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Spectrographic Investigation of the Ignited Mode of
Thermionic Converter Operation*

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Walter H. Reichelt
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

84796

MASTERABSTRACT

Electron temperature and ion density profiles across the interelectrode gap of a thermionic diode have been determined spectrographically. The diode was operating in the ignited mode and profiles were determined for a number of points on the I-V curves in both the power and non-power quadrants. Tungsten emitter temperatures were 1705°K, 1800°K, and 1910°K and the cesium reservoir temperatures were 548°K, 573°K, and 598°K. The current densities ranged from 2 amps/cm² to 10 amps/cm² for the cell spacing of 1 mm. The electron temperature and density values generally decreased toward the collector from a maximum near the emitter of 3200°K and 2 to 5 x 10¹⁴ ions/cm³, respectively.

Introduction

The current-voltage characteristics of low temperature thermionic converter operation display what is commonly referred to as the ignited mode in certain operating regimes. Onset of this mode is evidenced on the current-voltage curves by an abrupt departure from the space charge limited mode characterized by a small change in cell current with a change of cell voltage to a mode characterized by a much larger change in cell current for an equal change in cell voltage. The abrupt change is illustrated on the characteristic curves shown in Figures 5, 6, 7 and 8. This ignited mode is also characterized by a visible glow at the emitter side of the interelectrode gap. (1) Large power outputs from the converter operating in this mode have created a great deal of interest and many authors have concerned themselves with analyses of the mode. (2-9) Many approaches are based on E. O. Johnson's investigation of low voltage, hot cathode arcs. (10) Very little detailed information (1,6,11) has been available on the actual values of electron temperatures and ion densities in the plasma, information which is necessary to indicate the merits of the theories and provide data for future studies. In this paper, a mapping of the electron temperatures, (T_E), and ion densities, (N_i) in the interelectrode gap of a cesium thermionic converter operating in the ignited mode is reported for a variety of cell conditions.

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Spectrographic methods have been employed to provide quantitative values of the free electron* temperatures and ion densities in a manner described by Agnew (12) and Agnew and Stone, (14) respectively. The temperature and density profiles across the interelectrode gap are reported for a series of points on the current-voltage curves in both the power and non-power quadrants at a cell spacing of 1 mm. Electrostatic probe techniques such as those employed by Bullis and Wiegand (1,6) have been used to determine the temperatures and densities in a lower cesium pressure regime than those reported in this paper. Both probe and spectrographic techniques provide independent measurements in an overlapping regime. Agreement to date is quite good.

This paper will be divided into several sections as follows: 1) a description of the experimental cell and spectrographic arrangement, 2) a description of the analyses of Stone and Agnew, 3) the procedure used in obtaining the data, and 4) the presentation of the data and discussion of results.

Experimental Apparatus

I. Thermionic Diode

The experimental cell is shown in Fig. 1. As indicated, the cell spacing is variable, the geometry planar with an emitter and collector area of 2 cm², and the cell is continuously pumped by a liquid nitrogen trapped oil diffusion pump system. A small cesium refluxing zone in the pump-out tube keeps the cesium confined to the cell proper. The pressure in the cell at operating temperatures is of the order of 5×10^{-7} Torr after appropriate bake-out procedures.

The cell body is made from nickel and type 347 stainless steel. Metal-to-metal seals provide demountable sapphire windows and cesium reservoir. The emitter and collector assemblies are also demountable; vacuum seals for these assemblies are soft-nickel plated metal "O" rings. The emitter is a tantalum button welded to a support tube. A 0.012 cm layer of tungsten was plasma jet sprayed onto the button, ground, and outgassed to 2400°K before inclusion in the cell. The emitter is heated by electron bombardment from a hot tungsten filament as indicated in Fig. 1. The collector is made from high purity nickel bar stock suitably outgassed after machining. Collector temperatures are varied by changing the pressure of the gas between the collector and the oil-filled cylinder in the collector interior. A high purity alumina insulator electrically isolates the collector from the cell body.

*The term "free electron" is used to differentiate between the free or unbound species and the bound species. In the text following, it is understood that the term, electron temperature, refers to the free or unbound electron temperature unless otherwise stated.

The emitter temperatures are determined optically with a calibrated optical pyrometer by observation of a hohlraum in the emitter side. Corrections for the hohlraum and the transmission of the sapphire window have been included in the reported temperatures. As mentioned earlier, the emitter is heated by electron bombardment. The bombardment current is monitored by a simple saturable core reactor unit which in turn controls the power to the button. With this control, emitter temperatures are constant to within $\pm 5^\circ\text{K}$ of a given temperature setting during the time the measurements are made.

Heated, circulating silicone oil and electrical heating tapes are used to keep the cell temperatures at least 50°K above that of the cesium reservoir. The cell temperatures are monitored by sixteen chromel-alumel thermocouples attached to the cell at critical points. Outputs of these thermocouples are recorded on a sixteen point recorder. A nickel sheathed, chromel-alumel thermocouple is located in the cesium and its output leads are connected to a pulsed, Minneapolis-Honeywell Pyr-O-Vane controller. The controller governs the power input to the electrical heater on the cesium reservoir. With this arrangement, the temperature variation of the reservoir is less than $\pm 2^\circ\text{K}$ for a given setting.

II. Circuitry

Cell operation is maintained at a particular point on the current-voltage curve by means of the simple circuitry shown in Fig. 2. This arrangement permits the applied voltage across the cell to be varied by simply moving the rheostat slides. The "Y" axis of the x-y recorder records the potential drop across a calibrated shunt through which the cell current is passing. A current record is thereby obtained. The "X" input is the voltage drop across the cell taken as close as possible to the emitter and collector.

III. Monochromator and Optical Arrangement

A schematic diagram of the monochromator and optical set-up is shown in Fig. 3. Light from the interelectrode gap passes through the sapphire windows in the cell body and follows the light path indicated by the dashed lines. The mirrors are mounted on the carriage in such a way that the gap image projected on the entrance slit of the monochromator is rotated by 90° . The images of the electrode surfaces are, therefore, parallel to the entrance slit. By a simple movement of the mirror carriage in the direction indicated in the diagram, the gap image is swept across the slit. A large f value is used to insure a good depth of field. Magnification of the system is approximately 1.7. The volume of plasma observed has the dimensions of the slit area corrected for the magnification times the diameter of the emitter; typical values are $0.1\text{ mm} \times 1.4\text{ mm} \times 16\text{ mm}$. The plasma is assumed to be homogeneous in this volume.

The emitter and collector are located spectrographically by the light from their edges. Figure 4 illustrates these

locations. A dial indicating micrometer mounted on the carriage is used as a position monitor and readings from it are correlated to the spectrographically determined positions. Cell spacings are also determined by observation of the gap with a cathetometer.

The scanning monochromator is a Jarrell-Ash Model 82-000 with a grating of 30,000 LPI. An EMI 9558 photomultiplier tube is mounted at the exit slit. Signals from the tube are amplified in a Keithley Model 610A Electrometer and a Model G11A Varian Recorder and recorded on the strip chart of the latter. The photomultiplier tube and optical system have been calibrated with a standard tungsten strip lamp and the corrections applied in the course of data reduction.

Because of the relatively large slit width necessary to get adequate signals, it is extremely difficult to get data points close to the emitter and collector. Background signals from the emitter and collector overwhelm the plasma signals and it is necessary to stay away from these components. Using the present experimental set-up, data points are taken 0.015 cm from the emitter and collector edges. An advantage of the electrostatic probes is that it is possible to work much closer to the emitter surface with them than with spectrographic techniques as indicated by the work of Bullis and Wiegand (6).

Spectrographic Analysis

I. Electron Temperatures

The analysis to follow is not complete but will indicate the salient points described by Agnew (12). Electron temperatures are determined from the radiative recombination continuum which may be described as resulting from:

where $h\nu$ is the photon energy. Since an electron in the continuum generally makes a transition to some excited state, j , the photon energy, $h\nu$, may be written as:

$$h\nu = h\nu_j + \frac{1}{2}mv^2 ,$$

where v is the velocity of the electron and $h\nu_j$ is the photon energy released when a zero velocity electron makes a transition to state j . Since the velocity may have continuous values, $h\nu$ will have a continuous set of values resulting in continuum spectrum.

The time rate of change of electrons from the continuum to the state j may be written as:

$$\frac{dN_e}{dt} = N_+ \sigma_j(v) N_e F(v) dv ,$$

where:

$N_+ =$ ion density - $N_e =$ electron density

$\sigma_j(v) =$ cross section for electrons of velocity, v , to undergo a transition to state, j .

$F(v) =$ electron velocity distribution function, assumed to be Maxwellian.

Mohler (13) has experimentally determined the cross section, $\sigma_j(v)$, for $j = 6P$. This cross section is:

$$\sigma_{6P}(v) = \frac{1.5 \times 10^{-56} \text{ cm}^2}{\frac{1}{2} mv^2 \left(\frac{1}{2} mv^2 + h_{6P} \right)^2}.$$

Assuming $\sigma_{6P}(v)$ is correct it is possible to determine the time rate of change of electrons as a function of v and T_E where T_E is the electron temperature appearing in the Maxwellian distribution. Recognizing that each electron transition is accompanied by the release of a photon, a relationship between the intensity of light emitted and the rate of change of electrons may be derived. Through a suitable reduction of the equations, noting the relationship between frequency and wavelength, the following equation is forthcoming.

$$\ln \lambda S(\lambda) = C_1 - \frac{C_2}{T_E \lambda}$$

where:

$S(\lambda) =$ intensity at λ determined from monochromator scans

$\lambda =$ wavelength

$C_1 =$ constant

$C_2 =$ constant.

When the quantity on the left side of the preceding equation is plotted as a function of $1/\lambda$ the resulting curve should be a straight line (for $F(v)$ Maxwellian) with a slope C_2/T_E . The data plots are indeed straight lines. The electron temperatures reported in this paper have been determined from such plots.

II. Ion Densities

The ion densities were determined by the methods reported by Stone and Agnew (14). In their paper, they describe the broadening of emission lines due to the effects of the plasma ions and electrons, the former through the Stark effect and the latter through electron impact. The analysis is presented and checked experimentally by Stone and Agnew. They find a relationship between the full width of the emission lines at half maximum and the ion density. Specifically, they present a family of curves relating line width and ion density

for different fundamental transitions. In this work the width of the 6826A line resulting from the $5D_{3/2}-7F$ transition has been measured, corrected for monochromator broadening and the ion densities determined from the curves given in reference 14.

Procedure

Electron temperatures and ion densities were taken at four points in the interelectrode gap in order to arrive at a profile. Background scans were made with the cesium reservoir cold and these values subtracted out during data reduction. The slide on the rheostat was used to position the cell operation on a particular point on the current-voltage curve. Both electron temperature data and ion density data were taken one immediately following the other to insure the same cell conditions pertained for both data sets.

Experimental Results and Discussion

The electron temperature and ion density profiles are given in Figs. 5 thru 8 along with the appropriate current-voltage curve. The symbol used for a particular profile curve should be matched with that on the current-voltage curve indicating the point at which the measurement was made. Data agree with some preliminary data reported earlier (11). Error bars are not shown because of the amount of data presented. The maximum variation in the electron temperatures as obtained from plots of $\ln(\lambda S)$ is about 9% with most falling within 5% of the reported values. Because of the background light from the emitter, the uncertainty in the temperatures is largest for points taken closest to the emitter. The uncertainty in the reported ion density values is about 30% based on the comments of Stone and Agnew (14).

Measurements were made in the gap away from the emitter and collector; therefore, the data pertains to the plasma outside of any existing sheaths since the largest Debye length for the measurements was of the order of 10^{-4} cm.

The visible zone evident in the ignited mode where the data were taken was most intense close to the emitter. This intensity decreased toward the collector. In some cases a narrow dark zone was observable close to the emitter but could not be resolved with optical arrangement. The visible zone occupied about three quarters of the interelectrode gap. None of the electron temperature and ion density profiles displayed any breaks which might indicate the zone termination.

As indicated in the figures, the measured electron temperatures are quite a bit higher than the emitter temperature. This result is consistent with the electrostatic probe measurements of Bullis and Wiegand (1) whose experiments indicated the presence of an electron accelerating plasma potential in the gap. It is also apparent that the electron

temperatures are not constant across the gap even when the uncertainties in the experimental values are considered. The magnitude of the temperatures on the emitter side of the gap correspond fairly well with those calculated by Kitrilakis, Shavit, and Rasor (2) although they do not predict a change in temperature across the gap.

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FIGURE 1 - THERMIONIC DIODE

FIGURE 2 - CIRCUITRY TO MAINTAIN APPLIED VOLTAGE ON CELL

FIGURE 3 - OPTICAL & MONOCHROMATOR SET-UP

FIGURE 4 - EMITTER & COLLECTOR LOCATIONS

FIGURE 5 - TEMPERATURE & DENSITY PROFILES

FIGURE 6 - TEMPERATURE & DENSITY PROFILES

(a)

(b)

(c)

FIGURE 7 - TEMPERATURE & DENSITY PROFILES

FIGURE 8 - TEMPERATURE & DENSITY PROFILES