Time-resolved surface temperature measurement for pulsed ablative thrusters

Erik L. Antonsen[*] and Rodney L. Burton[**]
University of Illinois at Urbana-Champaign IL 61801
eantonse@uiuc.edu

Gregory G. Spanjers[†] and Ronald A. Spores[‡]
AFRL Propulsion Directorate, Edwards AFB CA 93524

IEPC 03-292

A time-resolved surface temperature diagnostic for ablation-controlled arcs is in development at the Air Force Research Laboratory at Edwards AFB. The diagnostic draws on heritage from the experimental dynamic crack propagation community which has used photovoltaic infrared detectors to measure temperature rise in materials in the process of fracture. The microsecond time scales involved in the fracture process suggest that such detectors may be applicable to the ablation-controlled discharges in pulsed plasma thrusters as a direct measurement of surface temperature during and after the arc. HgCdTe detectors are evaluated for use on the surface of a micro-pulsed plasma thruster invented at the AFRL. Evaluation of the diagnostic focuses on application of the detector in the presence of a plasma and initial studies of calibration techniques. Initial data is reviewed with future studies planned for advancement of the technique including applications to other types of pulsed thrusters.

Introduction

With the increasing presence of micro-propulsion options for spacecraft attitude control and propulsion, there is a corresponding need for the development of experimental techniques to better understand the operating physics of these devices. The Air Force Research Laboratory is currently developing a class of Micro-Pulsed Plasma Thrusters (MicroPPTs) using Teflon™ propellant to provide precise impulse bits in the 10 μN-s range. In the near term, these thrusters can provide propulsive attitude control on 150-kg class spacecraft at one-tenth the dry mass of conventional torque rods and reaction wheels.[1]

However, the micro-PPT still suffers the same deficiencies that standard PPTs have been dealing with since their inception. Low mass utilization coupled with spacecraft contamination concerns provide a continuing emphasis for research to improve these systems. Ultimately, post-pulse late-time ablation (LTA) in these thrusters defines operation and performance capability by sustaining significant propellant mass loss per pulse that fails to contribute to thrust. This LTA factor has been estimated between 40-90% of the total mass loss from various sources.[2,3]

Significant research effort has been expended attempting to characterize LTA in terms of plume effects both from neutral vapor interferometric measurements[4] and analysis of macro-particle ejection.[2] Past experiments have demonstrated a correlation between propellant temperature and thruster operating efficiency. Spanjers et al. inserted thermocouples into the Teflon propellant of parallel-plate PPTs to varying depths from the fuel face to measure steady-state operation temperatures at long times.[5] Of note from this study is an increased efficiency when the propellant operated at lower average temperatures.

*Ph.D. Candidate, Department of Aeronautical and Astronautical Engineering, Urbana, IL 61801 and Scientist, ERC Inc., Edwards AFB, CA 93524
** Professor, Department of Aeronautical and Astronautical Engineering, Urbana, IL 61801.
† Scientist, Space Vehicles Directorate, Kirtland AFB, NM 87117.
‡ Scientist, Air Force Research Laboratory, Edwards AFB, CA 93524.

Unfortunately, the thermocouple location behind the surface exposed to the plasma can only provide the steady state measurement of the bulk fuel temperature. The time resolution of these devices is also limited by the metal junction size. Additionally, any attempt to place thermocouples directly on the propellant surface exposes the thermocouple joint to the arc discharge. To obtain a time-resolved measurement of the surface temperature, we introduce a different approach. Photon detectors provide an unexplored alternative with the time-resolution required to investigate the micro-second discharges characteristic of these devices.

These detectors have found substantial use in the study of dynamic crack propagation, where they are used to evaluate conversion of work to heat at the tips of fast-moving cracks in solid materials.[6,7] Application of these detectors to the problem of an ablation-controlled arc requires significant analysis to determine the effects of the plasma and vapor layers, ablation characteristics of Teflon, proper selection of detector materials, and a validated means of translating the output voltages into temperatures.

Teflon Ablation

The use of Teflon in PPTs derives from the physics of conversion from solid to plasma. Since Teflon sublimates at increasing temperatures, losses associated with a liquid phase during the transition are not present. This sublimation process is characterized by Turchi's calculations[8] shown in Figure 1.

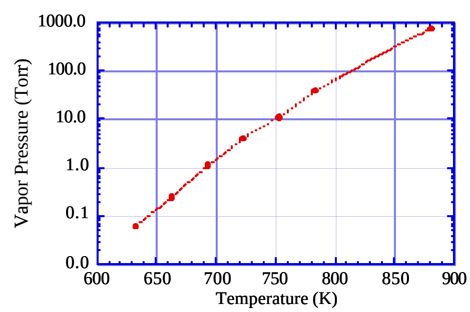

Figure 1: Vapor pressure vs. surface temperature for Teflon.

Because of the properties exhibited by this curve, Teflon exposure to a high temperature arc provides a feedback method for producing adequate current carriers and surface heating to ablate material to generate thrust. Mass loss to the arc is defined by this curve in the form of ablation rate. Since the ablation rate defines the number of potentially available current carriers as well as neutral vapor generated during and after the arc, surface temperature becomes a critical parameter controlling most aspects of the discharge process.

Keidar and Boyd predict surface temperature during and after the arc and the effect on ablation parameters.[9] They predict an ablation rate during the discharge of around 1 μg for a 2.25 J arc. However, they also suggest post arc ablation between 0.5 to 4.0 μg depending on the base surface temperature.[10] Propellant heating through normal thruster operation (~1 Hz pulsing) may introduce a systematic decline in performance (efficiency and I_{sp}) as the thruster approaches steady state operation. Characterization of the heating and cooling curves during single discharges while the thruster is operating in a steady mode could identify such a base temperature. Ultimately, this could lead to an experimental investigation into materials that show similar ablation characteristics, but perhaps better temperature response to attack the late-time ablation problem directly.

An immediate application is characterization of the cooling curve between pulses. Typically, these thrusters are operated at ~1 Hz, but can be throttled to higher frequencies. The surface will cool between pulses with a minimum late-time ablation rate defined by neutral vapor generation shown in Figure 1. The cooling rate is presently unknown and provides a starting point for application of the surface temperature diagnostic in terms of estimating post-pulse mass loss due to neutral vapor. Not considered here is the effect of macro-particle ejection which has been documented in these types of thrusters and which increase the total ablated mass per shot.

Another concern addressed by this diagnostic is spacecraft contamination. Models are in development to address the plume expansion of these thrusters for prediction of contamination effects.[9] These models require experimental validation to gauge the effectiveness of the predictions. They also may require experimentally determined inputs as boundary conditions for the processes being modeled. Direct measurement of the surface temperature provides an avenue for assessing the validity of these models and their application to the contamination problem.

Approaching the ablation problem requires consideration of the heat transfer from the arc to the surface of the Teflon. This can occur in two forms, radiation and particle convection to the surface. Keidar and Boyd take both processes into account in their assessment of the ablation problem, and their treatment of these processes can be evaluated with accurate temperature measurements.

Experimental Approach

Determining temperature by means of infrared emission requires a p-n junction with materials sensitive to the wavelengths of interest. The photodiodes used here are Mercury Cadmium Telluride (HgCdTe) detectors. These detectors have a pre-amplifier which supplies a bias voltage controlling sensitivity in the wavelengths of 2-12 µm. The output from the detector/preamp combination is a voltage which can be easily measured on an oscilloscope. For this experiment, four detector elements are used with 80 µm active areas arranged in a linear array with a 20 µm pitch. With a 1:1 magnification from the imaging optics, the spatial resolution is defined by this active area. The detectors are housed in an LN_2 dewar. Figure 2a. shows a scale drawing of the detectors imaged 1:1 on a 6.35 mm micro-PPT face. Figure 2b. shows a different (and more expensive) detector arrangement capable of yielding spatial resolution in the radial and angular directions.

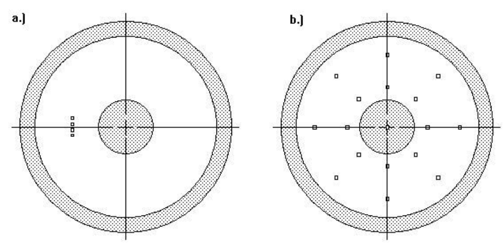

Figure 2: (a.) Present and (b.) future HgCdTe detector designs shown to scale on a micro-PPT face. The small squares are the detector images and the gray circles are the micro-PPT electrodes.

Determination of the proper detector material is based on the expected surface temperatures and the emissive properties of the material under consideration. Types considered include Indium Antimonide (InSb) and HgCdTe for an expected temperature swing between room temperature and 1000 K. While InSb is typically used for temperatures in the 600-1000 K range, the emissive properties of Teflon become a limiting factor for this detector material. Data from infrared spectroscopy of Teflon films suggest that the emissivity of Teflon reaches unity at 8.4 µm due to a stretching mode in the C-F bond.

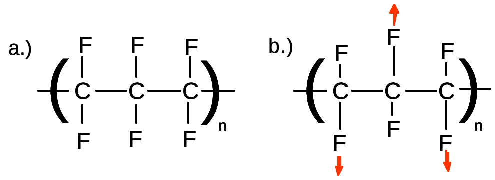

Figure 3: Teflon polymer (a.) has an asymmetric C-F stretching mode (b.) absorbing energy at 8.4 µm.

Some emissivity is exhibited around 4.4 µm due to overtones from the stretching mode, but the bulk of the emission and peak emissivity occur outside the response band of InSb which cuts off at 6 µm. For this reason along with a better response at low temperatures required to characterize cooling curves, HgCdTe detectors are chosen.

An estimation of the expected signal for calibration of the detector with Teflon relies on the wavelength-dependent radiation emitted in the band of interest. The Plank distribution[11] provides spectral emissive power as a function of material temperature, which is given by

$$P_E = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}} - 1\right)} \tag{1}$$

where C_1 is 3.742×10^8 W-µm^4/m^2, C_2 is 1.439×10^4 µm-K, λ is the radiation wavelength (µm), and T is the material temperature (K). Traces of the spectral emissive power for a black body at several relevant temperatures are shown in Figure 4.

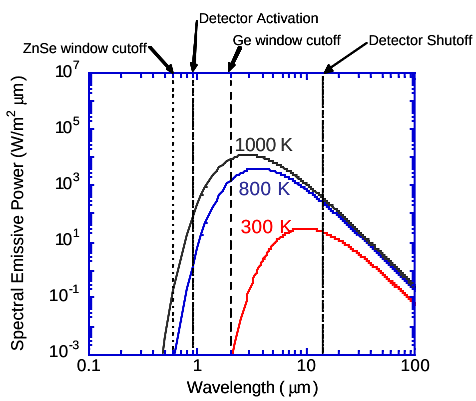

Figure 4: Several Plank distribution curves for blackbody emission at relevant temperatures.

Detector activation is shown at 900 nm along with the Ge transmission range (2-12 µm) and ZnSe transmission range (0.7-12 µm). Ge and ZnSe are window materials for infrared transmission. Multiplying the temperature curves by the wavelength dependent emissivity (ε_λ) provides an expected total emission from Teflon. Since Teflon emissivity is unknown, a rough estimate is used taking into account only the stretching mode discussed above and its overtone in the 2-12 µm region. All values outside these effects are set at 1% such that there is some contribution though minimal. Detector responsivity is taken into account as a wavelength-varying term also with the peak detector response (R_p) of 8.2 A/W at 10.5 µm.[12] The factory-supplied responsivity (D*) provides the wavelength dependence. These values must be integrated across the wavelength range of interest to determine an output current. However, the optical setup must be considered as well as the viewing geometry and preamplifier. The output voltage prediction is then calculated by

$$V = k_o G A (1 - \cos\theta) \int_\lambda \varepsilon_\lambda D^* R P_e \, d\lambda \tag{2}$$

where k_o is an optics constant, G is the amplifier gain (20000 V/A), θ is the conical half angle defined by the diameter of and distance to the large spherical mirror in the imaging optics, A is the detector active area (80 µm x 80 µm), and P_e is given by Eqn. 1. The results of this prediction are discussed below.

Actual measurement of the Teflon surface while the plasma is present may be possible, however a detailed analysis of the plasma optical depth is required. This analysis will be presented in further studies.

Results and Discussion

Two preliminary experiments are performed to evaluate the likelihood of successful application of this diagnostic. Figure 5 shows the general optical layout with a sample located in a vacuum chamber. MicroPPT operation is conducted in a vacuum and these conditions are required for valid measurements. However, this requires exotic optics for infrared transmission out of the optics chamber. Both Germanium (40% transmission) and Zinc Selenide (70% transmission) are considered for these experiments.

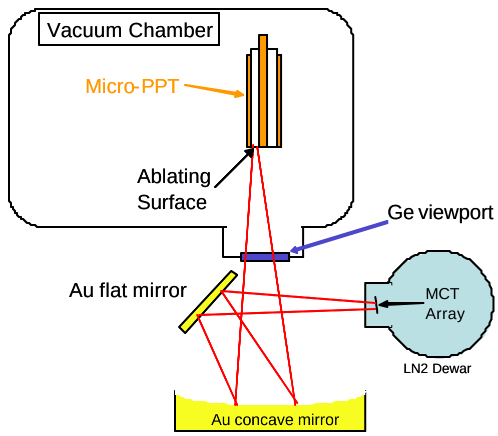

Figure 5: IR detector experimental layout.

Prior to thruster testing, calibration with heated Teflon fuel is required. The first experiment performs this calibration at vacuum. Teflon is heated on a hotplate with the surface temperature measured by K-type thermocouples seated on the fuel face. The experimental setup is shown in Figure 6 with the external optics looking down on the Teflon sample through a Germanium window.

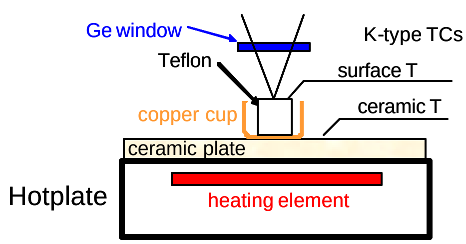

Figure 6: Calibration procedure in-tank layout.

The thermocouples measure surface temperature in close proximity to the point on the fuel face being imaged. This allows an experimental voltage vs. temperature curve which is compared to predictions from Eqn. 2 in Figure 7.

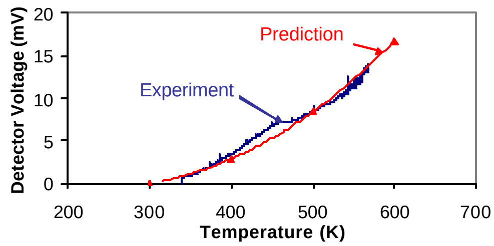

Figure 7: Measured and predicted Teflon response.

The experimental results shown in Figure 7 indicate that the initial estimate of the contributions of the 8.4 and 4.4 μm wavelengths are indeed the main contributors in the emissivity estimate.

The second experiment performed is an uncalibrated application of the diagnostic to a micro-PPT. The setup for this is shown in Figure 8.

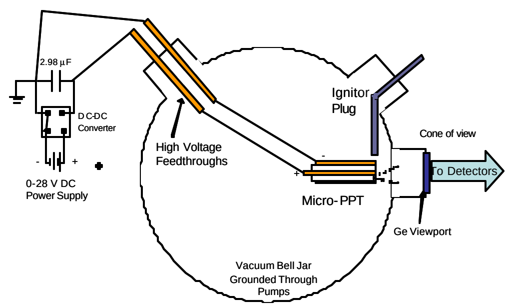

Figure 8: Experimental layout used for thruster IR data.

This configuration is used only temporarily to address problems with the capacitor in the tank. The effect of this arrangement is the addition of circuit inductance which tends to extend the pulse from the typical 20 μs to about 120 μs.

The current pulse can be fit using[13]

$$I = \frac{V_o}{wL} EXP\left[-(R/2L)t\right]\sin(wt) \tag{3}$$

where Vo is the breakdown voltage, L is the inductance, R is the resistance, and

$$w = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{4}$$

with capacitance C. It was shown that a linearly increasing resistance fit the experimental data well. Figure 9 shows this fit. For the current trace measured with a self-integrating Rogowski coil, the curve-fit parameters are V_o = 2.8 kV, C = 2.98 μF, and L = 1190 nH. To match the current pulse, the resistance must vary from 45 to 81 mΩ in the 120 μs of the pulse duration. This allows calculation of the arc power using $P=I^2R$ and integration with time provides the instantaneous energy deposited. Figure 9 shows the current pulse along with a fit calculated using the linearly increasing resistance.

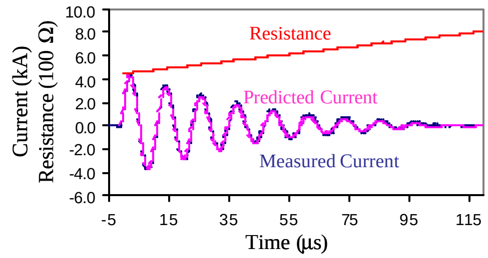

Figure 9: Comparison of measured and calculated current with linearly varying resistance.

Measurement of the plasma contribution to the signal is taken by focusing the optics perpendicular to the thruster axis to a point above its face. This is shown on the left in Figure 10. The grey area shows the optical focal depth of ±1 mm as measured with a heated wire filament.

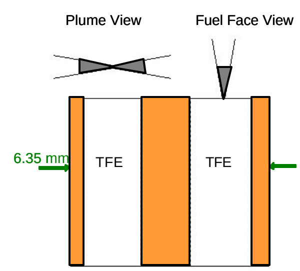

Figure 10: Optical depth of focus and measurement areas shown for facial surface measurement and plume measurement.

For the plasma measurements, the focal point is located above the ablating fuel surface at varying distances from 1-7 mm. The results are shown in Figure 11.

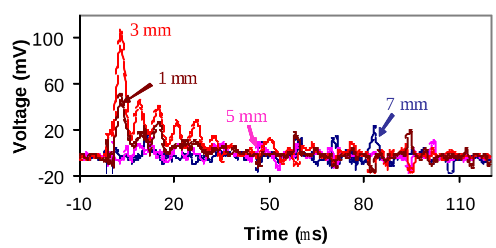

Figure 11: Typical observed plasma signals at varying distances from the fuel face.

At 3 mm from the fuel face the plume signal reaches a maximum. The 1 mm case also shows a plume signal, although it is consistently smaller than the 3 mm case. The signal from the plume drops into the noise at 5 mm from the fuel face indicating that the plume expansion at that point has limited the total emission that the detectors can sense. These measurements are all in terms of voltage since calibration with the plasma and neutral vapor has not been achieved.

Uncalibrated measurement of the fuel face is attempted next with the detector imaged to a point as shown on the right side of Figure 10. Figure 12 shows a typical measurement of the fuel face plotted with the 3 mm plume data. Also plotted is the total energy to the arc from the capacitor.

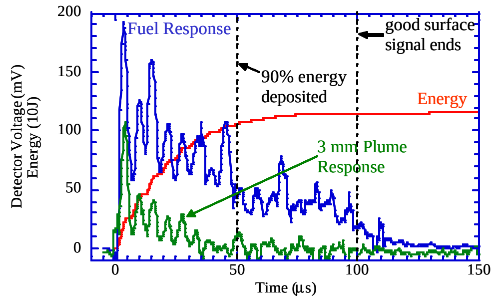

Figure 12: Plume and surface response with energy deposition over time.

Note that at ~50 µs (90% energy deposited) the signal from the plume ends. Most significantly, the signal from the fuel face is still appreciable out to ~100 µs. This means that after the plume has stopped contributing to the signal, the signal remaining indicates that an actual surface temperature measurement is being made.

Conclusions

Time-resolved surface temperature measurements would greatly expand knowledge of the pulsed plasma thruster. Experiment and analysis suggest that the physics underlying Teflon emission in the IR and detection with HgCdTe detectors are basically understood. More work is needed to refine calibration predictions and comparison with experiments at the higher temperatures expected in the micro-PPT plasma. Ultimately, the calibration procedure will take into account any effects not considered here such as the temperature dependence of emissivity for Teflon. Several calibration methods may be required to translate detector voltage data into surface temperatures.

Initial measurements on a Teflon face exposed to an ablative discharge show promising results. Although these results are uncalibrated, the preliminary findings show a signal for 40 µs after the end of the plume signal that indicates a hot surface. During the early discharge, the noise involved with plasma emission may mask any signal from the surface preventing a measurement at peak energies. But mid- and post-discharge measurements are probably attainable. These measurements are significant for an evaluation of late-time ablation and to verify modeling assumptions about cooling characteristics.

With these initial results showing promise, this effort proceeds to evaluate fully the capability of this diagnostic and define useful system resolutions and uncertainties. Future work will focus on understanding the effects of Teflon transmissivity in the wavelengths in question. The differences between surface heating during the arc and bulk heating used in calibration will be addressed and changes in surface roughness during thruster firing will be factored in to give a realistic assessment of Teflon ablation in these devices.

Acknowledgements

This work is funded by the Air Force Research Laboratory at Edwards AFB, CA and performed at the Electric Propulsion Laboratory on-site. E. Antonsen acknowledges support from ERC Inc. Drs. M. Keidar and I. Boyd from the University of Michigan provided significant discussions concerning ablation physics. Both of these efforts are supported by AFOSR/NA. Dr. Mitat Birkan is the program manager. Additional thanks to the following people: Dr. Bro from DuPont Corporation provided material information on Teflon including infrared spectroscopy data. Dr. J. Lambros with the University of Illinois at Urbana-Champaign (UIUC) provided hands-on experience with HgCdTe detectors. Dr. D. Keefer of the University of Tennessee Space Institute (UTSI) provided information on plasma optical depths.

References

1. Spanjers, G.G., Bromaghim, D.R., Lake, Capt. J., Dulligan, M., White, D., Schilling, J.H., Bushman, S.S., Antonsen, E.L., Burton, R.L., Keidar, M., Boyd, I.D., "AFRL MicroPPT Development for Small Spacecraft Propulsion," AIAA Paper No. 2002-3974, Indianapolis, IN, July 2002.
2. Spanjers, G. G., Lotspeich, J. S., McFall, K. A., Spores, R. A., "Propellant losses Because of Particulate Emission in a Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 14, No. 4, 1998, pp 554-559.
3. Burton, R. L., Rysanek, F., Antonsen, E. L., Wilson, M. J., Bushman, S. S., "Pulsed Plasma Thruster Performance for Microspacecraft Propulsion," Chap. 13, AIAA Progress Series, Micropropulsion for Small Spacecraft, M. Micci, ed., 2000.
4. Antonsen, E.L., Burton, R.L., Spanjers, G.G., Engelman, S.F., "Herriott Cell augmentation of a quadrature heterodyne interferometer," Rev. Sci. Instrum., 74 (1), Jan 2003.
5. Spanjers, G. G., Malak, J. B., Leiweke, R. J., Spores R. A., "The effect of propellant temperature on efficiency in a pulsed plasma thruster," Journal of Propulsion and Power, Vol. 14, No. 4, July-August 1998, 545-553.
6. Zehnder, A. T., Rosakis, A. J., "On the temperature distribution at the vicinity of dynamically propagating cracks in 4340 steel: experimental measurements using high-speed infrared detectors," *Journal of the Mechanics and Physics of Solids*, 39 (3), 385-417, 1991.
7. Mason, J. J., Rosakis, A. J., "On the dependence of the dynamic crack tip temperature fields in metals upon crack tip velocity and material parameters," *Mechanics of Materials* , 16 (4), 337-350, 1992.
8. Burton, R. L., Turchi, P. J., "Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 14, No. 5, pp. 716-735, 1998.
9. Keidar, M., Boyd, I. D., "Ionization non-equilibrium and ablation phenomena in a micro-Pulsed Plasma Thruster," AIAA Paper No. 2002-4275, Indianapolis, IN, July 2002.
10. Keidar, M., University of Michigan, Ann Arbor, MI, private communication, 2002.
11. Planck, M., *Theory of Heat Radiation*, Dover Publications, New York, 1959.
12. Fermionics, Simi Valley, CA, www.fermionics.com.
13. Jahn R. G., *Physics of Electric Propulsion*, McGraw-Hill Book Co., New York, NY 1968.