the accuracy of temperature determinations was about 15 per cent, what is marked out in the relevant figures.

The author expresses his sincere gratitude to Professor dr François Cabannes, director of the Centre de Recherches sur la Physique des Hautes Températures CNRS, Orléans, for attention paid to the work he carried out there. Thanks are also due to Professor dr Joseph Chapelle for advice and helpful hints during discussions.

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