Measurements of Spectral Emission and Absorption of a High Pressure Xenon Arc in the Stationary and the Flashed Modes

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Concurrently with emission measurements of a high pressure xenon arc in the spectral range 3000 Å to 2 μ, its absorption in the ir was measured by a technique based on modulating the less intense radiation of a carbon arc used as background source. The emission measurements were repeated with a rapid scanning spectrometer while flashing the xenon arc for 0.1 sec at 10 kW, which is five times the normal power input. The arc showed excellent stability and reproducibility both in the stationary and the flashed modes. The intensity increase of the continuum was proportional to the increase of power input during the flash. A simple expression was derived connecting the spectral radiance of the continuum directly with the temperature and pressure of the arc. The temperature profile of the xenon arc was obtained using this expression and also by applying the Planck-Kirchhoff method to the Abel inverted emission and absorption of an ir xenon line. Both approaches show fair agreement at the arc center. The wavelength dependence of the correction factor for departures from hydrogenic behavior of the xenon continuum was derived from the measured spectral radiances and compared with theoretical calculations.

I. Introduction

Emission spectra are extensively used in plasma diagnostics, but only rarely is the absorption of arc plasmas measured quantitatively. One reason seems to be the widely held opinion that arc plasmas at atmospheric pressure viewed over short optical paths are always optically thin, except for the resonance lines. Another reason is the difficulty of finding a suitable background source for absorption measurements. Laboratory plasmas, typically at 10,000°K are so much brighter than the brightest light sources commonly available (e.g., carbon arc or tungsten strip lamp), that the latter are unsuitable. Finally, the methods for deriving the radial distribution of emission and absorption coefficients of optically thick arc plasmas from line-of-sight measurements have been slow to develop, and this has limited the value of absorption spectra for plasma diagnostics. Freeman and Katz were the first to obtain a practical solution for the Abel inversion of plasmas with self-absorption,[1] but a more general approach was only recently found by Elder *et al.*[2] Elder *et al.* also derived the radial temperature profile by the Planck-Kirchhoff method from the Abel inverted emission–absorption measurements. To demonstrate their method, Elder *et al.* used a plasma seeded with sodium and determined the temperature from a sodium resonance line. The peak temperature was below 3000°K, which is not typical for a laboratory plasma.

Tourin[3] found that the strong ir lines of argon can become optically thick (self-absorbing) at atmospheric pressure. He measured the absorption by a technique based on modulating the radiation from the background source; thus, absorption measurements can be made even when the intensity of the plasma is higher than the intensity of the background source. For the measurements reported in Ref. 3 a tungsten strip lamp could be used, because the mismatch of intensities in the ir is less than at shorter wavelengths. If absorption measurements of plasmas are to be extended into the visible or uv regions of the spectrum, however, a much brighter light source has to be used.

The high pressure xenon arc appears to have the desired characteristics. Since the early measurements of Baum and Dunkelman,[4] its strong continuum in the uv and visible part of the spectrum is known to be considerably more intense than the radiation from the carbon arc. Goncz and Newell's[5] recent work with stationary and flashed xenon arcs covers a more extended spectral range. However, their data were obtained by measuring the spectral irradiance from these arcs and are therefore of limited value for a background source evaluation, where the spectral radiance of the brightest part of the arc is the parameter of interest. The peak temperature of a high pressure xenon arc has been determined by Kopec[6] from wavelength scans of two ir lines, using Bartels' method[7] to estimate the peak temperature of an inhomogeneous plasma from line-of-sight emission measurements of lines showing self-reversal.

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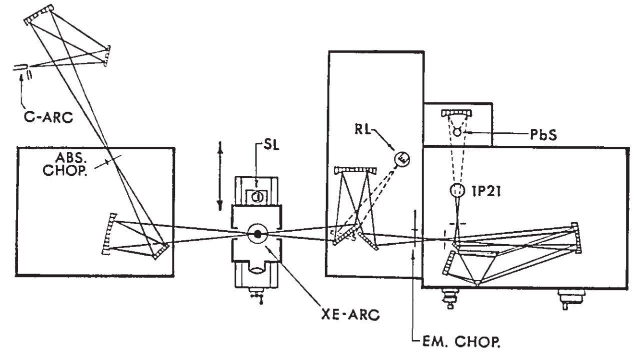

Fig. 1. Optical system used for concurrent measurements of emission and absorption of the stationary xenon arc.

The absorption of a xenon arc has been measured by Rovinskii and Razumtseva,[8] using another xenon arc as a background source. They determined the plasma to be optically thick, but, because of the use of interference filters instead of a monochromator, their measurements were of poor spectral resolution and limited to three wavelength bands in the visible.

It was the primary purpose of the work described here to measure by a refined technique the spectral absorption of the high pressure xenon arc and, simultaneously, its emission. The temperature could then be derived by the Planck-Kirchhoff method. Local values for homogeneous zones of the plasma were obtained by Abel inversion, applying the technique of Elder *et al.*[2] to the absorption measurements. A consistency check was made by comparing the temperature profile of the arc obtained by the Planck-Kirchhoff method with the temperature profile derived independently from the emission measurements of the continuum using the modified Kramers-Unsoeld theory. Since the xenon plasma is optically thick, recourse to seeding as in the work reported in Ref. 2 was unnecessary. Because of its high electron density, the xenon plasma can be expected to be in strict local thermodynamic equilibrium. Thus, these measurements should provide a good case for comparing the emission–absorption method with established diagnostic techniques for plasmas based only on emission.

Concurrently with this program, the spectral radiance measurements were used to evaluate the xenon arc as a background source for absorption measurements of plasmas. We selected a commercially available high pressure xenon arc* since, as a distinct advantage, this lamp can be flashed at ten times the normal power input for pulse durations of the order of a tenth of a second. The increase of spectral radiance was measured with a rapid scanning spectrometer developed in this laboratory.†

* Hanovia 491C39.

† Warner & Swasey Model 501 rapid scanning spectrometer.

II. Experimental

The optical system used for the measurements of the stationary arc is shown schematically in Fig. 1. The xenon lamp housing was mounted on a linear drive table for traversing the arc laterally to the optical axis with a precision of 0.01 mm. Through circular openings in the lamp housing on the two sides along the optical axis, light from the background source could be focused on the xenon arc, and the light emerging from the arc was collected by the foreoptics and focused on the entrance slit of the monochromator. For emission measurements of the arc in the stationary mode, a chopper placed in front of the entrance slit was used; for absorption measurements another chopper modulated only the radiation from the background source. By synchronous rectification of the ac signal from the detector, absorption was measured without interference from the dc signal due to the emission from the xenon arc. This technique of concurrent measurement of emission and absorption has been described in greater detail by Tourin.[9]

The conversion of detector output into units of spectral radiance was achieved by calibration against a tungsten strip lamp, done in two steps. A tungsten strip lamp, held at a constant voltage, was used as a reference lamp and incorporated into the foreoptics of the Perkin-Elmer monochromator (*RL* in Fig. 1). This type of lamp is also a standard component of the Warner & Swasey Model 501 rapid scanning spectrometer used in conjunction with the flashed xenon arc. The reference lamps can be imaged onto the entrance slit simply by rotating a mirror and their signal compared with the signal for the arc. This is done immediately after each measurement to eliminate errors due to changes in slit setting or electronic drift. From time to time the reference lamp is checked, in turn, against another strip lamp, which is positioned at the same location as the arc and whose spectral radiance is determined, following standard practice, from its

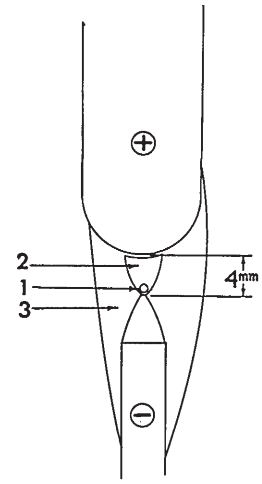

Fig. 2. Zones of different brightness in the high pressure xenon arc: (1) cathode spot, (2) arc plasma, (3) red halo.

temperature accurately measured with an optical pyrometer. It has been our experience that this procedure increases the ease of intensity measurements without loss of accuracy.

The image of the xenon arc projected on a screen appears to the eye as shown in Fig. 2. A small area of intense brightness—the cathode spot—is discernible within the bell-shaped arc plasma. A dim reddish glow partially envelopes the cathode and extends from the cathode to the round tip of the anode. This phenomenon to which no reference in the literature could be found, is called here *red halo*. It has the characteristic of being asymmetric with respect to the arc axis and this asymmetry appeared always at the same location when the arc was started. When the arc is turned off, the red halo does not disappear instantly as does the bright central arc region, but persists over several seconds. We believe that it originates from convectively heated xenon gas streaming upwards from the white hot cathode.

Our measurements were made in a horizontal plane through the arc containing the cathode spot, i.e., the hottest region of the xenon plasma. The entrance slit of both the spectrometers used was masked to a height of 0.25 mm, since spatial scanning of the arc in the vertical direction had shown that near the center, i.e., in the region of major interest, intensity gradients over this length were still small.

In the stationary mode the arc was run at a current of 100 A at 22.5 V. A welder rectifier with line voltage compensator and ripple filter* proved to be a convenient and stable power supply. By displaying the output of the two detectors (1P21 and PbS) on an oscilloscope, the ac ripple of the light intensity was measured to be less than 2% in both cases. If started from cold, the arc reached a stable regime in about 5 min, then the long term drift measured over 30 min was of the order of 1% for the peak of Xe I 9923 Å, and less than 5% for the continuum at 5000 Å. When the arc was extinguished and restarted with the current control of the rectifier at a fixed position, spatial scanning of the arc proved that the cathode spot always formed at exactly the same location with very good repeatability of light intensity (typically to within 2% for the peak of Xe I 9923 Å).

It is standard practice to use a condenser discharge for flashing the xenon arc[5,6]; the total pulse duration is then at most of the order of a few milliseconds. To make the flashed xenon arc useful as an extremely bright source for absorption measurements in conjunction with modern fast scanning spectrometers, a different approach was followed. A water-cooled stainless steel tube was used as a resistor capable of dissipating a high load and was connected to the rectifier in parallel with the xenon arc. In the *simmering* mode, 100 A flowed through the xenon arc and 450 A through the parallel resistor. A power switch was used to flash the arc by manually opening the

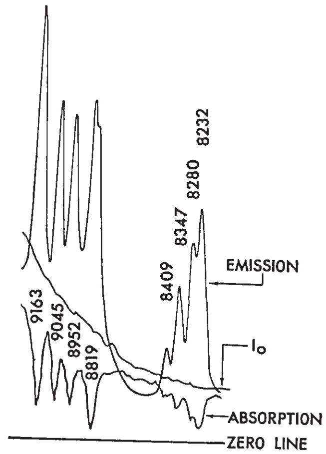

Fig. 3. Strip chart record for emission–absorption measurements of the cathode spot of the xenon arc. The gain was 20 for the emission and 350 for the I_0 and absorption scans. Slit width: 30 μ.

resistor circuit. Oscilloscope displays showed that after a fast rise time of the order of a few milliseconds, constant lamp current and voltage, i.e., a steady state, was achieved for the duration of the flash (typically 100 msec). For our measurements we flashed the lamp at 10 kW, although double this power is still permissible.

III. Measurements

A. Stationary Mode

A Perkin-Elmer Model 98 monochromator was used and the detector (1P21 tube or PbS) output displayed on a strip chart recorder. Measurements were made in the spectral range from 3000 Å to 2.7 μ, using a glass prism. Absorption measurements were made with a carbon arc† as background source. We resorted to hand regulation of the arc since the automatic regulator provided by the manufacturer was not sensitive enough for our purpose. The carbon arc operated best under the conditions recommended by Null and Lozier,[10] with a 6.5-mm thick pure graphite anode and the current held at about 11 A just below the hissing point. The use of a 6-mm diam cored cathode (Norris H), however, gave a definite improvement in arc stability over the thin (3.2-mm), pure graphite rod specified by Null and Lozier. This is in agreement with recent observations by Magdeburg and Schley.[11]

Since long term stability of the carbon arc could not be achieved, it proved advisable when measuring the lateral absorption profile, to obtain an I_0 reading in conjunction with every measurement. This was also indicated because of other considerations (see Sec. V. A). Owing to its excellent reproducibility, extinguishing and restarting the xenon arc did not alter its characteristics. A typical emission and absorption record is shown in Fig. 3. The absorptance of Xe I

* Miller SRH–444–Cl with LVC-8.

† Made by Spindler & Hoyer, Goettingen, W. Germany.

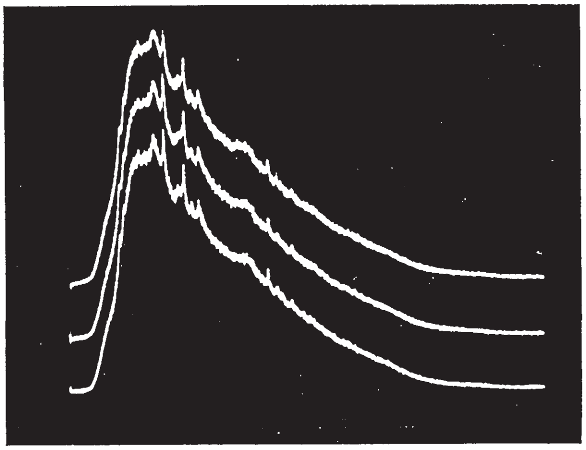

Fig. 4. Oscillogram showing three wavelength scans for a flashed xenon arc. The wavelength range 4200–6500 Å was scanned in 10 msec, using an RCA 4473 photomultiplier. Three flashes are superimposed (total of nine scans shown).

8819 Å, for instance, could be accurately measured to be 91%, although the detector signal for the peak of this line is sixty times stronger than for the carbon arc (I_0 in Fig. 3).

Because of the large number of Xe I lines in the near ir, the wavelength assignment of the lines in the spectrum of the high pressure arc proved to be difficult. Therefore, the following procedure was used: the carbon arc was replaced by a mercury arc and the spectrometer focused at the edge of the xenon arc plasma, where the temperature is lower and consequently the lines are sharper and match better the intensity of the mercury lines. With the emission chopper being used, the xenon and mercury spectra appeared simultaneously; an external wavelength standard had thus become, effectively, an internal standard. The increase in accuracy of wavelength correlation over the standard procedure based on a separately run reference spectrum permitted to assign unambiguously all spectral features of the xenon arc.

B. Flashed Mode

For the measurements of the flashed xenon arc the Warner & Swasey Model 501 rapid scanning spectrometer was used. This instrument has been described in detail elsewhere.[12] Four detectors (RCA 1P28, 4473, and 7102 photomultipliers, and an InAs photovoltaic detector) were used to scan the xenon spectrum from 3000 Å to 2 μ. Because of the availability of two exit slits, the contiguous spectral ranges for two detectors could be scanned simultaneously.

The scans were displayed on oscilloscopes and recorded photographically. An oscillogram of the flashed xenon arc spectrum in the wavelength range 4200–6500 Å is shown in Fig. 4. For this measurement, the controls of the Model 501 were set for a scanning time of 10 msec, a repetition rate of one scan each 37.5 msec, and a delay of 30 msec. Thus, the start of the first scan occurred 30 msec, of the second 67.5 msec, and of the third scan 105 msec, after the flashing circuit had been opened. Successive scans are shifted vertically upwards on the oscillogram. To test for reproducibility, the xenon arc was flashed two more times after an interval of a few seconds, and all spectra were recorded on the same photograph. In Fig. 4, each set of three superimposed traces appears as one trace, and all nine scans are identical. Thus, it is proved that the radiation from the xenon arc remains constant during a flash, and that there is excellent flash-to-flash reproducibility. The same results were obtained for two spectral ranges in the near ir from 7000 Å to 1.9 μ. When the experiment was repeated in the uv (3000 Å to 4200 Å) we detected a variation in radiant output during a flash of less than 5%.

Because of the excellent shot-to-shot reproducibility, it was possible to obtain a measure of the plasma absorptance, imaging the cathode spot back on itself by means of a spherical mirror positioned on the optical axis on the opposite side of the xenon arc from the spectrometer. A measurement of emission alone, obtained by placing a shutter in front of the mirror while flashing the arc, was followed by a measurement of emission with added back reflection during a consecutive flash. The reflection and transmission loss of the back-reflected light at the hot quartz envelope, which can be considerable, is difficult to determine. Therefore, measurements of absorption by this technique are inherently inaccurate. It can, however, be determined unequivocally for which lines the absorption is very close to 100%. Thus, the core of Xe I 8232 Å and the self-reversed peak of Xe I 8819 Å in Fig. 5 are black.

IV. Theory

Following Unsoeld's development of the classical Kramers theory, the emission coefficient (spectral radiance per unit depth) for the combined recombination (*free–bound*) and bremsstrahlung (*free–free*) continuum of an optically thin plasma, expressed in

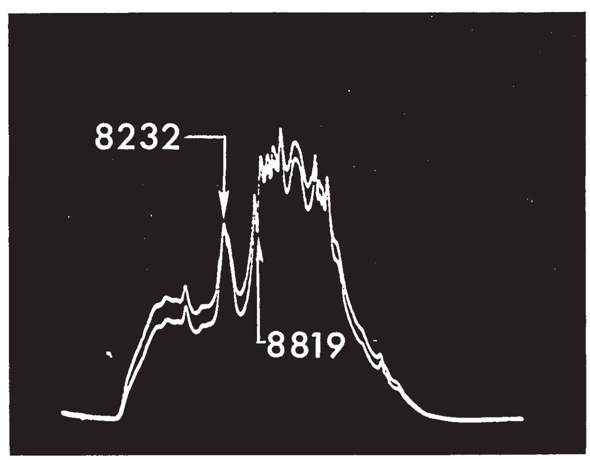

Fig. 5. Wavelength scan of the emission and emission plus back reflection from a mirror of the cathode spot of a flashed xenon arc. The wavelength range 0.7–1.2 μ was scanned in 10 msec using an RCA 7102 photomultiplier.

W $cm^{-3}\mu^{-1}sr^{-1}$, is given at wavelengths longer than a critical wavelength λ_c, by

$$\epsilon_\lambda = 1.63 \times 10^{-31}[\xi(\lambda)/\lambda^2](n_e^2/T^{\frac{1}{2}}), \quad (1)$$

with λ in μ and T in °K. In deriving Eq. (1), it has been assumed that the ionization stages beyond the first can be disregarded; then the concentration of first ions equals n_e, the concentration of electrons (condition of plasma quasi-neutrality). The factor $\xi(\lambda)$ accounts for departures from hydrogenic behavior and quantum mechanical (Gaunt) corrections. Schlueter[13] has calculated $\xi(\lambda)$ as a function of wavelength at a temperature of 14,000°K, although he found this factor to be practically temperature independent.

In the limit of vanishing ionization, Dalton's law and the Saha equation can be combined to a simple expression for the electron density as a function of the state variables T and P of the plasma. With the pressure in atm,

$$n_e = 5.953 \times 10^{18}(Q_i/Q_0)^{\frac{1}{2}}P^{\frac{1}{2}}T^{\frac{1}{4}} \exp(-E_i/2kT). \quad (2)$$

For a xenon plasma in the temperature range of 9000–14000°K, an average value of 4.44 can be used for Q_i/Q_0, the ratio of the partition functions for first ions and neutrals, since this value is constant to within 2% in this range, and its pressure dependence is also very small.[14] Substituting n_e from Eq. (2), with the ionization energy E_i = 12.127 eV (Ref. 14), the emission coefficient for the continuum of a xenon plasma (in $Wcm^{-3}\mu^{-1}sr^{-1}$) is given, approximately, by:

$$\epsilon_\lambda{}^{Xe} = 2.57 \times 10^7 \frac{\xi(\lambda)}{\lambda^2} P \exp(-140{,}760/T). \quad (3)$$

In order to assess the validity of this expression, we have calculated the electron density for a xenon plasma at 16 atm pressure, using Eq. (2) as compared with the electron density calculated more rigorously using Unsoeld's and also Ecker and Weizel's approach[14] to obtain the lowering of the ionization potential in a plasma. It appears that up to the temperature reached in a high pressure xenon arc (below 12,000°K), the departure of n_e [Eq. (2)] from n_e (Unsoeld) is smaller than the discrepancy between n_e (Unsoeld) and n_e (Ecker and Weizel). Since there exists no general agreement as to which theoretical approach gives the best quantitative estimate of the lowering of the ionization potential, the inaccuracy in n_e of less than 20% at the lower temperatures, introduced by the simplifications used in deriving Eq. (2), is of the same order of magnitude as the theoretical uncertainties. Recourse to an elaborate calculation seems therefore hardly to be justified, and, because of its simplicity, Eq. (3) is useful for obtaining the temperature directly from the measured emission coefficient if the pressure is known. The temperature derived by this method is quite insensitive to relatively large errors in the emission coefficient. Thus, it follows from Eq. (3) that an error of 40% results in an error of only 3% in temperature at 11,000°K, the peak temperature of the stationary xenon arc, and is still less at lower temperatures.

It follows from Eq. (1) that $N_\lambda{}^0$, the spectral radiance of the continuum measured through the center of an optically thin cylindrical symmetrical xenon plasma of radius R, is given by

$$N_\lambda{}^0 = \int_{-R}^{R} \epsilon_\lambda(r)dr = C\,\frac{\xi(\lambda)}{\lambda^2} \int_{-R}^{R} \frac{n_e^2[P,T(r)]}{T^{\frac{1}{2}}(r)}\,dr. \quad (4)$$

Unlike the case of line radiation, the integral containing the temperature gradient is not a function of wavelength. Since the $\xi(\lambda)$ factors are practically temperature independent, relative experimental values for these factors can be obtained directly from line-of-sight measurements of an optically thin plasma. If the temperature profile and the pressure are known, the spectral radiance measurements of the continuum have to be inverted only for one wavelength in order to obtain the $\xi(\lambda)$ at the other wavelengths without an Abel inversion. The line-of-sight measurements are conveniently related to the emission coefficients at the center of the arc by introducing the equivalent optical pathlength L:

$$L \equiv [N_\lambda{}^0/\epsilon_\lambda(r = 0)]. \quad (5)$$

From an Abel inversion at one wavelength λ_1, ϵ_{λ_1}-$(r = 0)$ is derived; thus, L can be calculated and used in turn to derive the emission coefficients at other wavelengths.

The Abel inversion of cylindrically symmetrical plasmas is a straightforward procedure, provided the plasma is optically thin. Different numerical methods are available; we prefer the one proposed by Barr,[15] which combines effective smoothing of small random errors with ease of computation. If the plasma is optically thick, but its minimum measured transmittance higher than about 70–80%, a simple correction procedure suffices. Thus, each intensity measurement has only to be divided by the square root of the transmittance measured along the same line of sight, otherwise the Abel inversion proceeds as in the optically thin case [see Eq. (4) in Ref. 2]. If the transmittance is lower, accurate values of the radial intensity distribution can only be obtained by iteration.[2]

The measurement of plasma absorption is important not only for correcting the emission measurements. If the absorption measurements are also Abel inverted, the radial distribution of emission and absorption can be used to derive the temperature profile of the plasma from first principles (the Planck-Kirchhoff law). In the case of strongly absorbing lines, however, Elder *et al.* in Ref. 2 point out difficulties in performing the Abel inversion of the measured absorption, if monochromators of only moderate wavelength resolution are used. In effect, for large variations of transmittance over the spectral slit width $\Delta\nu$, the approximation used,

$$\log\left(\frac{1}{\Delta\nu}\int_{\Delta\nu} \tau(\nu)d\nu\right) \simeq \frac{1}{\Delta\nu}\int_{\Delta\nu} \log\tau(\nu)d\nu, \quad (6)$$

is valid only if the transmittance $\tau(\nu)$ is larger than about 70% for all frequencies in the internal $\Delta\nu$.

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