Non-contact high-temperature measurement using Raman spectroscopy

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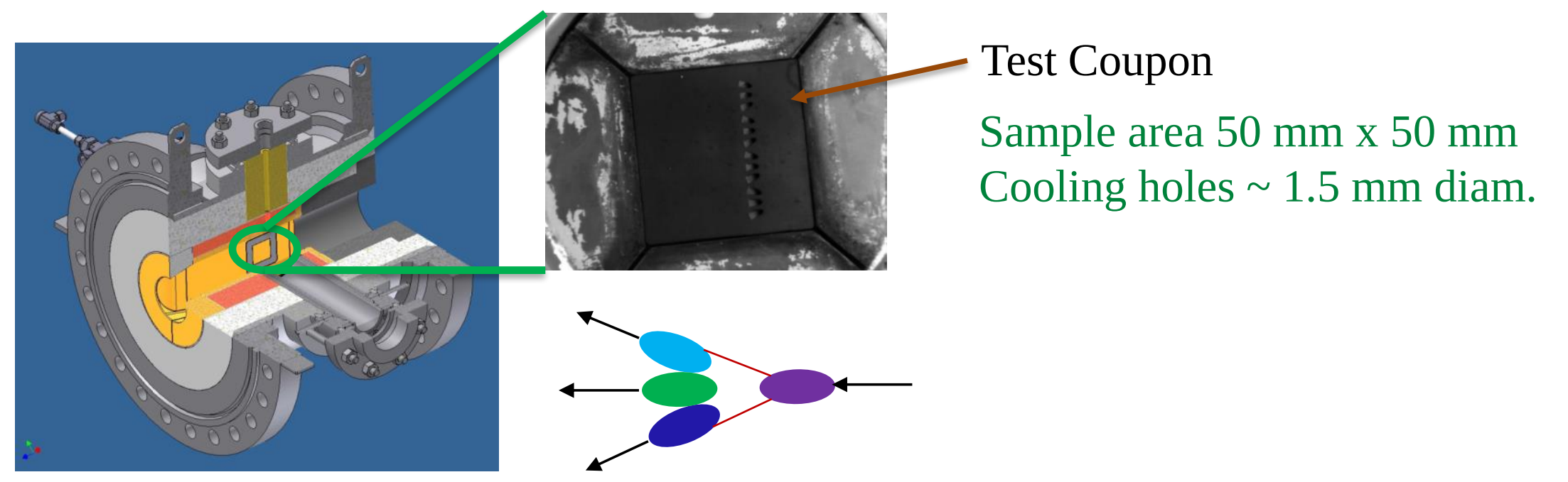
Introduction

Improving the performance of high-temperature fossil energy power generation systems, such as turbines, solid-oxide fuel cells, gasifiers and coal-fired boilers, requires careful control of temperatures experienced by key components. In gas turbines, advances in alloys, coatings, and film cooling of turbine blades allows higher firing temperatures and greater efficiencies, or longer component lifetimes. Obtaining the greatest benefit from these advances requires accurate temperature measurement on the component surfaces.

The present work supports the research goal to verify the performance of advanced, CFD-designed aerothermal cooling through experimental measurements. Measurements of surface temperatures and heat transfer under high-temperature flow conditions are desired for the greatest fidelity with turbine operating conditions.

Raman spectroscopy allows accurate, non-contact, high-temperature measurement, without interfering with the heat transfer processes. Unlike an infrared camera, a Raman temperature measurement is not confused by the thermal radiation emitted from hot surroundings which reflects from the test surface.

This work shows that, on high-temperature stable materials such as alpha-alumina (single-crystal sapphire and polycrystalline ceramic, melting point ~2050°C) and yttria-stabilized zirconia (YSZ, melting point ~2700°C), Raman spectroscopy can be utilized for non-contact temperature measurement.



Test coupon with trident cooling holes surrounded by hot refractory walls in aerothermal test rig

Determination of temperature with Raman spectroscopy

1. **Peak position as a function of temperature**
   - Fit the Raman spectral peaks with Lorentzian line shape to obtain correct peak position.
   - Perform temperature calibration using second degree polynomial fit.

$$T(R) = A + BR + CR^2$$

T=Temperature (function of R)
A (°C) , B (°C/cm^{-1}), and C (°C/cm^{-2}) are fitting parameters
R=Raman Parameter (Peak position)

As the temperature increases, bond length increases and energy of the vibrational mode decreases. This results in the peak (line) position shift.

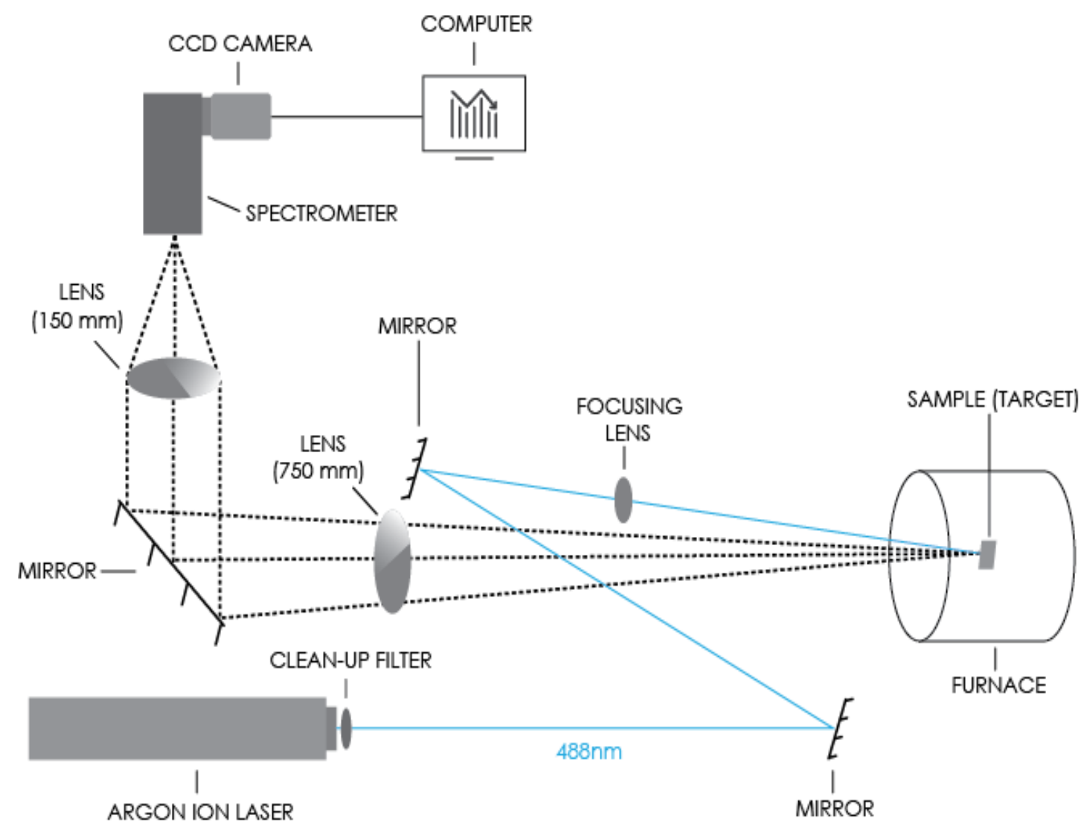
2. **Intensity ratio of the peaks as a function of temperauture**

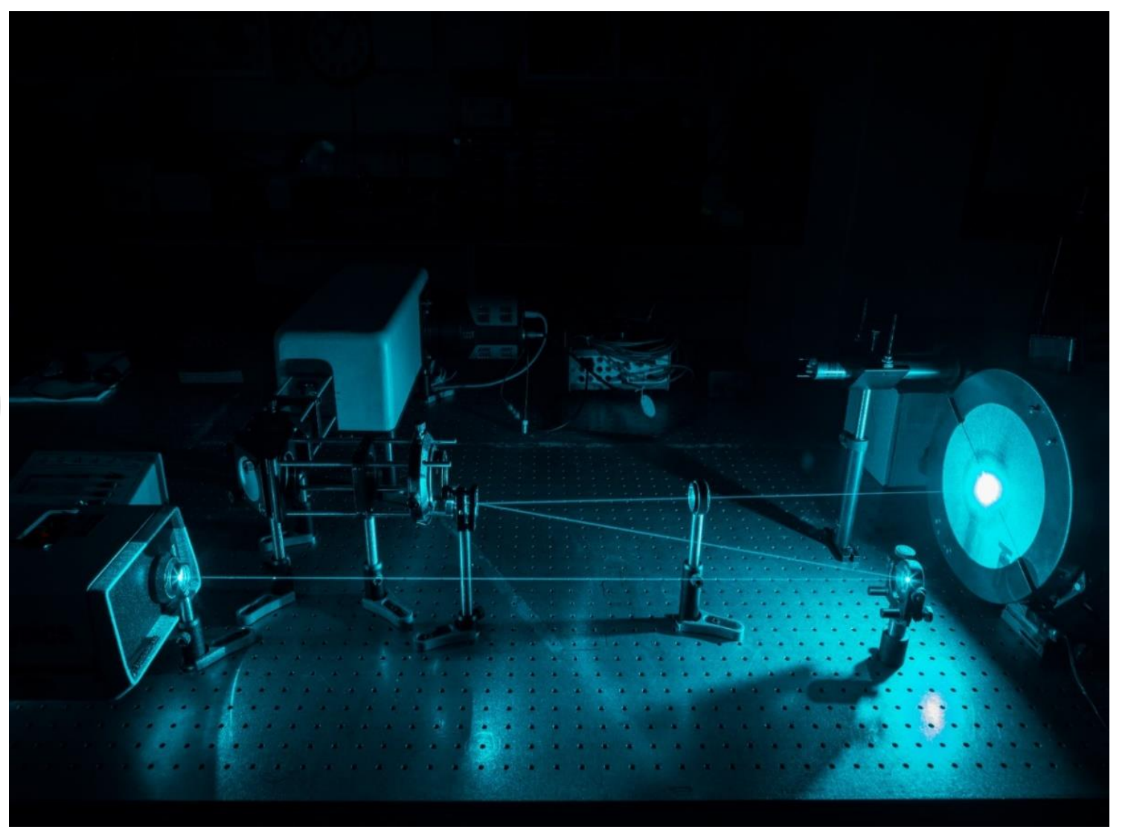
$$\frac{I_{AS}}{I_S} = \frac{(\upsilon_0 + \upsilon_R)^3}{(\upsilon_0 - \upsilon_R)^3} exp(\frac{-h\upsilon_R}{K_B T})$$

I_{AS}=Intensity of anti-Stokes
I_S=Intensity of Stokes
υ_0=Frequency of excitation light
υ_R =Raman band position (frequency of vibrational mode)
h=Planck's constant
K_B=Boltzmann constant
T=Temperature

Temperature determined from the peak position shift has been found to be more accurate than from the intensity ratio.

Lab-bench Raman temperature experiment



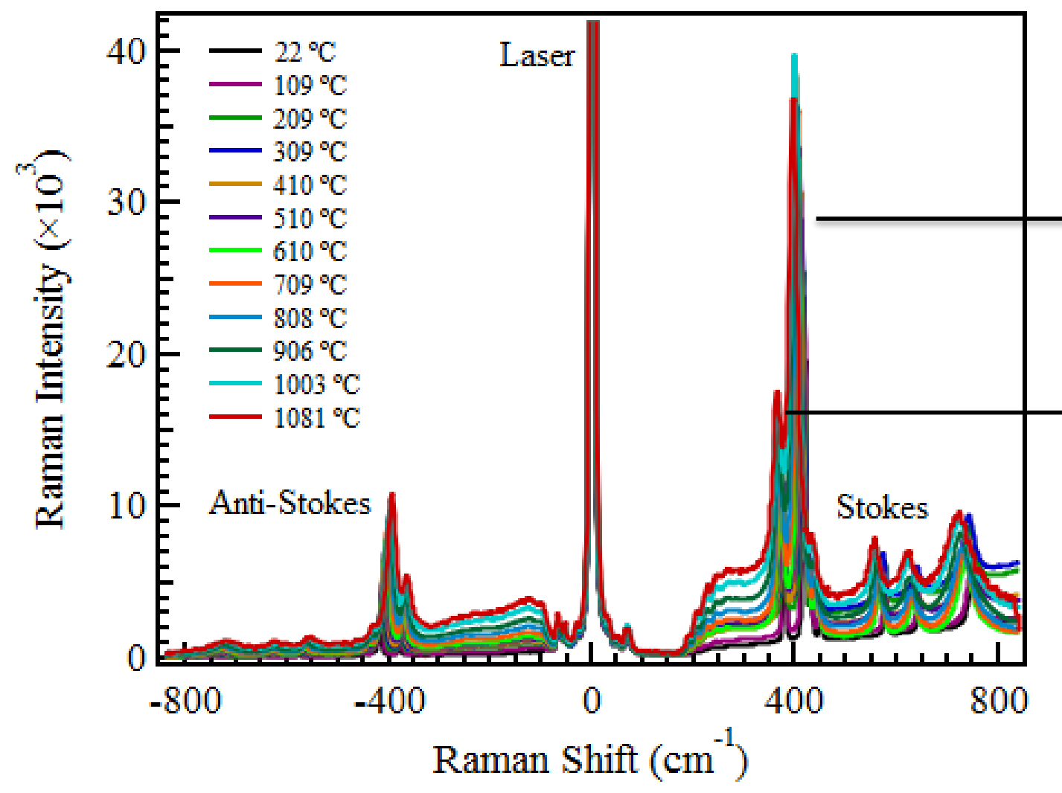


Temperature sensitivity of Raman spectra of selected high-temperature materials

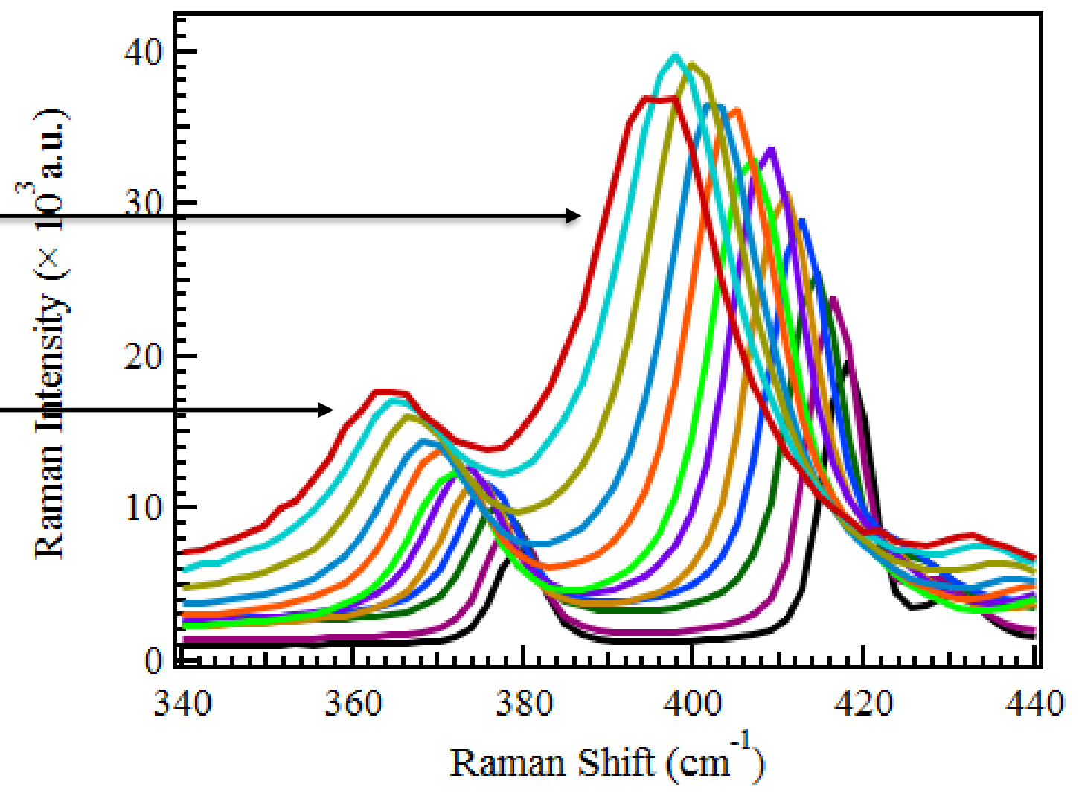
Single-crystal sapphire (alumina)

1.7W laser power and 20s integration time

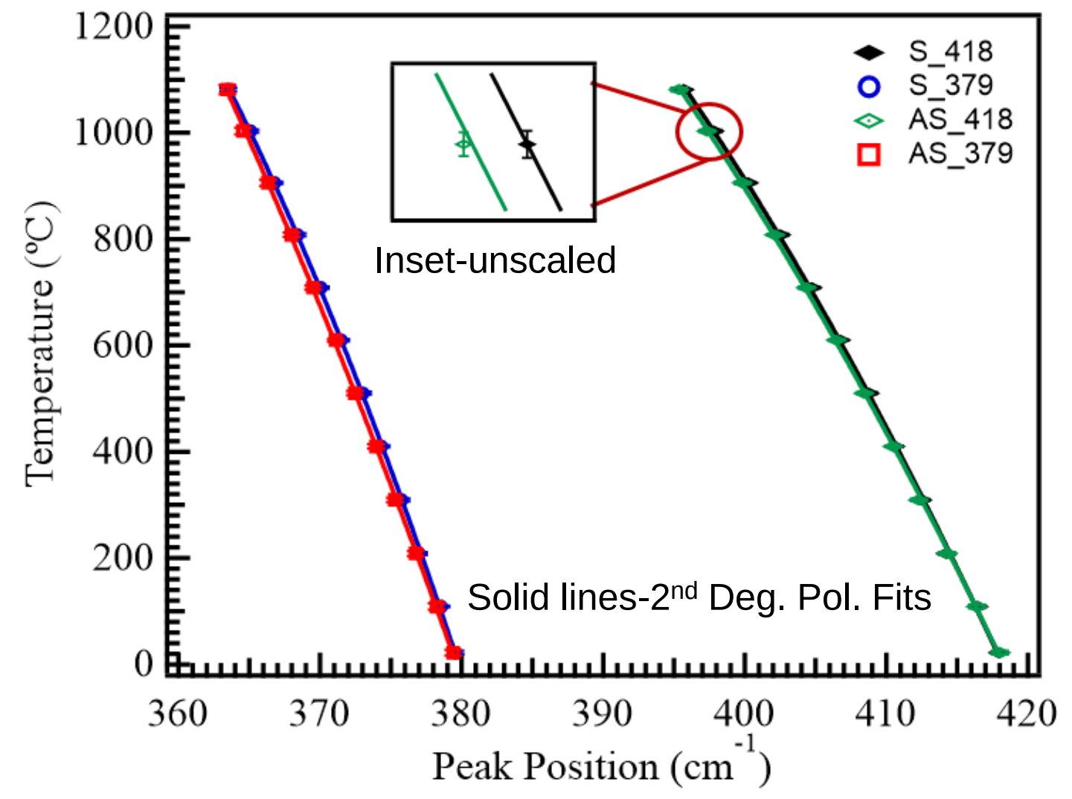
Peaks narrower, more symmetrical, and better separated



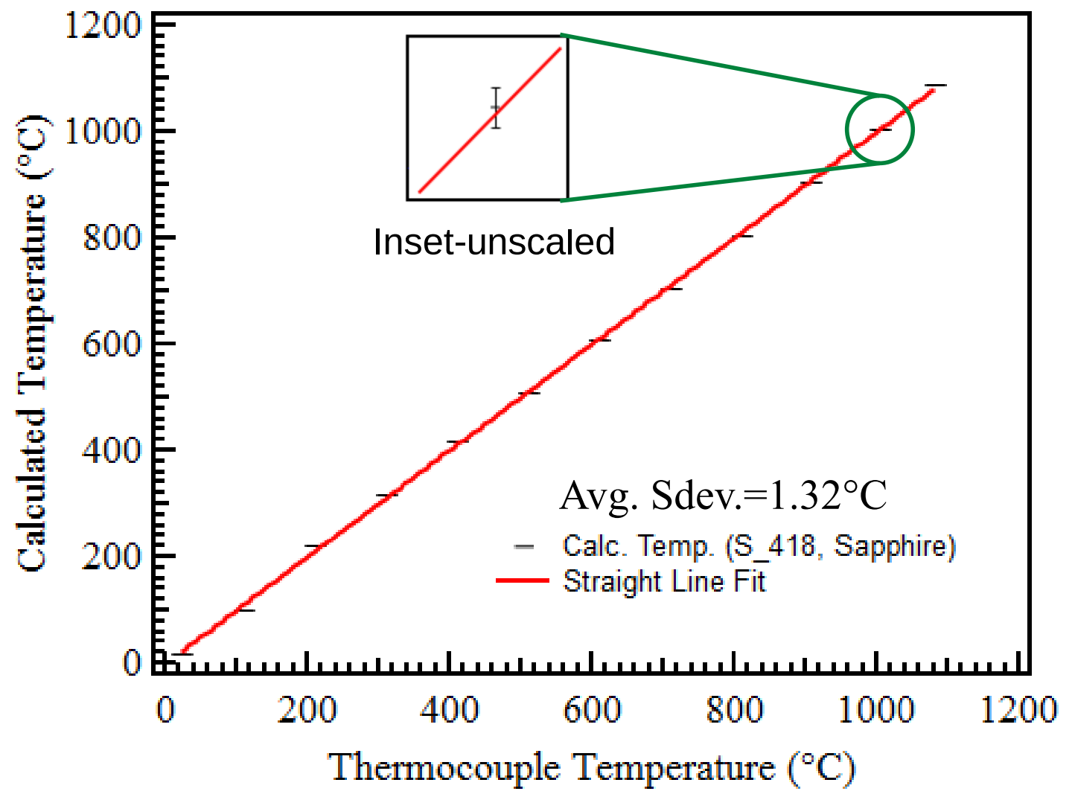
Stokes and anti-Stokes peaks in sapphire rod (average of 22 spectra)



Stokes peak position shifts from room temp. to 1081°C



Temperature change of peak positions in sapphire rod

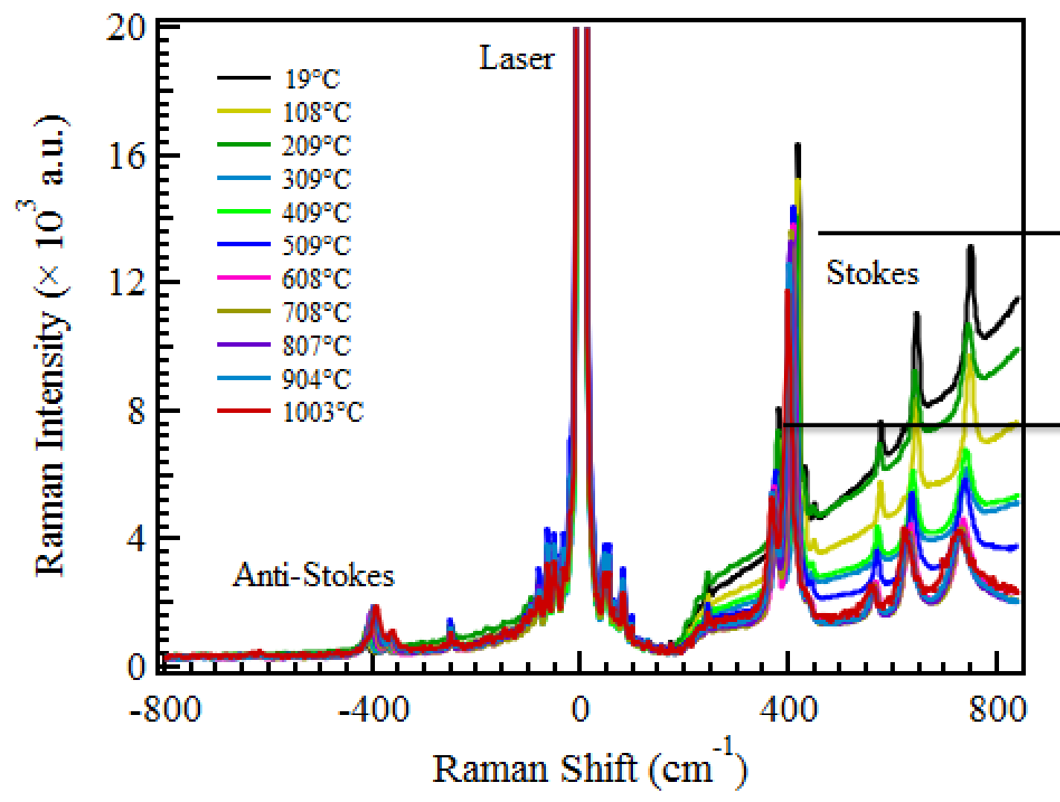


Calculated temperature from S_418cm^{-1} (room temperature position) peak vs thermocouple temperature

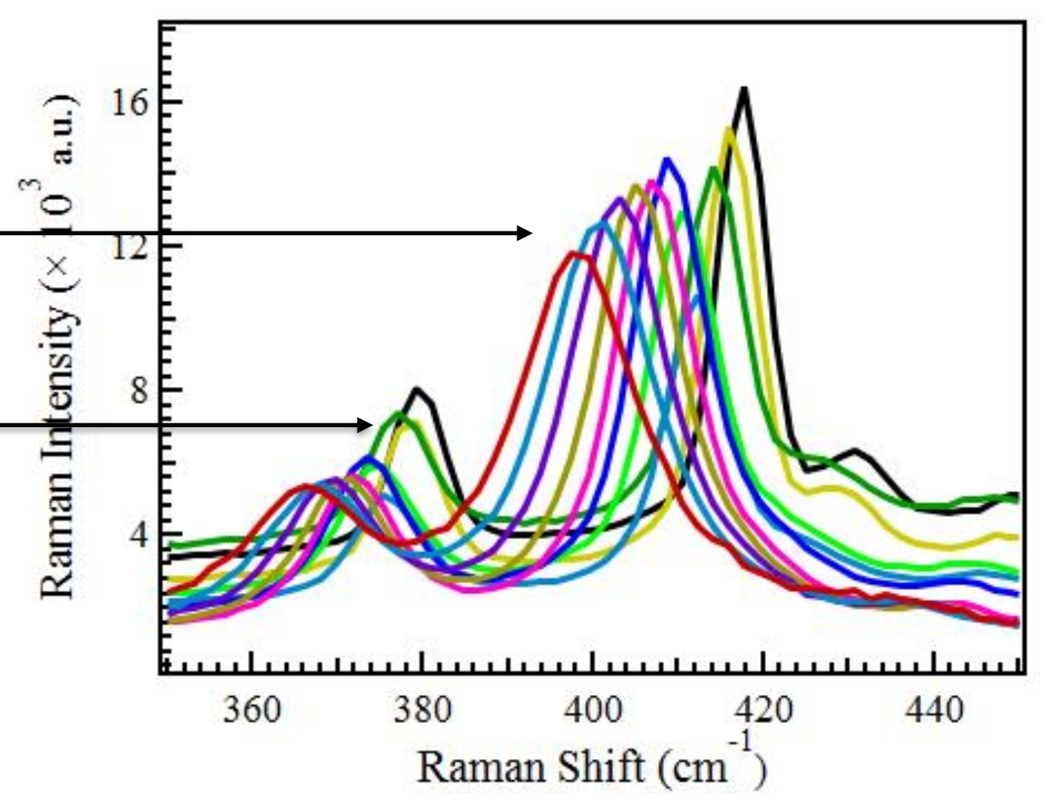
Polycrystalline alumina ceramic: investigated as a thermal barrier coating material (in combination with other materials)

1.7W laser power and 10s integration time

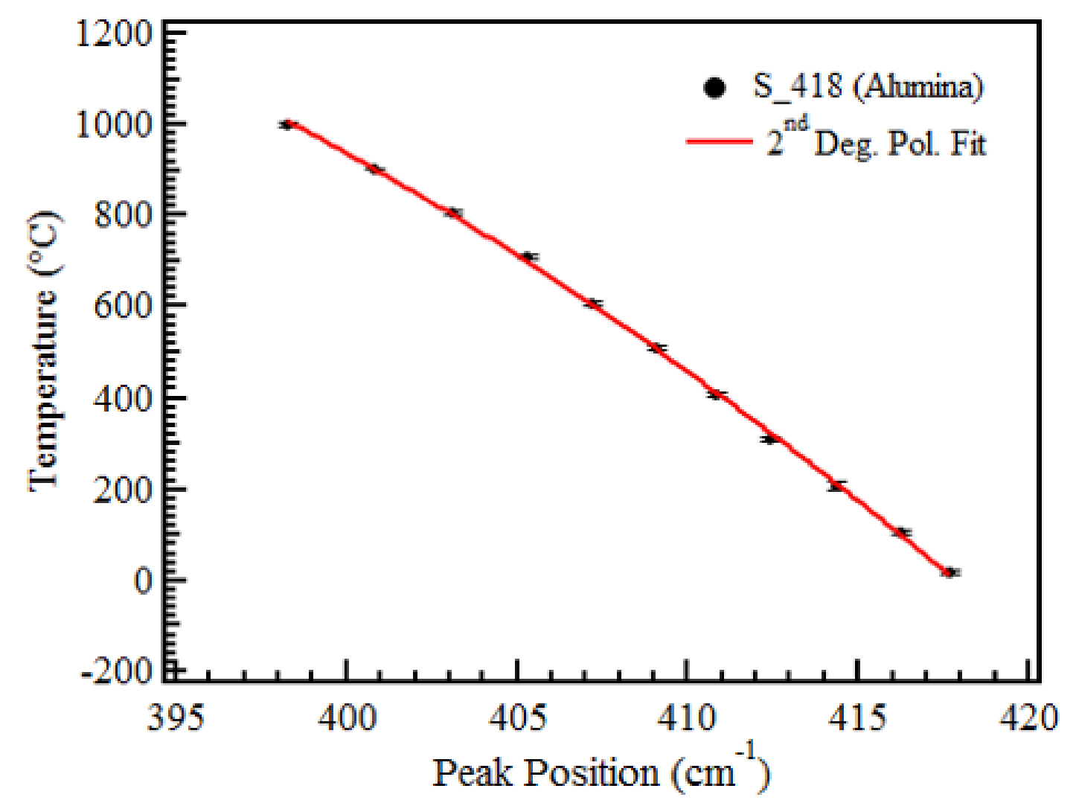
Peaks narrower, more symmetrical, and better separated



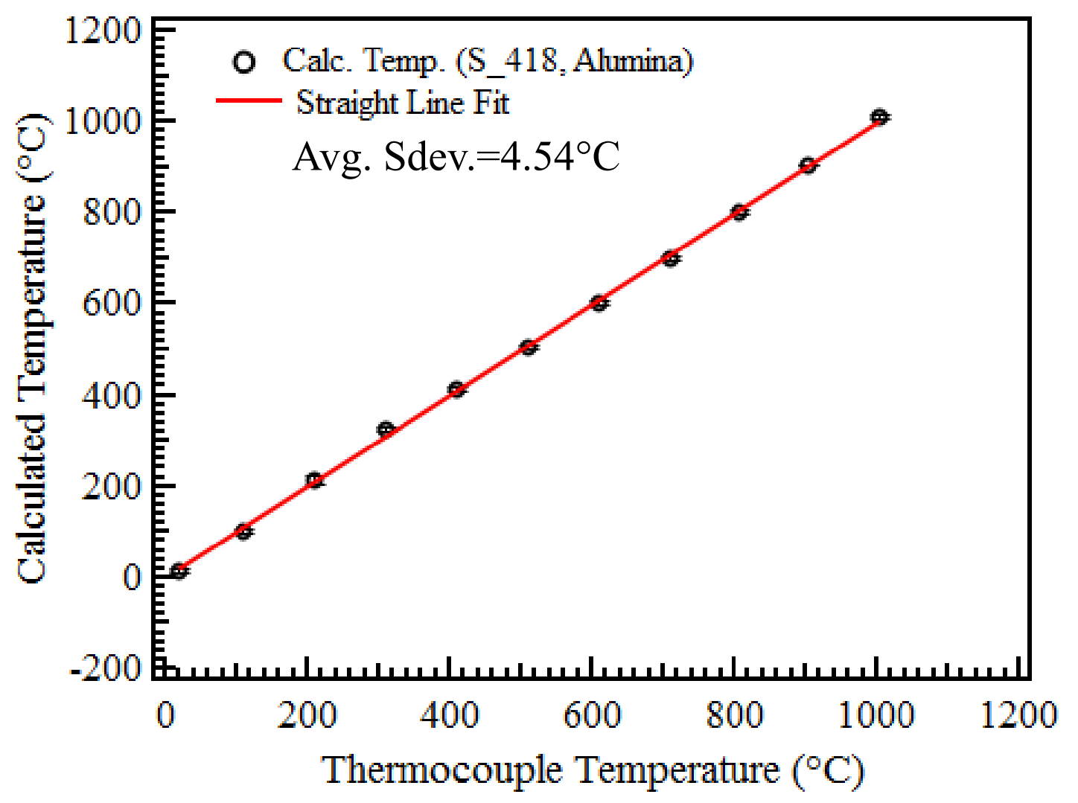
Stokes and anti-Stokes peaks in polycrystalline alumina ceramic (average of 12 spectra)



Stokes peak position shifts from room temp. to 1003°C



Temperature change of peak positions in polycrystalline alumina ceramic

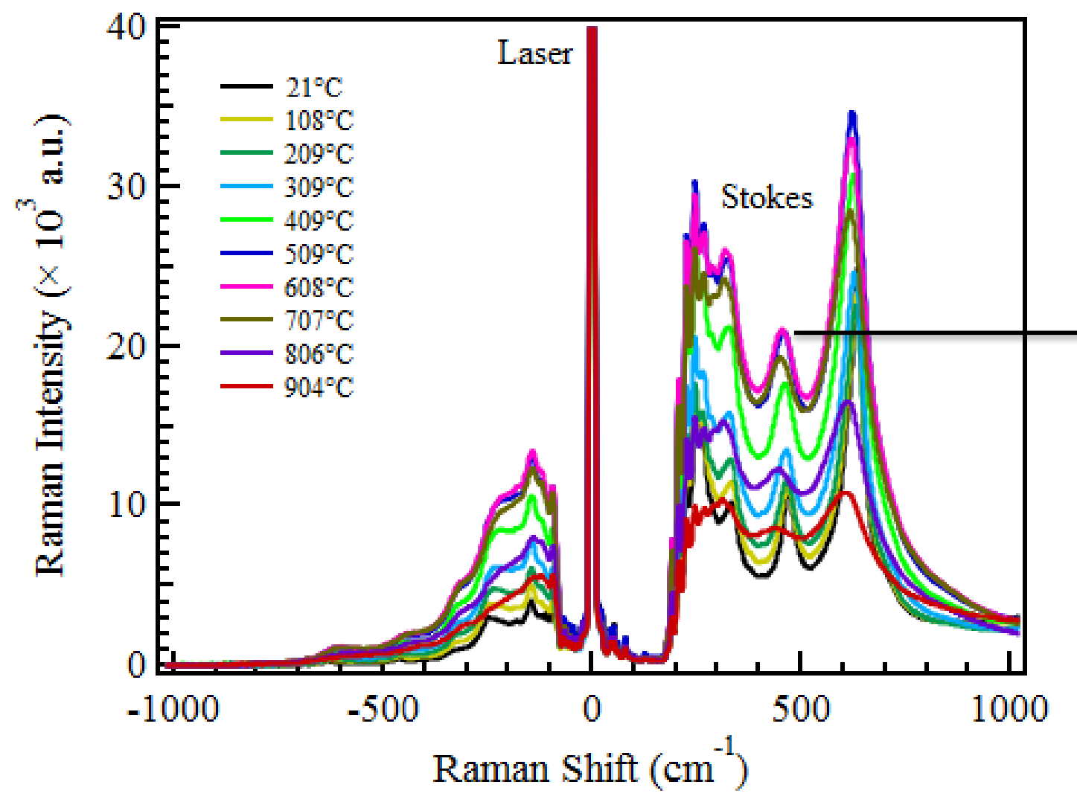


Calculated temperature from S_418cm^{-1} (room temperature position) peak vs thermocouple temperature

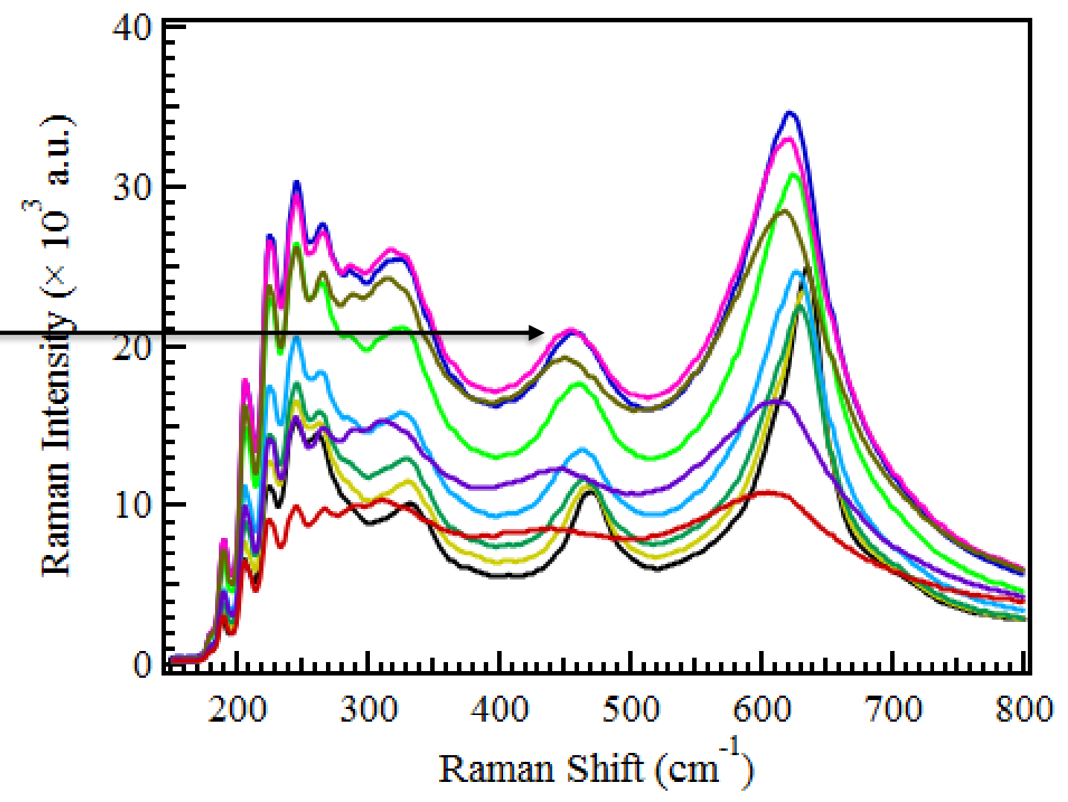
Yttria-stabilized zirconia (8% YSZ): widely used as a thermal barrier coating material e.g., in turbine blade

1.7W laser power and 3s integration time

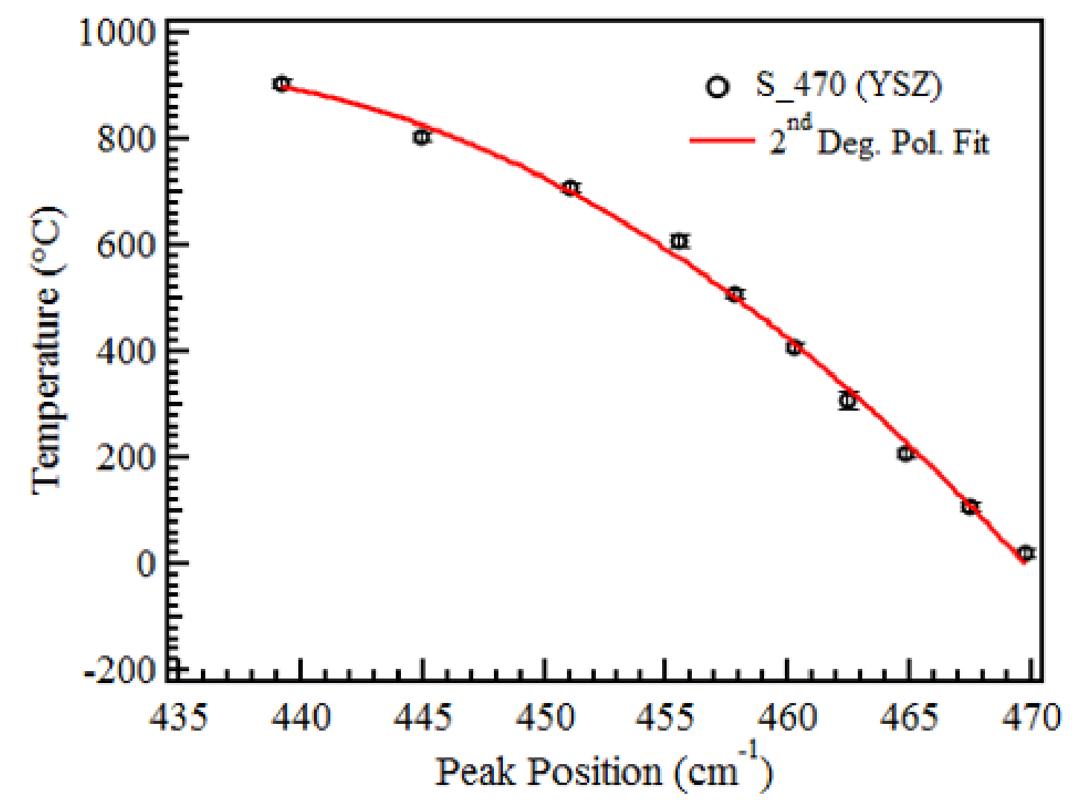
Peaks broader, less symmetrical, and heavily overlapped



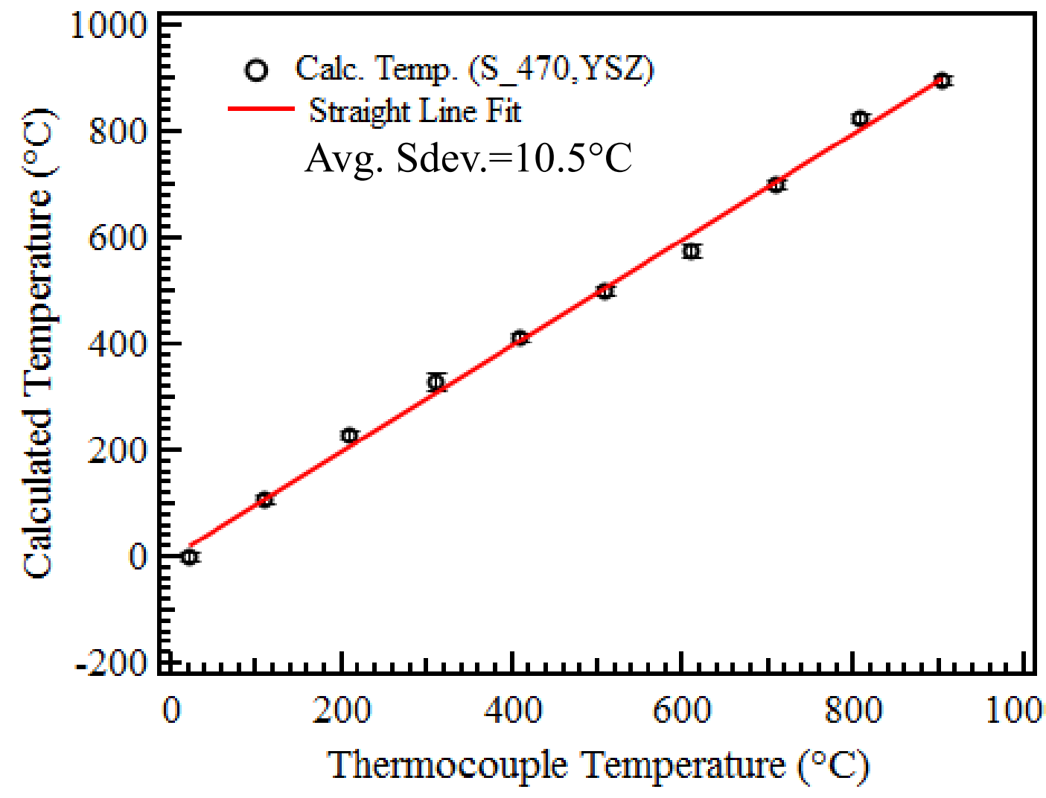
Stokes peaks in YSZ ceramic (average of 15 spectra)



Stokes peak position shifts from room temp. to 904°C



Temperature change of peak positions in YSZ



Calculated temperature from S_470cm^{-1} (room temperature position) peak vs thermocouple temperature

Sources of error: sample impurities and fluorescence, broadening of the peaks with temperature, and spectrometer calibration.

Future directions

- Obtain temperature mapping of 2D TBC (thermal barrier coating) surface.
- Improve portability of system for application on aerothermal rig.
- Test performance with other TBC materials.

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