Use of thermocouples and argon line broadening for gas temperature measurement in a radio frequency atmospheric microplasma jet

S. J. Doyle and K. G. Xu

Citation: Review of Scientific Instruments 88, 023114 (2017); doi: 10.1063/1.4976683

View online: http://dx.doi.org/10.1063/1.4976683

View Table of Contents: http://aip.scitation.org/toc/rsi/88/2

Published by the American Institute of Physics
Use of thermocouples and argon line broadening for gas temperature measurement in a radio frequency atmospheric microplasma jet

S. J. Doyle and K. G. Xu

Department of Mechanical and Aerospace Engineering, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA

(Received 1 August 2016; accepted 3 February 2017; published online 21 February 2017)

This paper presents the use of thermocouples and line broadening of argon 2p-1s emission lines for the measurement of gas temperature of an atmospheric argon microplasma jet. The measured temperatures are compared with rotational spectra fitting of OH (A-X) and N$_2$ (C-B) emission. An rf microplasma jet with two electrical configurations and different temperature ranges was used. The calculated gas temperatures with thermocouples, argon lines, and OH ranged from 290 to 423 K and 393-510 K for the two configurations, depending on the rf power. The temperature from fitting the N$_2$ spectra overestimated the gas temperatures in both configurations (593-680 and 664-853 K). The non-nitrogen temperature measurements agree well with each other within the measurement uncertainty. The results show that not all optical emission temperature methods are appropriate and the accuracy of argon line broadening is dependent on the device configuration. The results also show that conventional thermocouples are surprisingly accurate and viable for these plasmas. Published by AIP Publishing.

[http://dx.doi.org/10.1063/1.4976683]

I. INTRODUCTION

Atmospheric microplasma jets (AMPJs) are of a great interest due to their low gas temperatures but high electron temperature and charged particle densities, which makes them ideal for a variety of biomedical and material processing applications. Atmospheric pressure operation also removes the need for expensive and complicated vacuum equipment required for low pressure plasmas. To safely treat living tissue and low temperature materials, it is important to be able to readily determine the gas temperatures quickly and in situ.

In the lab, the gas temperature is commonly measured with optical techniques such as emission spectroscopy of OH and N$_2$ or Rayleigh scattering. These techniques require significant post-processing to obtain a temperature. Commercial programs such as Specair can speed the post-processing with built-in databases and automated spectra fits to provide an in situ measurement of gas temperature. These measurements can also provide both spatial and temporal resolution, although this is not a focus of this study. An additional challenge in optical AMPJ temperature measurements is the loss of local thermodynamic equilibrium (LTE), which requires careful attention when performing optical measurements.

For future industrial or commercial applications, simpler methods with direct temperature measurement or minimal post-processing are desirable. Thermocouples are a common tool to measure surface, mixture, or gas temperatures in many industrial applications. They are inexpensive and provide immediate readings. The difficulty for plasma use is the presence of charged particles and local electric fields that can interfere with the readings. A simple and minimal post-processing optical method to measure gas temperature is van der Waals or Doppler broadening. From knowledge of the broadening profile of a spectral line, the gas temperature can be directly calculated from a single equation. At low temperatures <1000 K, van der Waals has a much larger effect and broadening profile than Doppler, thus it is used in this work where the gas temperature is expected to be low.

This paper examines four different methods to determine the gas temperature of AMPJs: van der Waals broadening of argon spectral lines, spectral fitting of OH (A-X) and N$_2$ (C-B) spectra, and type K thermocouples.

II. GAS TEMPERATURE DETERMINATION METHODS

A. OH (A-X) and N$_2$ (C-B)

The rotational temperature of the OH (A-X) and N$_2$ (C$^3$Π_g–B$^3$Π_g) (second positive system) can be obtained by comparing the measured spectra to simulated spectra. The R$_1$ and Q$_1$ branches of OH between 306 and 312 nm and the N$_2$ rotational lines with a $\Delta v = -3, -2$, and $-1$ between 334 and 405 nm are commonly used for temperature measurements. Simulated spectra can be obtained from commercial programs such as Specair and Lifbase. While Specair has databases for both OH and N$_2$ second positive system, Lifbase can only calculate the OH spectra, but it is available as freeware. Lifbase can simulate the first negative system of N$_2$ $^4$Π, but those peaks were not observed here due to the low energies and use of ambient nitrogen.

A common assumption of these simulated spectra is that the rotational states have a Boltzmann population distribution. This is a valid assumption for most atmospheric pressure plasmas and has been assumed for this work.
B. Argon spectral line broadening

The gas temperature can also be obtained from argon spectral lines through the use of line broadening techniques.\textsuperscript{4,7,12–14} An advantage of this method is that trace gases do not need to be added to the argon plasma. In this work, the measurements are taken in the jet that emanates into ambient air where ambient N\textsubscript{2} and OH are present, but for measurements of the plasma inside the tube, argon line broadening removes the need for the addition of air, nitrogen, or water vapor.

Following the method of Ionascut \textit{et al.}\textsuperscript{5} the gas temperature can be determined from the van der Waals broadening assuming Stark broadening is negligible in comparison. This is true for relatively low electron temperatures and electron densities \(<10^{16}\text{ cm}^{-3}\), where collisions between the neutral and emitter species are frequent. The validity of this assumption has been demonstrated by other research groups\textsuperscript{4–6} and is also examined for this work in Section IV A. The plasma density for this source ranges from $10^{10}$ to $10^{14}\text{ cm}^{-3}$.\textsuperscript{15} Therefore, only instrument, Doppler, and van der Waals broadening are considered.

The instrument and Doppler contributions have a Gaussian form, while the van der Waals contribution has a Lorentzian form. The instrument broadening was calculated by observing a He–Ne laser and determining the full width at half maximum (FWHM) of the Gaussian profile. The Gaussian fit of the He–Ne line is shown in Fig. 1 with a FWHM of 0.0992 nm. The Doppler broadening is given by Eq. (1),

\[
\Delta\lambda_{\text{Doppler}} = 7.16 \times 10^{-7} \times \lambda \times \left(\frac{T}{M}\right)^{1/2},
\]

where \(\Delta\lambda_{\text{Doppler}}\) is the FWHM and \(\lambda\) is the emission wavelength, both in angstrom, \(T\) is the gas temperature in K, and \(M\) is the atomic mass in g/mol.\textsuperscript{5} The van der Waals broadening is given by Eq. (2),

\[
\Delta\lambda_{\text{VDW}} = 4.09 \times 10^{-13} \times \lambda^2 \times \left(\frac{\alpha R^2}{\mu}\right)^{1/2} \times \left(\frac{T}{\mu}\right)^{0.3} \times n,
\]

where \(\alpha\) is the average polarizability of the neutral perturbers in cm\textsuperscript{3}, \(R^2\) is the mean square radius of the emitting atom in cm\textsuperscript{2}, \(\mu\) is the reduced mass of the emitter-perturber system in g/mol, and \(n\) is the perturber density in cm\textsuperscript{-3}.\textsuperscript{5} The convolution of a Gaussian and Lorentzian profile results in a Voigt profile whose FWHM can be approximated through Eq. (3),

\[
\Delta\lambda^2_{\text{V}} = \Delta\lambda^2_{\text{V}} \times \Delta\lambda^2_{\text{L}}.
\]

Thus by separating out the instrument from the measured Voigt profile, the gas temperature can be calculated from Eq. (3).

After taking into account the Voigt profiles of each argon line and the instrument contribution, the only unknown for the Doppler and van der Waals calculations is the gas temperature. Therefore, Eq. (3) became a function of only the gas temperature, allowing for an iterative solver to be used to determine the value.

III. EXPERIMENT

A drawing of the atmospheric microplasma jet experimental setup is shown in Fig. 2. The device consists of a 6 mm OD, 3 mm ID quartz tube with a 1 mm diameter central tungsten pin electrode. An external stainless steel collar placed near the exit served as the second electrode. Argon gas was flowed through the quartz tube at a constant rate of 2 l/min with a MKS mass flow controller. The plasma was operated at 14 MHz using a FT 950 radio transceiver, an AT5K matching network, and an LP-100A wattmeter. The plasma was tested at forward rf powers of 50, 70, and 90 W. For all measurements, the power was maintained at \(\pm0.5\) W and the standing wave ratio (SWR) was kept \(\leq 1.05\). All temperature measurements were taken of the microplasma jet that emanated directly into open air.

The argon lines of interest were selected based on a detailed review of the current literature.\textsuperscript{13,16} The lines chosen include 696, 706, 738, 751, 800, 810, 811, and 842 nm, which

![FIG. 1. He–Ne laser emission spectra centered at 632.8 nm. The plot shows both the experimental data and the resulting Gaussian fit with the corresponding FWHM.](image)

![FIG. 2. Schematic of the experimental setup. All dimensions are in mm. The red dot represents the location of the thermocouples.](image)
all originate from 2p-1s transitions. The specified transitions can be found in Table I. Two different type-K thermocouples (T/C) were used. The first was a bare bead attached to the bottom of a 2 mm thick Pyrex plate with adhesive, and the second was a 1/16 in. Inconel sheath and ungrounded T/C. They are referred to as the “adhesive” and “shielded” in the results. The T/C’s were placed 3 mm below the tube exit centered directly under the jet. They were given 10 min to reach a stable temperature before measurements were read after disabling the rf power source, which can cause interference.

The emission spectra were captured with a fiber optic cable connected to an Acton SP2500 spectrometer with a 500 mm focal length, 1200 g/mm grating, and a PI-MAX4 ICCD camera. The entrance slit width was set to 70 μm and the resolution was 0.0409 nm/pixel. The spectrometer and fiber were calibrated for both wavelength and intensity using Princeton Instrument’s IntelliCal spectral calibration system. 300 images were taken for each spectra and averaged to produce a final raw spectrum. A total of 9 averaged raw spectra were obtained for each measurement. The programs Specair and Lifbase were used to simulate the spectra of OH and N2 plasmas with relatively low gas temperatures and electron densities <10^{16} cm^{-3}. In order to verify the impact of neglecting this broadening parameter, sample calculations of broadening values for two argon lines were done for specific gas temperatures, electron temperatures, and electron densities. Data from prior experiments with the linear-field configuration were used for the expected electron temperature and density.

A simplified formula to calculate the Stark broadening component is given in Eq. (4),

\[ \Delta \lambda_{\text{Stark}} = 2.0 \times 10^{-16} \times w \times N_e, \]  

with \( w \) as the electron impact parameter and \( N_e \) as the electron density in cm\(^{-3}\). The electron impact parameter is tabulated for different temperatures. Therefore, as the electron temperature and density increases, the Stark broadening value increases. One can also see that the broadening value is independent of the emission wavelength being analyzed.

Past experiments with the linear-field configuration provided electron temperature and density values between 3.05 and 3.45 eV and 5.0 \times 10^{10} - 2.5 \times 10^{12} cm^{-3}, respectively. In order to simulate conditions where the Stark component would be at its maximum value, which corresponds to the point of the highest electron temperature and density, the values of 3.45 eV and 2.5 \times 10^{12} cm^{-3} were used.

The instrumental broadening component is also assumed independent of the emission wavelength being analyzed, thus remaining a constant 0.0992 nm. The Doppler and van der Waals broadening parameters are calculated from Eqs. (1) and (2) for the assumed gas temperatures. Table II shows the results of this analysis for two different argon lines at gas temperatures of 300 and 400 K. The results show that the Stark component is two to three orders of magnitude smaller than the Doppler and van der Waals components. This confirms that it is acceptable to consider the Stark broadening parameter negligible for this microplasma jet.

### IV. RESULTS AND DISCUSSION

#### A. Comparison of argon broadening components

In plasmas where the collisions between the neutral and emitter species are frequent, the Stark broadening parameter can be neglected. As mentioned prior, this is often true for plasmas with relatively low gas temperatures and electron densities <10^{16} cm\(^{-3}\). In order to verify the impact of neglecting this broadening parameter, sample calculations of broadening values for two argon lines were done for specific gas temperatures, electron temperatures, and electron densities. Data from prior experiments with the linear-field configuration were used for the expected electron temperature and density.

A simplified formula to calculate the Stark broadening component is given in Eq. (4),

\[ \Delta \lambda_{\text{Stark}} = 2.0 \times 10^{-16} \times w \times N_e, \]  

with \( w \) as the electron impact parameter and \( N_e \) as the electron density in cm\(^{-3}\). The electron impact parameter is tabulated for different temperatures. Therefore, as the electron temperature and density increases, the Stark broadening value increases. One can also see that the broadening value is independent of the emission wavelength being analyzed.

Past experiments with the linear-field configuration provided electron temperature and density values between 3.05 and 3.45 eV and 5.0 \times 10^{10} - 2.5 \times 10^{12} cm^{-3}, respectively. In order to simulate conditions where the Stark component would be at its maximum value, which corresponds to the point of the highest electron temperature and density, the values of 3.45 eV and 2.5 \times 10^{12} cm^{-3} were used.

The instrumental broadening component is also assumed independent of the emission wavelength being analyzed, thus remaining a constant 0.0992 nm. The Doppler and van der Waals broadening parameters are calculated from Eqs. (1) and (2) for the assumed gas temperatures. Table II shows the results of this analysis for two different argon lines at gas temperatures of 300 and 400 K. The results show that the Stark component is two to three orders of magnitude smaller than the Doppler and van der Waals components. This confirms that it is acceptable to consider the Stark broadening parameter negligible for this microplasma jet.

#### B. OH (A-X) temperature

An example of the measured OH (A-X) spectrum at a power level of 50 W under the linear-field configuration can

---

**TABLE I.** Argon transition information.

<table>
<thead>
<tr>
<th>Argon line wavelength (nm)</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>696.5</td>
<td>2p₂ → 1s₅</td>
</tr>
<tr>
<td>706.7</td>
<td>2p₁ → 1s₅</td>
</tr>
<tr>
<td>738.4</td>
<td>2p₃ → 1s₄</td>
</tr>
<tr>
<td>751.5</td>
<td>2p₅ → 1s₄</td>
</tr>
<tr>
<td>800.6</td>
<td>2p₆ → 1s₄</td>
</tr>
<tr>
<td>810.4</td>
<td>2p₇ → 1s₄</td>
</tr>
<tr>
<td>811.5</td>
<td>2p₉ → 1s₅</td>
</tr>
<tr>
<td>842.5</td>
<td>2p₈ → 1s₄</td>
</tr>
</tbody>
</table>

**TABLE II.** Broadening parameter values \( T_e = 3.45 \text{ eV} \) and \( n_e = 2.5 \times 10^{12} \text{ cm}^{-3} \) (units of nm).

<table>
<thead>
<tr>
<th>Argon line</th>
<th>Gas temperature (K)</th>
<th>Instrumental</th>
<th>Doppler</th>
<th>van der Waals</th>
<th>Stark</th>
</tr>
</thead>
<tbody>
<tr>
<td>738.8</td>
<td>300</td>
<td>9.92 \times 10^{-2}</td>
<td>1.45 \times 10^{-4}</td>
<td>3.70 \times 10^{-2}</td>
<td>3.32 \times 10^{-5}</td>
</tr>
<tr>
<td>800.6</td>
<td>300</td>
<td>9.92 \times 10^{-2}</td>
<td>1.57 \times 10^{-4}</td>
<td>3.97 \times 10^{-2}</td>
<td>3.32 \times 10^{-5}</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>9.92 \times 10^{-2}</td>
<td>1.81 \times 10^{-4}</td>
<td>3.24 \times 10^{-2}</td>
<td>3.32 \times 10^{-5}</td>
</tr>
</tbody>
</table>
be seen in Fig. 3(a). As the power level increases, two main regions show noticeable change. These regions correspond to two subsets of three peaks each, being centered at 307 (R$_2$) and 308 (Q$_1$) nm, respectively. Fig. 3(b) shows this small but noticeable change of the 307 nm peaks.

Each of the OH spectra was imported into both Specair and Lifbase. In order to obtain an accurate estimate of the gas temperature, the slit or instrument function must be accounted for. While Specair allows direct importing of the actual instrumental broadening data, Lifbase does not. Lifbase allows for the user to set the FWHM of the instrumental spectrum and provide the line shape. For the purposes of this study, the line shape was set to Gaussian and the measured instrument broadening FWHM was used in Lifbase. In Specair, the measured instrument function was imported into the simulation software.

Fig. 4 shows the results of the simulation analysis. Specair and Lifbase results for each configuration appear to agree to each other within the uncertainty for all power levels. The cross field results are also higher than the linear-field, which is expected due to the immersion of the powdered pin in the plasma for the cross field configuration. The large error attributed to the Lifbase results is an artifact of the small difference in comparisons between two distinct peak groups, centered at 307 (R$_2$, lines 8-10) and 308 (Q$_1$, lines 1-3) nm. Depending upon which peak group is primarily considered as the basis of the temperature determination, the simulation software results in different temperature values.

The Specair simulation for the 50 W linear-field configuration is shown in Fig. 5(a). The majority of the simulation
FIG. 6. Lifbase simulation results for 50 W, linear-field configuration, OH (A-X): (a) priority given to Q$_1$ branch, (b) priority given to R$_2$ branch. The Q$_1$ branch resulted in a simulated temperature of 300 K, while the R$_2$ branch resulted in a simulated temperature of 350 K.

FIG. 7. (a) N$_2$ (C-B) emission spectrum at 70 W for the linear-field configuration. Numbers above individual lines indicate the transition. (b) Variation on the emission spectra due to varying power levels, centered at 401 nm and showing the $\Delta v = -3$ peak set.

peaks match the experimental data, yielding a final gas temperature of 297 K. The Lifbase simulation results are shown in Fig. 6. Figs. 6(a) and 6(b) show the results with priority given to the Q$_1$ (300 K) and R$_2$ (350 K) OH (A-X) peaks, respectively.

The difference in simulation results may be caused by the difference of the slit function input. Another factor to consider is that Lifbase does not provide automatic temperature determination. In other words, the user must set the temperature to test and determine visually if the experimental data matches. Lastly, as mentioned prior, the Lifbase results are dependent upon which peak set is primarily used for comparison. When prioritizing the Q$_1$ peaks, the temperature results for Lifbase are lower, matching very well to the Specair simulations. When focusing on the R$_2$ peaks, the Lifbase temperatures are higher and show more deviation from those of Specair. All of these contribute to small but noticeable differences between each simulation’s results.

C. N$_2$ (C-B) temperature

N$_2$ rotational lines with a $\Delta v = -3$, $-2$, and $-1$ were captured with the optical emissions spectroscopy system. The N$_2$ (C-B) spectra at 70 W for the linear-field configuration are shown in Fig. 7(a). Fig. 7(b) shows minor differences in the results for varying power levels at $\Delta v = -3$.

Lifbase is not capable of simulating the second positive system of nitrogen, thus only Specair was used. The results of the analysis are shown in Fig. 8. As expected, the cross field temperatures are higher than the linear-field.

The Specair simulation for the 50 W linear-field configuration at $\Delta v = -2$ is shown in Fig. 5(b). The simulation appears to adequately capture the 0-2 transition and “finger” regions between the main peaks. There is a visible difference in the

FIG. 8. Temperature determination from N$_2$ (C-B) spectra comparison to Specair simulations.
1-3 and 2-4 peak intensities. This particular spectrum yielded a final gas temperature of 592 K.

D. Argon (2p-1s) temperature

In order to determine the gas temperature from van der Waals broadening techniques, individual argon emission lines were measured. The argon spectra at 50 W for the linear-field configuration are shown in Figs. 9(a)–9(c). Fig. 9(d) shows the variation of two argon emission lines, 800 and 801 nm, due to varying power levels for the linear-field configuration. While the change between lines in some cases is very small to the eye, it does impact the temperature calculation noticeably.

Fig. 10 shows six argon lines that produced reasonable temperatures for the linear-field configuration. The other two lines provided non-realistic results that were either much too high (>1000 K) or could not be calculated. This was due to an inability to obtain a good Voigt fit of the spectra. The specific grating angle affects how many measurements are taken for a given peak on the CCD. Error bar values were determined from a set of nine measurements at each data point. The 738, 800, and 810 nm argon lines appear to agree to each other within the uncertainty for all power levels. The 842 nm line yields elevated temperatures, but matches very well at 90 W. The 751 and 811 nm lines show elevated temperatures at all power levels.

Fig. 11 shows temperature measurements obtained for the cross field configuration. Once again, the error bar values are based on a set of nine tests for each data point. The 738, 751, 800, and 810 nm lines appear to show similar groupings and trends across all power levels. The 842 nm line start off roughly at the same temperature value at 50 W, but has drastically lower values at 70 and 90 W.

E. Thermocouple temperature

As previously mentioned, two type-K thermocouples were used as a cost effective method to directly obtain an estimate of the gas temperature. Fig. 12 shows the temperature
results as a function of power. For the linear-field configuration, the shielded and adhesive T/Cs yield results within range of each other. The cross field configuration results show an increase in temperature across all power levels. This is expected as the temperature is expected to increase for the cross field plasma jet.

F. Method comparison

The results of the nitrogen simulations show drastically elevated temperatures in comparison to those of other gas determination methods, having values ranging from 593 to 850 K, depending on the configuration. The inaccuracy of the N$_2$ second positive system has been observed by others as well, especially for argon plasmas. The cause is an energy transfer from the Ar($^3$P$_{0,2}$) state via Ar($^3$P$_{0,2}$) + N$_2$(X) $\rightarrow$ Ar($^1$S$_0$) + N$_2$(C)$_0$. This causes the rotational sublevel populations to deviate from a Boltzmann distribution, which in turn leads to inaccurate gas temperature measurements. Another reason for the inaccuracy of the second positive system is based on the location of the optical measurements in relation to the electric field being applied to the system. Due to the measurements taking place downstream of the applied electric field and in the emanating plasma jet, the electric field is lower. Popov and Rusterholtz et al. have shown that in the presence of weak electric fields (E/N < 80 Td), the N$_2$ (C-B) rotational distribution drastically changes and the gas temperature is overestimated. It is for these reasons that some studies recommend the utilization of the first positive system, which more closely follows the gas temperature when the electric field is below 80 Td. Unfortunately the first positive system was not strong enough to be used in this work.

The results of the simulations are in better agreement to the argon and thermocouple results. Figs. 13(a) and 13(b) show this comparison for the linear-field and cross field configurations, respectively. The simulation temperatures were similar for the van der Waals broadening method, regardless of the simulation software used. For the linear-field jet, the T/C temperatures matched well to the Lifbase OH results, but were elevated compared to Specair. For the cross field jet though, the OH spectra and T/C values showed an extremely tight grouping, with values ranging from 393 to 510 K.

One can see that the individual argon lines exhibit different behavior depending on the configuration utilized and not all are accurate. A similar experiment was conducted with a high voltage pulsed dc AMPJ and showed different argon lines (696, 706, and 794 nm) matched OH and T/C temperatures compared to the rf AMPJ.

The cross field jet yielded much higher temperatures from the argon lines. This can be due to the sensitivity of the spectrometer and the change in van der Waals broadening with temperature. The cross field jet is expected to produce higher gas temperatures due to a direct contact between the powered electrode and the plasma. With assumption that the Stark and instrumental broadening remain constant over the change in gas temperature, the changing broadening of the emission line can be directly attributed to the variation in the Doppler and van der Waals components. As shown in Fig. 14, an increase in the gas temperature results in a decrease of the van der Waals value and an increase of the Doppler value. At low temperatures, due to the higher order of magnitude for the van der Waals broadening, the convoluted sum of the two decreases. At temperatures much higher than the crossing point of the two broadening parameters around 1200 K, an increase in temperature will result in a net increase in the sum due to the increasing Doppler component. The AMPJ in this work operates in the range of 300-500 K, meaning that only a decrease in the sum is observed. Indeed, the higher temperature cross field jet had an overall smaller broadening than the colder linear-field jet. This decrease in broadening is important as smaller values can cause larger errors due to the fact the method subtracts small numbers from small numbers.
Thus lower van der Waals values will result in the temperature measurement with more uncertainty, for a given spectrometer resolution. Therefore, the use of van der Waals gas determination methods may be invalid for higher temperature systems.

V. CONCLUSIONS

In conclusion, the OH spectra yielded the most consistent temperatures and can be considered the baseline for comparison. The results indicate that there is a noticeable difference in not only each of the different gas temperature determination methods but also for individual argon spectral lines when using van der Waals broadening. In addition, the usefulness of argon spectra lines as a gas temperature measurement appears to vary with electrode configurations and temperatures.

Thus while van der Waals broadening is relatively easy to implement, careful consideration must be made when choosing the spectral lines. The resolution of the spectrometer system may also play a role in the accuracy of the line broadening method as the method uses very small numbers that can be strongly impacted by small uncertainty. A comparison measurement should be done to ensure the accuracy of the chosen argon lines for any given microplasma device.

The T/C yielded surprisingly accurate, if slightly elevated temperatures compared to the OH results; <13% for the linear-field configuration, and <5% for the cross field configuration. Thermocouples thus may be considered a viable option to reliably estimate the microplasma gas temperatures, as long as proper shielding between the plasma and T/C is provided. A thin ceramic coating or sleeve such as those used for harsh environment T/Cs may provide sufficient insulation for these low temperatures and still allow fast response times.