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SOME EXCITATION TEMPERATURE MEASUREMENTS OF INDUCTION-COUPLED ARGON PLASMAS*

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The relative line-intensity method of measuring excitation temperature was used to find the radial temperature profile in induction-coupled argon plasmas at reduced (about 1 Torr) and atmospheric pressures. The result shows that the maximum temperature does not necessarily occur on the axis of the flow in contrast with the previous result obtained by the Larenz method, for instance. An interpretation is suggested in terms of the skin effect of electromagnetic fields.

1. Introduction. In a preceding paper [**3**], a description was made on some observation of the induction-coupled argon plasma at atmospheric pressure. Such a plasma flame may produce a contamination-free gas stream of very high temperature, and owing to this fact the inductive plasma generation is receiving much attention from the viewpoint of practical applications. For better understanding of its mechanism, however, it seems still necessary to pile up an extensive amount of experimental knowledge under diverse conditions.

In order to meet this requirement partly, the experimental apparatus has been somewhat modified and improved since the last paper. Especially, by adding a mechanically pumping system connected to the discharge tube the range of working pressure has extended down to about 1 Torr. At atmospheric pressure we have to use a "starting rod" or the like to start the discharge [**3**, **6**], while at reduced pressures the breakdown takes place immediately without the aid of such a special device.

This paper is a progress report, not a final one, on a series of experiments with argon, where the main interest has been centered in the temperature distributions of induction-coupled plasma flows. Thus, some excitation temperature

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measurements by means of the relative line-intensity method will be described below for several experimental conditions at reduced and atmospheric pressures.

2. Experimental Apparatus. The general schematic of the experimental apparatus is shown in Fig. 1. High-frequency power is supplied by a 30 kw tuned-plate

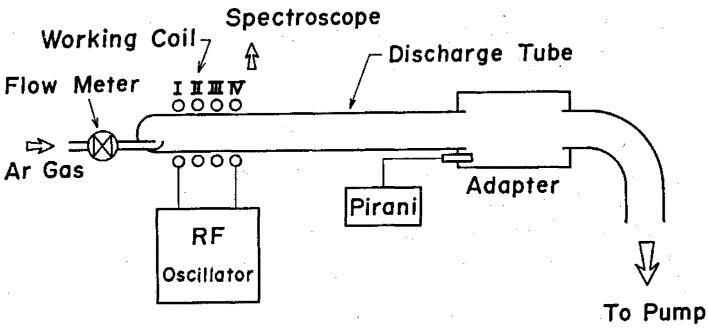

Fig. 1. Schematic diagram of apparatus for reduced-pressure experiments.

oscillator (Kokusai Electric Co., Ltd., Japan), which operates at a frequency near 3 MHz usually. However, under certain conditions of the oscillator circuit one can make experiments at about 11 MHz also, though high power levels are not attainable in that case. To the oscillator is connected an 80 mmϕ four-turn rf solenoid of 7 mmϕ Teflon coated copper tubing.

The pumping system consists of a rotary pump and a mechanical booster pump joined to the discharge tube via a dust trap and an adapter. The effective pumping speed is about 20,000 l/min at 1 Torr and 3,000 l/min at 760 Torr. For determination of the pressure, a pirani gauge calibrated by a MacLeod gauge is conveniently used.

In the present experiment the discharges were produced for the most part in Vycor tubes of 2 m long, and 65 mm, 45 mm, 25 mm, respectively in diameters, at reduced pressures. The rf solenoid was placed about 30 cm downstream from the upstream end of the tube where the working gas was fed either tangentially or axially. Because the wall of the tube was not cooled in this arrangement, the operation had to be limited to lower power levels only. At atmospheric pressure, on the other hand, use was made of a water-cooled quartz tube with a tangential inlet such as previously explained [**3**].

In order to measure the relative intensities of argon spectral lines, a diffraction grating 1.0 m spectroscope (type GE-100, Shimadzu Seisakusho Ltd., Japan) was used throughout. The spectroscope was installed with a Bausch & Lomb plane grating (1,200 lines/mm) mounted in the Ebert manner [**1**] ; the dispersion was 8.3 Å/mm for the first-order spectrum. The spectral intensities were converted photoelectrically to electric signals to be amplified and recorded. Figure 2 shows the measured spectral sensitivity of the photomultiplier (RCA 1P 28). In passing, the spectroscope was placed on a traversing carriage driven by a screw mechanism.

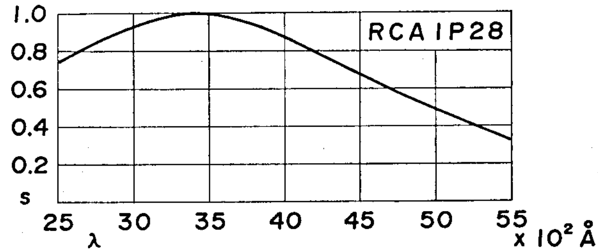

Fig. 2. Relative spectral sensitivity *s* of photoelectric system.

3. Types of the Discharge at Reduced Pressures. According as the gas flow rate, pressure, dimensions of the tube, power level, working frequency and other factors, various types of the discharge could be observed in argon flows at reduced pressures (1 to 10 Torr). Among them the measurements were primarily concerned with the two distinct ones in particular : the *ring discharge* and the *column discharge*, say, both of which were sufficiently steady in time.

The ring discharge could be typically produced at 11 MHz band and in the 65 mmϕ tube within a certain lower range of the flow rate (below 0.5 g/s). Being characterized by a luminous ring concentric with the working coil, it closely resembled that described in the early work of J. J. Thomson [7] (Photo. 1). As the flow rate increased from the optimum range the ring became unsteady and less sharply outlined. Either at 3 MHz band or in the finer tubes, this type of the discharge could not be observed.

The column discharge, on the contrary, could be maintained under wider experimental conditions covering 3- and 11 MHz bands as well as 25 mmϕ to 65 mmϕ discharge tubes. In this type of the discharge, the luminous column extended streamwise, especially downstream, with general features rather similar to the plasma-torch flame at atmospheric pressure [3][1] (Photos. 2 to 4).

4. Excitation Temperature Measurements. Considering that the assumption of

1) At reduced pressures, however, the vortex-stabilization effect confirmed at atmospheric pressure [3] was observed to be of minor importance.

thermal equilibrium between electrons and heavy particles is hardly valid at reduced pressures, the gas excitation temperature was measured by means of the relative line-intensity method which only assumes the Maxwell-Boltzmann law of distribution among the number densities of the different excitation levels. The principle and technique of this method are not repeated here in detail ; they will be found elsewhere, e.g., [**1**, **5**].

The gist is that under the assumption cited above the spectral intensity I_{nm} (of the frequency ν_{nm} or the wave-length λ_{nm}) associated with the transition $n \rightarrow m$ of the energy levels is related to the excitation temperature T_{ex} in such a manner as

$$I_{nm} = Kg_n A_{nm} \nu_{nm} \exp(-E_n/kT_{\text{ex}}), \tag{1}$$

that is,

$$\log_e \left(\frac{I_{nm}\lambda_{nm}}{K' g_n A_{nm}} \right) = -\frac{E_n}{kT_{\text{ex}}}, \tag{2}$$

where k is the Boltzmann constant, A_{nm} the transition probability, E_n and g_n are the energy and the statistical weight respectively characterizing the level n, and K, K' are certain constants independent of n and m. Thus a logarithmic plot of the quantity $I_{nm}\lambda_{nm}/g_n A_{nm}$ (in arbitrary unit) for a number of spectral lines versus E_n yields a straight line whose negative slope $(kT_{\text{ex}})^{-1}$ will determine T_{ex}. Available data of the atomic parameters including the experimental values of A_{nm} have been published by several authors. Among them the transition probability data for argon neutral lines ArI compiled in [**1**] were referred to in the present work.

Now, in Eq. (1) or (2), one has to use the spectral intensity at one point, not the measured integral intensity $J_{nm}(x)$, to find the spatial distribution of the temperature. With the assumption of axisymmetry and negligible self-absorption, the radial intensity profile $I_{nm}(r)$ is given by an integral equation of Abel type :

$$J_{nm}(x) = 2\int_x^R \frac{I_{nm}(r)r}{(r^2-x^2)^{1/2}}\, dr \tag{3}$$

at each cross-section (Fig. 3). Practically, $J_{nm}(x)$ was measured at a constant interval of $\Delta x = 2$ mm and the computation of $I_{nm}(r)$ in terms of $J_{nm}(x)$ was performed numerically after the standard scheme [**4**]. Because of various errors to be enumerated later some scatter was inevitable in the relative-intensity plot of the experimental points thus obtained, and therefore the "best slope" was determined with the aid of the least square method.

The similar excitation temperature measurements were made at atmospheric

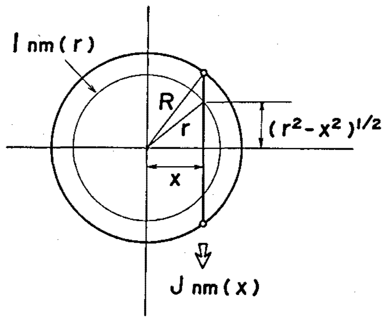

Fig. 3. Local and integral spectral intensities for axisymmetric plasma.

pressure as well, although the assumption of thermal equilibrium may be a good approximation there [**6**].

5. Results. Among the experimental results obtained under various working conditions, the four typical cases (Table 1) are presented here in particular.

No.	(a) MHz	(b) Torr	(c)	(d)	(e) mmϕ	(f) g/s	(g) kV	(h) Å
1	11.0	0.7	Ring	Vycol	65	0.45	3.5	3948, 4044, 4159 4164, 4182, 4198 4201, 4251, 4259 4266, 4272, 4300 4344, 4345
2	2.8	0.7	Column	Vycol	65	0.24	3.5	
3	2.8	1.0	Column	Vycol	25	0.62	3.5	
4	2.8	760	Torch	Quartz	30	0.15	5.0	4159, 4198, 4201 4259, 4266, 4272

Table 1. Working conditions for typical examples.
(a) : Frequency. (b) : Pressure. (c) : Type of the discharge.
(d) : Material of the tube. (e) : Inner diameter of the tube.
(f) : Mass flow rate. (g) : Plate voltage of the oscillator.
(h) : Measured spectral lines ArI.

In the ring discharge (Fig. 4) the maximum temperature occured at about 10 mm from the center ($r/R \sim 0.3$) in rough accordance with the visual observation; namely, the temperature profile also was found to be a ringlike one. It is interesting to note that apart from some secondary irregularities and complications the essentially similar feature was seen in the column discharge also at and near the coil-sections (Figs. 5 to 7). However, as one proceeded downstream,

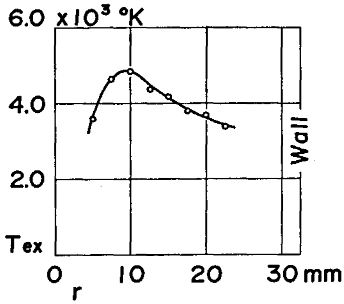

Fig. 4.- Radial temperature profile of ring discharge plasma (Run No. 1 of Table 1).

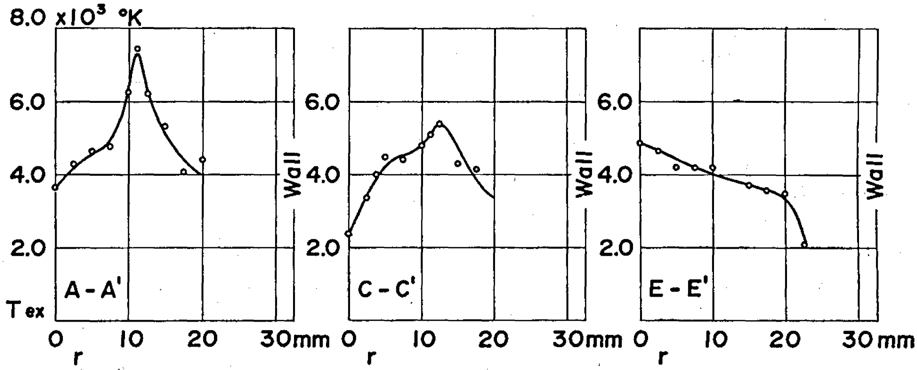

Fig. 5. Radial temperature profiles of column discharge plasma in 65 mm ϕ tube (Run No. 2 of Table 1).
See Fig. 6 for the positions of test sections; profiles at B-B′ and D-D′ sections are not reproduced here.

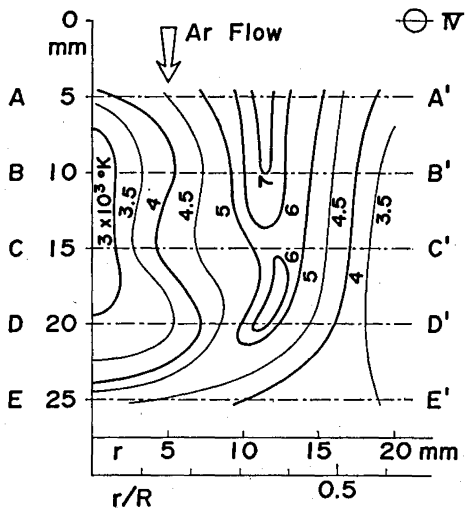

Fig. 6. Isothermal lines corresponding to Fig. 5.
Axial positions are measured from the coil IV-section; the radial position of the coil is not to scale.

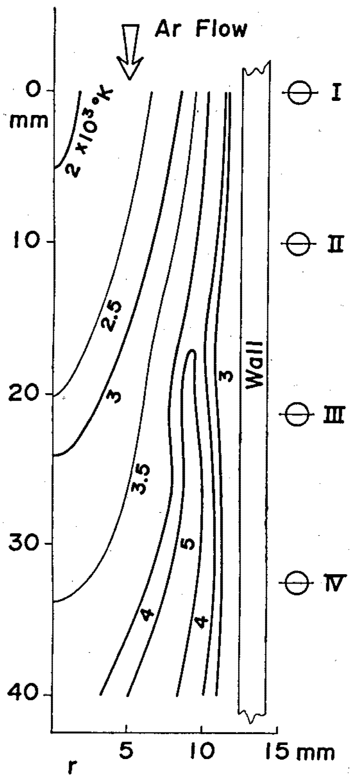

Fig. 7. Isothermal lines of column discharge plasma in 25mmϕ tube (Run No.3 of Table 1).
Axial positions are measured from the coil I-section.

the radial temperature profile turned to a monotonic one with its vertex on the axis of the tube. Figures 6 and 7 are the isothermal lines summarizing the profile measurements. Even at atmospheric pressure the same tendency was observed contrary to Reed's result obtained by the Larenz method [6] (Fig. 8).

6. Discussion and Remarks. With regard to the present experiment there are various sources of errors associated with the measurements. Especially, the followings may be of prime importance : (i) errors in measuring the intensity $J_{nm}(x)$, (ii) errors in the numerical treatment of Eq. (3), (iii) the neglect of self-absorption, (iv) errors embodied in the experimental values of A_{nm}, (v) deviations from axisymmetry of the plasma. They are roughly estimated to be less than 10 % for (i) to (iii) and sometimes more than 20 % for (iv) and (v), but the quantitative conclusions must wait on future closer examinations.

Nevertheless, it seems a new finding at least qualitatively that the maximum temperature of an induction-coupled plasma flow does not necessarily occur on the axis in apparent contrast with the case of dc or

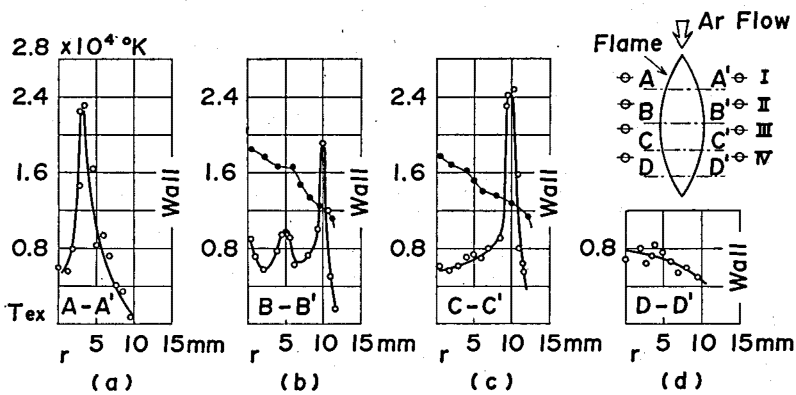

Fig. 8. Radial temperature profiles of plasma-torch flame (Run No. 4 of Table 1) with indication of test sections.
——○—— : relative line-intensity method,
——●—— : Larenz method (4201Å)

ac discharges such as an arc jet, e.g., [4]. This fact may perhaps be attributed to the skin effect which is well-known in the induction heating of conducting bodies by rf electromagnetic fields. In the presence of a conductor the fields can not penetrate into its interior beyond a certain thin layer beneath the surface. The thickness of this layer is represented by the "skin-depth":

$$r_{*} = (2\omega\mu\sigma)^{-1/2} \tag{4}$$

for a uniform conductor, where ω $(=2\pi f)$ is the angular frequency, μ the magnetic permiability and σ the electric conductivity[2]. Though σ is not a constant but varies from point to point in non-isothermal plasmas, Eq. (4) may still serve as a rough estimate of the skin depth characterizing this effect. If $\sigma \sim 10^2$ mho/m is assumed for the time being, r_{*} is of the order of 1 cm when $f=$ 3MHz.

Under these circumstances, the use of the Larenz method [2, 4] for temperature measurements would lead to fallacious results, since it assumes a monotonically decreasing temperature profile in addition to a thermal equilibrium. Figures 8 (b) and (c) also show, for illustration, the corresponding results obtained by an application of the Larenz method; they are quite different from those by the relative intensity method. Because of the thermal conduction and heat transfer, however, such a wavy temperature profile cannot be permanent, and thus it is not surprising that the profile becomes monotonic downstream. Some analytical studies of these effects are now in progress.

Finally, it should be noted again that the present measurements were solely concerned with the excitation temperature T_{ex}. At atmospheric pressure T_{ex} may safely be identified with the gas temperature T_g [6], while at reduced pressures one must be extremely cautious in making a guess on relations between T_{ex} and T_g and/or the electron temperature T_e.

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2) MKSA-units are used here. Hence $\mu = 4\pi \times 10^{-7}$ henry/m is to be understood in plasmas as well as in a vacuum.

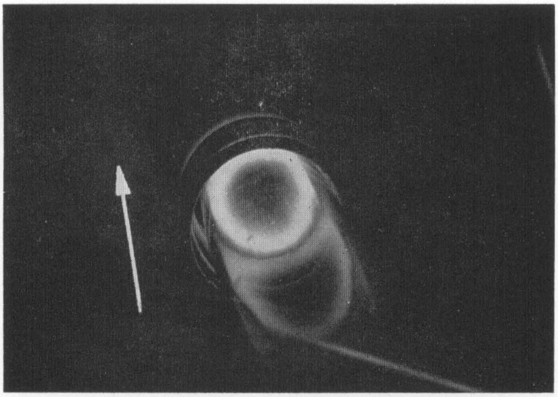

Photo. 1. Ring discharge. (Here and hereafter arrows indicate the direction of the main flow.)

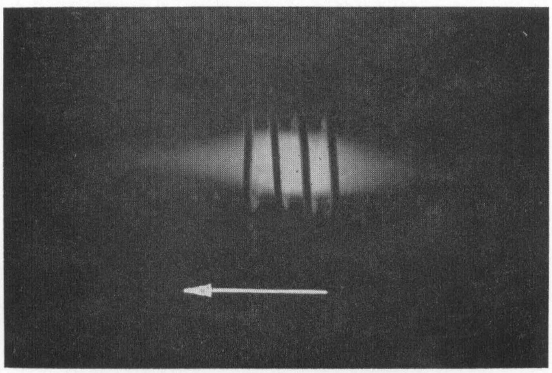

Photo. 2. Column discharge in 65 mmϕ.

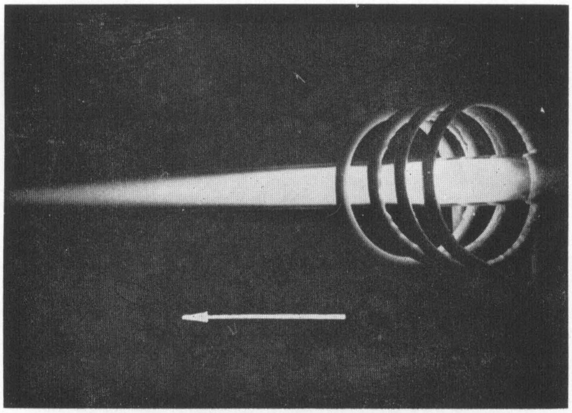

Photo. 3. Column discharge in 25 mmϕ.

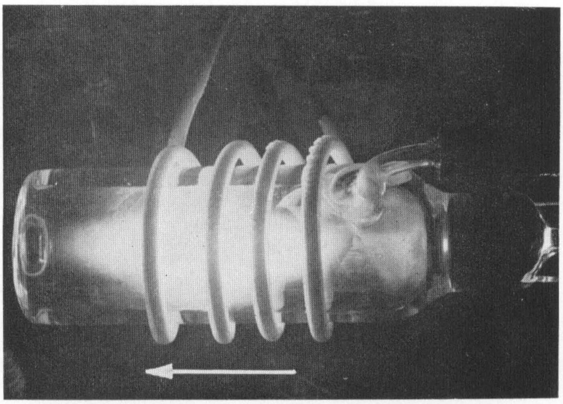

Photo. 4. Plasma-torch at atmospheric pressure.

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