Surface Temperature Measurements from a Stator Vane Doublet in a Turbine Engine Afterburner Flame Using a YAG:Tm Thermographic Phosphor

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Background

- Thermographic phosphors for temperature measurements exhibit unique advantages over thermocouples and pyrometers for turbine engine environments.
  - Non-contact
  - No interference from reflected radiation
  - Insensitive to surface emissivity
  - Intrinsically surface sensitive

- AFRL VAATE project successfully demonstrated temperature measurements from thermographic phosphor coated Honeywell stator vane doublet in afterburner flame of AEDC J85-GE-5 turbojet test engine.

- Component Testing in Engine Afterburner Flame
  - Vane doublet with temperature sensing coating in test fixture.
  - Afterburner flame from J85 test engine.

- However, overwhelmed by reflected combustion radiation during Honeywell HTF7000 engine test.

- Challenge: Develop thermographic phosphor that emits at wavelength coinciding with greatly reduced reflected radiation intensity.
• Blue emission effective for low thermal background produced by hot surface.
• UV emission will be necessary for low thermal background from reflected combustor radiation.
Objectives

• Implement blue and UV emission bands from YAG:Tm for engine probe measurements.
• Demonstrate temperature measurements from YAG:Tm-coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand.
  – Monitor vane surface temperature
    – Steady-state conditions
    – Engine acceleration
Characterize and Calibrate YAG:Tm Luminescence Decay Temperature Dependence (blue and UV Emission)
Emission Spectrum from YAG:Tm-Coating
355 nm excitation

UV emission will be needed in presence of reflected combustor radiation.
Stark Energy Levels Associated with $^3\text{H}_6 \rightarrow ^1\text{D}_2$ Absorption and $^1\text{D}_2 \rightarrow ^3\text{H}_6$ Emission in YAG:Tm Luminescence

Skipped forbidden transitions between like symmetry Stark levels & transitions involving $^3\text{H}_6(9-13)$
YAG:Tm(0.8%) Powder Excitation & Emission Spectra

Excitation Spectrum @460 nm Emission

Emission Spectrum @352 nm Excitation

YAG:Nd 3rd harmonic at 355 nm excites into phonon sideband.

Bandpass filter FWHM
Stark Energy Levels Associated with $^{3}H_{6} \rightarrow ^{1}D_{2}$ Absorption and $^{1}D_{2} \rightarrow ^{3}F_{4}$ Emission in YAG:Tm Luminescence

- There are nine emission bands.
- The transitions are forbidden between like symmetry Stark levels.
- Transitions terminating in $^{3}F_{4}(8,9)$.
The $^1D_2 \rightarrow ^3F_4$ emission is more complex than the $^1D_2 \rightarrow ^3H_6$ emission. Broad background in SPPS coating suggests somewhat more disordered structure.
SPPS YAG:Tm(1.0%) Coating Emission Decay Curves

Decay behavior of 365nm emission matches behavior observed at 456nm emission.

Decay rate (slope) sensitive to temperature for $T > 800^\circ C$.

365 nm Decay

$^3H_6 \rightarrow ^1D_2$

456 nm Decay

$^1D_2 \rightarrow ^3F_4$
Fitting Procedure for Emission Decay

- Fitting Window Selection Based on Probe Data
- Model for Emission Decay

Fitting Window Selection Based on Probe Data

1. Select 600 ns as $I_0$. (avoids backreflection peak)
2. Intensity-based fitting window from 60% to 10% $I_0$.
3. Fit with double exponential.
4. Discard $\tau_1$.
5. Use $\tau_2$ for temperature indication.

Biexponential Decay

$$I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}; \tau_2 > \tau_1$$
**Fitting Procedure for Emission Decay**

- When fit to double exponential is unstable at high temperatures
- Fit with single exponential instead

**Single Exponential Decay**

\[ I = I_0 e^{-t/\tau} \]

- **PLA=104, 456nm emission data**
- **fit**

**τ = 499 ns**

- **600 ns**
- **60%**
- **10%**
Modeling Decay Time Temperature Dependence
SPPS YAG:Tm 365 & 456nm emission bands

\[ \frac{1}{\tau} = \frac{1}{\tau_R} + \frac{1}{\tau_{NR}} e^{-\Delta E/kT} \]

Simple model with quenching due to thermally activated nonradiative decay
(by cross-over to charge transfer state).
Transitioning from Coupon Specimens to Engine Component Testing

YAG:Tm coated superalloy coupon

YAG:Tm coated Honeywell stator vane doublet

SPPS = solution precursor plasma spray

EB-PVD = electron-beam physical vapor deposition
Probe Design for Vane Measurements

Constraints for probe design
• Do not protrude into gas flow.
• Limited space: integrated excitation & collection.
• End of probe exposed to gas flow temperatures.
• Temperature-sensitive optical components require cooling.

Final probe design by Rob Flori, Honeywell.
Cooling Fixture for Mounting in Afterburner Flame at UTSI J85 Test Stand

High-Velocity Exhaust Gas up to 1760°C
YAG:Tm Emission Decay at Steady-State Afterburner Conditions
456 nm decay

Measurements acquired at:
- PLA = 15 (idle)
- PLA = 90 (full military)
- PLA = 94 (with afterburner)
- PLA = 96
- PLA = 98
- PLA = 100
- PLA = 102
- PLA = 104
Each decay was averaged over 16 laser pulses (20 pulses/s)

PLA = 98 is onset of obvious temperature sensitivity.
YAG:Tm Emission Decay at Steady-State Afterburner Conditions
Comparison of 456 nm & 365 nm Decay

- Much longer, more intense probe autofluorescence distortion out to 2 µs.
- Can only use decay past 2 µs.
- Data not useable beyond onset of temperature sensitivity at PLA = 98.

Only 456 nm emission decay could be used to make temperature measurements for afterburner tests with probe.
YAG:Tm Emission Decay Time vs. PLA Throttle Setting

PLA = 98 is onset of obvious sensitivity of decay time to temperature.
Temperature vs. PLA Throttle Setting
(temperature determined from YAG:Tm decay time)

- ±5°C at 1250°C!
- 1297°C highest temperature for thermographic phosphor field measurement!
Temperature Measurements During Throttle Acceleration from PLA = 94 to 104

~1 Hz temperature reading acquisition rate
Probe Artifacts and Recommended Remedies

- Laser back reflection spike at 530 ns using 50 m collection fiber optic.
  - Remedy: Locate PMT near engine & use short collection fiber.

- Probe introduces distortion of initial decay that is much more severe for 365 vs. 456 nm emission.
  - Greater distortion prevented useful 365 nm emission decay data from afterburner tests.
  - Distortion associated with Raman scattering inside fiber optics that is worse for 365 nm emission because it is near 355 nm excitation wavelength.
  - Remedy: appropriate short-pass filter at output of laser delivery fiber and long-pass filter before collection fibers.
Conclusions

• Successfully demonstrated temperature measurements in lab environment for both blue and UV emission band decays from YAG:Tm.
• Successfully demonstrated temperature measurements (static & dynamic) up to 1300°C from YAG:Tm-coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand using blue YAG:Tm emission band decay.
• Redesign of engine probe optics will allow implementation of UV YAG:Tm emission band decay for superior rejection of background reflected combustion radiation.
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