EFFECT OF COLD GAS INJECTION ON PLASMA TEMPERATURE MEASUREMENTS

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ABSTRACT
A uniform radial flow of three times the base flow is injected into a 1 atm, 200 A, 10 mm dia. argon wall stabilized arc. The temperature distributions upstream, at injection and downstream are examined spectroscopically using a high temperature multithermal equilibrium (MTE) diagnostics model. The line ratio and total ionization temperatures stay relatively constant. The electron temperature increases significantly at the injection point but decreases downstream. The atom/ion gas temperature decreases at the injection point but increases downstream. The MTE analysis yields realistic electron density distributions, whereas the usual LTE analysis is insensitive to the Non-LTE effects.

1. INTRODUCTION
Plasma processing usually involves the injection of particulate laden, relatively cold gas flows into the plasma stream. The interaction of the cold gas and hot plasma must be understood to properly mold the gas-particulate processes. Numerous experimental studies have shown that local thermodynamic equilibrium (LTE) does not necessarily exist in atmospheric plasmas. Some studies assume local thermal equilibrium (LTE) employing equilibrium between electronic level population temperatures, \( T_e \), and the electron kinetic temperature, \( T_e \). The assumption of partial-LTE (PLTE), over highest excited levels, \( T_{ex} = T_e \), has also been shown to be invalid [1,2]. The present paper uses the multithermal equilibrium (MTE) model [1] to determine the Non-LTE states of the interaction of a cold gas and a plasma. The MTE model should not be confused with other multitemperature models [3,4] and criticism thereof [5].

The MTE model allows subsets of energy mode distributions to be populated according to a Maxwell-Boltzmann temperature from each individual pair of population densities at the statistical equilibrium limit to LTE at the other limit. MTE therefore covers the full spectrum of thermal nonequilibrium. It has been rigorously derived and applied to a variety of electric arcs.

The MTE model to be used here is found to require 6 temperatures: the electron temperature \( T_e \); the atom/ion or gas temperature, \( T_a = T_i = T_g \); the atom and ion upper level excitation temperatures \( T_{ex,a} \) and \( T_{ex,i} \); and the atom and ion total excitation or ionization temperatures, \( T_{exa} = T_{ia} \) and \( T_{ex} = T_{i,a} \). The total excitation (or ionization) temperature represents
ionization from the ground state to the ionization limit as shown in Fig. 1, and is found to be the temperature dominating the partition function $Z_{\text{ex}}$ in MTE. The free-bound continuum temperature $T_{\text{cont}}$ is taken as equal to $T_{\text{exB}}a^2$ as a good approximation. Complete MTE (CMTE) occurs when all levels are populated with a Boltzmann distribution at one temperature (e.g. $T_{\text{exB}}a = T_{I,a}$). Otherwise partial-MTE (PMTE) prevails.

The validity of the MTE model is demonstrated by comparing continuum free-bound $\xi_{fb}$ values obtained under various conditions as shown in Fig. 2. Experimental $\xi_{fb}$ values obtained from 1 atm arc experiments of Schulz-Gulde [6] and others agree with Schluter's theoretical curves [7] if the transition probability scale $A_{mn}$ of Wende [8] is used. Experimental $\xi_{fb}$ values from arcs at 3-30 atm [9,10] agree with 5 atm data of Morris and Krey [11] which are much larger than the theory and are probably in LTDE. Another study [12] of a 1-atm arc using Wende's transition probabilities uses both a LTDE analysis ($\dagger$), which agrees with theory, and a MTE analysis ($\Delta$), which agrees with the high pressure LTDE data, when identical transition probabilities from NBS-NSSONS-22 [13] are used ($\times$). It is shown that the 1-atm data is not in LTDE and hence agreement with the high pressure LTDE $\xi_{fb}$ values and the 1-atm MTE values validates the MTE model. This causes a problem because the above discussion results in the conclusion that the $A_{mn}$ and $\xi_{fb}$ scales are inversely proportional and are presently inconsistent. We are studying this inconsistency at Georgia Tech. Preliminary indications give support to the $\xi_{fb}$ scale (which means $A_{mn}$ would be approximately one-half the NBS values [13]); however, there is some contradictory evidence at high pressures that supports the NBS scale. A discussion is beyond the scope of this work but is in preparation.

In conclusion, the present analysis uses Schluter's scale for $\xi_{fb}$ but adapted for MTE analysis [12] and the NBS-$A_{mn}$ divided by 1.33 which corresponds to the Wende scale identical with that recommended by Baessler and Kock [14], and which was used previously in the low temperature analysis of this data [15]. The low-T analysis found the data to have a much stronger non-LTE than expected. The intensities were at or near the peaking or normal condition for the extent of non-LTE found, thus requiring a "high" temperature analysis to obtain accurate temperatures.

2. Theory

Two high temperature diagnostic methods are used to analyze the results. The low-T method (LTAC), discussed elsewhere [1,12], uses several atom lines and at least one continuum intensity. It is characterized by $T_{\text{LTDE}}a = T_{I,a}$, $N_i = N_e$ with electron densities obtained via the continuum.

The medium-low-temperature method (MLTIA) uses both ion and neutral lines intensities. Now $T_{I,a} \neq T_{\text{LTDE}}$ but $T_{I,i} = T_{\text{LTDE}}, i$, where a and i represent being obtained from atom or ion lines. $N_e$ still equals $N_i$ and can be obtained from

$$N_e = N_i, \text{LTDE} = N_i = N_{m,i}(Z_{\text{exI}}/g_m)\exp[-E_{m,i}/kT_{I,i}],$$  \hspace{1cm} (1)

where $N_{m,i}$ is the ion $m^{th}$ level population density obtained from an ion emission coefficient. One must use one of the highest levels and/or correct for partial-MTE (PMTE) effects using Boltzmann factors through the ionization limit $n_i/g_i^k$,

$$I_{\text{CMTE}} = I_{\text{PMTE}} \exp[-(E_m - E_i)(1/T_{\text{I}} - 1/T_{\text{exB}})/k].$$  \hspace{1cm} (2)
This holds for either atom or ion PMTE populations. The atom lines are used to obtain $T_{exB,a}$ and $N_e/g_1 |_a$ in a similar manner. $T_e$ is then obtained from [1,2]

$$T_e = \left( \frac{\hbar^2}{2m_e k} \right) N_e^{4/3} / \left[ 2Z_{exl} (N_e/g_1 |_a)^{2/3} \right]. \quad (3)$$

One problem is that a good value of $T_{I_a}$ is difficult to calculate. We use a subroutine from a MTE thermodynamic property program which recalculates tables of $I_a$ vs. $N_e$ for families of $T_e/T_{I_a}$ (strong sensitivity) and $T_e/T_a$ (weak sensitivity). A double interpolation using experimental $I_a$ and $N_e$ gives a good value for $(T_e/T_{I_a})$ and hence $T_{I_a}$ from $T_e$. Then $N_a$ is calculated from

$$N_a = (N_e/g_1 |_a) Z_{exa} \exp[-E_{I_a}/k T_{I_a}] \quad (4)$$

and finally $T_a$ from the equation of state. The MLTIA method is valid for atmospheric arcs at $T_{I,a} < 13,000$ K, which is the case here. The major error is in the uncertainty of the ion transition probability scale.

The medium temperature method (MTAC) uses several atom line and at least one continuum intensity, as in the low-T method. $N_e$ is obtained from the MTE continuum equation in the form

$$\epsilon_v [W-s/cm^3-sr] = 5.44 \times 10^{-46} T_e^{-1/2} N_e^{2/3} Z^2 \epsilon(v, T_e, T_{exB}), \quad (5)$$

where the Birberman $\xi$-factor is expressed in the appropriate MTE temperatures [12] with $T_0$ being estimated on the first iteration. $T_e$ is then found from Eq. (3). After several iterations for $N_e$ and $T_e$, the procedure is the same as with the MLTIA method but is applicable at temperatures $(T_{I,a})$ above the normal point.

3. EXPERIMENT

The test arc is a 10 mm dia., 200 A, 1-atm argon wall-stabilized arc. The base flow is 0.17 g/s. A flow of 0.48 g/s is radially injected through a 0.305 mm circumferential slit. The injection slit is located 60 mm from the cathode and 48 mm from the anode. Intensity measurements were made through window view ports located 10 mm upstream and downstream, as well as at the injection slit. A minimum of six optically thin neutral lines (L4259, L6871, L6937, L7030, L7141 and L7272), three ion lines (4764, 4806 and 4879), and five selected continuum (C3916, C4235, C4794, C5690 and C6831) intensity measurements were made for reasons and using procedures discussed elsewhere [12].

4. RESULTS

Electron density determinations made from various continuum at various axial locations and radii are compared for the LTDE and MTE analyses in Figs. 4 and 5 respectively. It is observed that the MTE analysis is sensitive to the injection of the cold gas, whereas the LTDE analysis is oblivious to the effect. The downstream distance was selected based on flow visualization studies [16] and represents the vena contracta.

Temperature plots at the upstream, injection downstream and the effluxing jet locations are shown in Figs. 6-9. The values of the temperatures are suspect because a true, non-LTE independent transition probability scale has not yet been determined. In addition, the values are from the LTAC method. The MLTIA and MTAC methods are being finalized and results will be presented at the meeting. The unrealistic increase in $T_g$
with radius is due to the inadequacy of the LTAC method for the
temperatures obtained. The relative values are indicative of the cold gas
and hot plasma interaction. In general,

$$T_g < T_{\text{exB, a}} < T_{\text{i, a}} < T_e.$$  \hfill (6)

The gas temperature decreases from the upstream to the injection point, but
then increases substantially at the downstream location remaining
relatively constant through the jet. The contrary is true of the electron
translational temperature which increases at the injection point, then
decreases substantially downstream, but is again increased by the field
before leaving the cascade. The total (excitation or ionization
temperature (usually taken as the LTDE temperature) is relatively constant
throughout this is as we would expect since it is largely determined by the
entrapped resonance radiation. The upper level excitation temperature,
$T_{\text{exB, a}}$ is relatively constant but is susceptible to the pull and push of
the local collisional and non-local radiative processes. Its value
increases slightly downstream but then decreases in the jet.

5. CONCLUSIONS

The temperatures obtained indicate significant deviations from LTDE
when cold gas is injected into a plasma. Understanding these processes is
important in modeling the collisional and radiative processes in plasma
chemistry. It is recommended that additional emphasis be placed on non-
LTDE analysis.

ACKNOWLEDGEMENTS

The authors acknowledge National Science Foundation Grant GK31453 and
the assistance of C. J. Cremer and H. S. Hsia in the taking of the
original data, as well as current NSF Grant CPE-8311325 under which the
present analysis was developed. We also acknowledge the excellent
preparation of the manuscript by Miss Melinda Wilson.

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Fig. 1  Argon Wall-stabilized arc with injection and view ports.

Fig. 2 Boltzmann plot of various MTE temperatures.

Fig. 3 Comparison of various free-bound continuum factor determinations.

Fig. 4 Radial electron density as a function of location assuming local thermodynamic equilibrium.

Fig. 5 Radial electron density as a function of location using MTE analysis.
Fig. 6 Radial temperature profiles 10 mm upstream from injection point.

Fig. 7 Radial temperature profiles at injection point.

Fig. 8 Radial temperature profiles 10 mm downstream from injection point.

Fig. 9 Radial temperature profiles 10 mm beyond exit of constricted arc (Jet 1).