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DUAL-LINE DETECTION RAYLEIGH SCATTERING MEASUREMENTS OF DENSITY AND TEMPERATURE

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Abstract

Measurements of the laser Rayleigh scattering signal in a flow to determine density and temperature have been commonly employed in open flames and wind tunnel environments. In these measurements, the density or reciprocal temperature is correlated with the Rayleigh scattering signal intensity. A major advantage of Rayleigh scattering for these applications is the simple experimental arrangement allowed by this technique. Intensity-based Rayleigh scattering measurements of density and temperature have been limited though to rλelatively clean flows in open environments so that interference from particle scattering and laser scattering from surfaces is minimal. A new approach, using Dual-Line Detection Rayleigh (DLDR) scattering[1], extends the applicability of Rayleigh scattering measurements of density and temperature to enclosed environments where surface scattering interference is high. Depending on particle size and optical properties, this approach may also reduce interference from particle scattering.

The Dual-Line Detection Rayleigh scattering technique requires use of laser output at two wavelengths, such as can be produced by copper vapor, argon ion, or frequency-doubled Nd-YAG lasers. The approach uses the inverse λ^4 dependence of the Rayleigh scattering signal to discriminate between the desired Rayleigh scattered signal and interferences from surface and particle scattering, which in general do not have the inverse λ^4 dependence. Experiments performed in a hot jet using the 510 and 578 nm lines of a copper vapor laser have shown that reliable temperature measurements can be performed even when the background interference level due to surface scattering is 2.5 times higher than the Rayleigh scattering signal.[1] Potential applications for the DLDR technique for which measurement precision estimates are presented include measurements of temperature in the main shuttle main engine, the turbine inlet region of gas turbine engines, and shock induced temperature transients in gas flow lines.

[1] M.V. Otugen, K.D. Annen, and R.G. Seasholtz, "Gas Temperature Measurements Using a Dual-Line Detection Rayleigh Scattering Technique," AIAA J. 31, 2098 (1993).

DUAL-LINE DETECTION RAYLEIGH SCATTERING TECHNIQUE

MOTIVATION

- NEED FOR 'SIMPLE' NONINTRUSIVE TEMPERATURE/DENSITY DIAGNOSTIC
  - INTENSITY-BASED POINT MEASUREMENT IN RELATIVE 'CLEAN' FLOWS
  - SIMPLE DETECTION CONFIGURATION
  - COMPATIBLE WITH WIDE VARIETY OF LASER EXCITATION SOURCES
- DUAL-LINE DETECTION
  - REDUCES SURFACE-SCATTERED LASER LINE CONTAMINATION OF RAYLEIGH SCATTERING SIGNAL
  - ALLOWS MEASUREMENTS IN ENCLOSED ENVIRONMENTS

DUAL-LINE DETECTION RAYLEIGH SCATTERING TECHNIQUE

THEORY

$$E_R = E_L C \sigma n$$

$$E_T = E_R + E_B = E_L C \sigma n + E_L C C'$$

$$\frac{E_T}{E_L} = C\sigma \frac{P}{\kappa T} + CC'$$

DUAL-LINE DETECTION RAYLEIGH SCATTERING TECHNIQUE

THEORY (CONTINUED)

$$\frac{E_{T,1}}{E_{L,1}} = \left(\frac{C_1 P \sigma_1}{\kappa}\right) \frac{1}{T} + \beta C_1 C'$$

$$\frac{E_{T,2}}{E_{L,2}} = \left(\frac{C_2 P \sigma_2}{\kappa}\right) \frac{1}{T} + C_2 C'$$

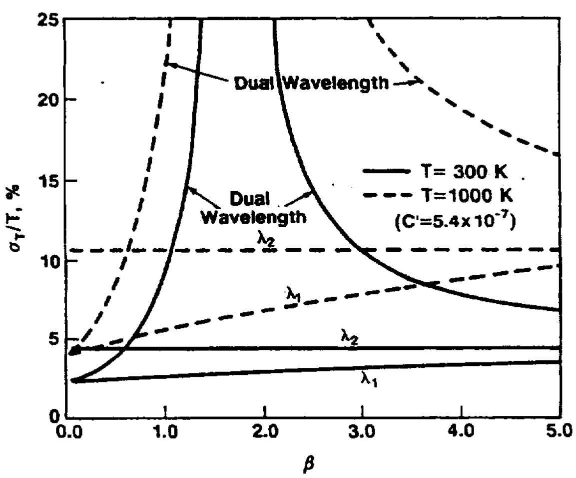
DUAL-LINE DETECTION RAYLEIGH SCATTERING TECHNIQUE

THEORY (CONTINUED)

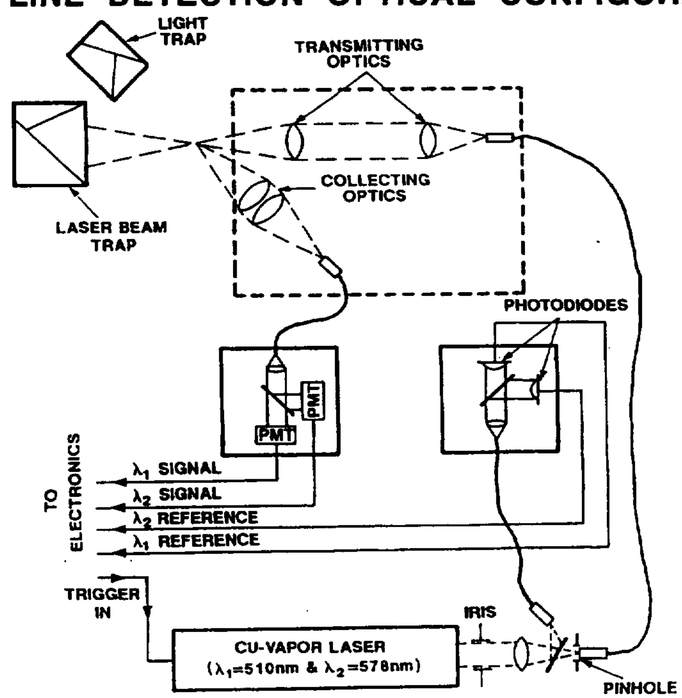
$$T = \frac{(P/\kappa)\,(\sigma_1 - \beta\sigma_2)}{(E_{T,1}/E_{L,1})\,(1/C_1) - (E_{T,2}/E_{L,2})\,(\beta/C_2)}$$

$$C' = \frac{(E_{T,2}/E_{L,2})\,(\sigma_1/C_2) - (E_{T,1}/E_{L,1})\,(\sigma_2/C_1)}{(\sigma_1 - \beta\sigma_2)}$$

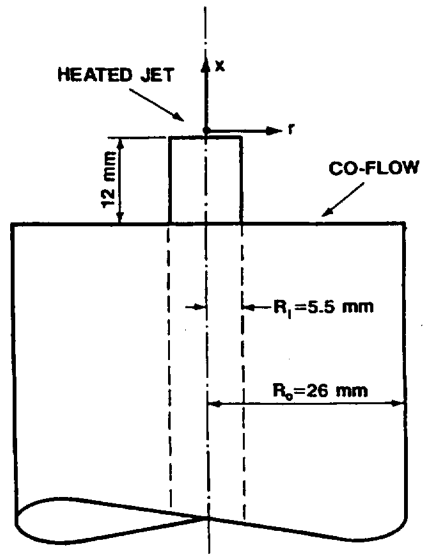
SINGLE-SHOT TEMPERATURE MEASUREMENT PRECISION



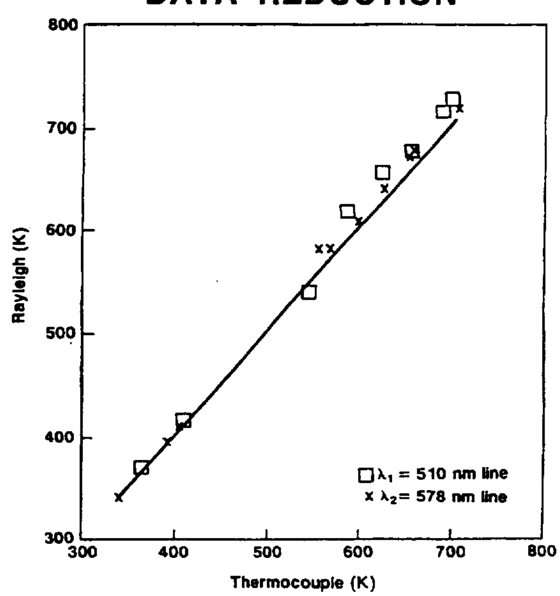
DUAL-LINE DETECTION OPTICAL CONFIGURATION



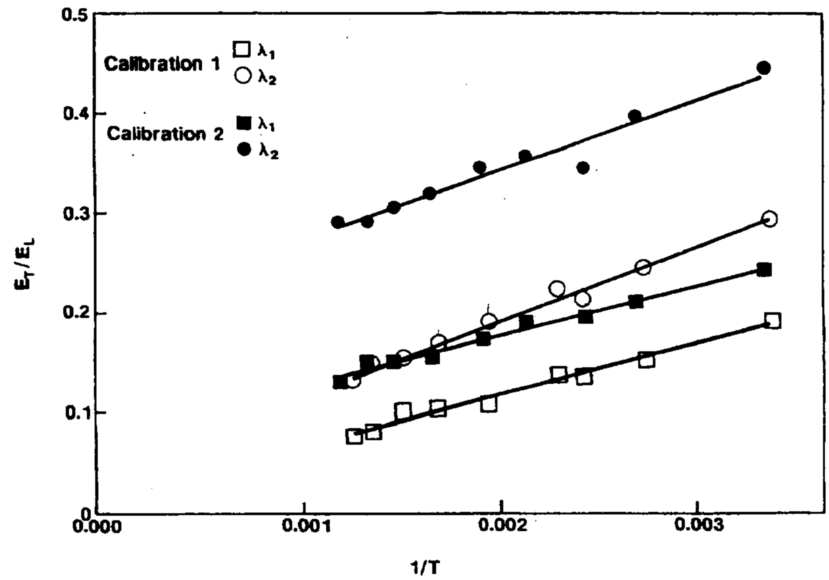
HEATED JET APPARATUS FOR SYSTEM CALIBRATION AND MEASUREMENTS



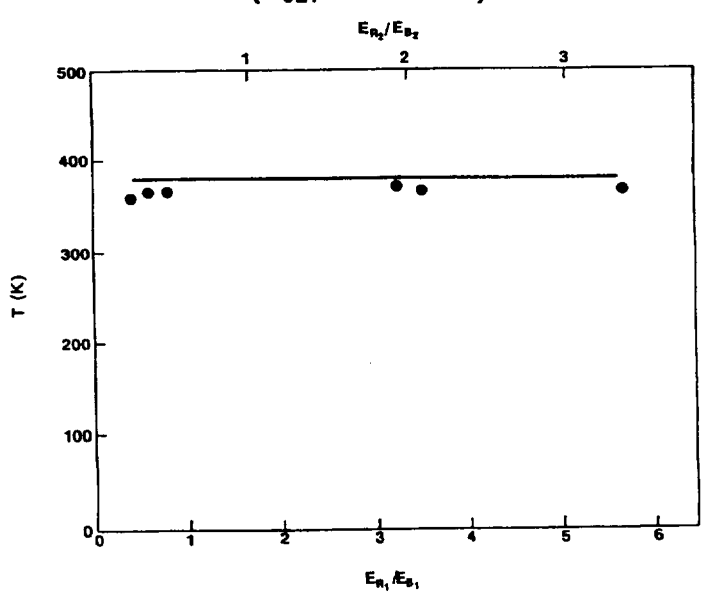
RAYLEIGH SCATTERING TEMPERATURE MEASUREMENTS USING SINGLE LINE DATA REDUCTION



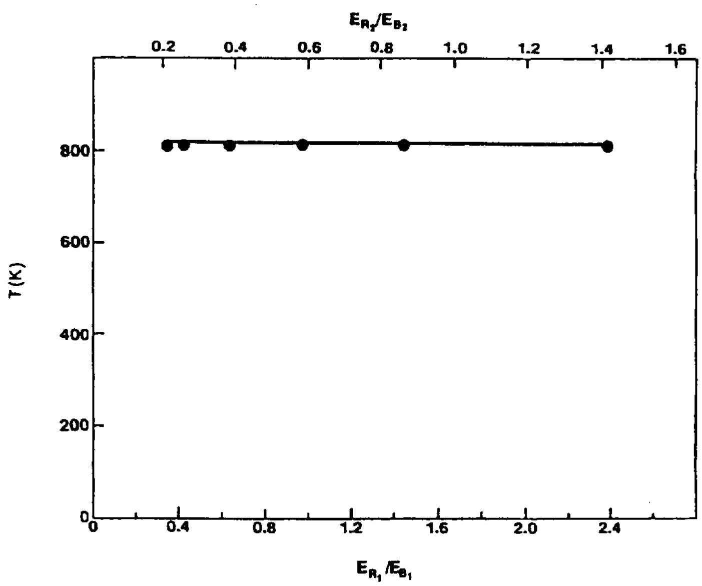
TYPICAL CALIBRATION CURVES FOR DIFFERENT BACKGROUND CONTAMINATION LEVELS



TEMPERATURE MEASUREMENTS WITH BACKGROUND LEVEL VARIATION (T_{JET} = 380 K)



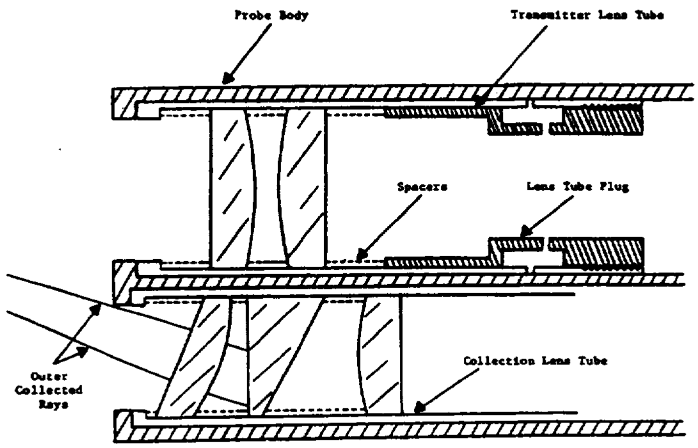
TEMPERATURE MEASUREMENTS WITH BACKGROUND LEVEL VARIATION (T_{JET} = 805 K)



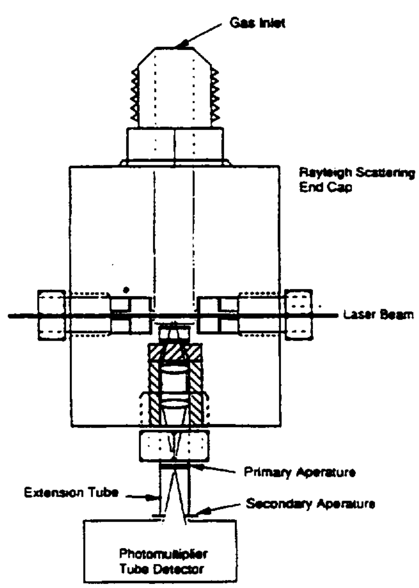
APPLICATIONS OF DUAL-LINE DETECTION RAYLEIGH SCATTERING MEASUREMENTS

- SSME TURNAROUND DUCT TEMPERATURE MEASUREMENTS
  - VERY HIGH PRESSURE, CLEAN FLOW
- GAS TURBINE COMBUSTOR EXIT TEMPERATURE MEASUREMENTS
  - MODERATE PRESSURE, RELATIVELY CLEAN FLOW
- HIGH PRESSURE FLEX HOSE TEMPERATURE MEASUREMENTS
  - HIGH PRESSURE, CLEAN, TRANSIENT FLOW

COMBUSTOR TEMPERATURE MEASUREMENT PROBE



FLEX HOSE TEMPERATURE PROBE



RAYLEIGH SCATTERING PROBE CHARACTERISTICS

- GAS TURBINE COMBUSTOR EXIT PROBE
  - RAYLEIGH SCATTERING/BACKGROUND LEVEL ~1
  - WATER-COOLED PROBE DESIGNED FOR 500 W/cm^2 HEAT FLUX
  - 0.05 mm^3 MEASUREMENT VOLUME
  - 1.7% SINGLE SHOT TEMPERATURE MEASUREMENT PRECISION AT 1200 K, 20 atm CONDITIONS AND 5 kHz Cu VAPOR LASER REP RATE
  - 0.2 % SINGLE SHOT MEASUREMENT PRECISION FOR SSME CONDITIONS
- FLEX HOSE PROBE
  - RAYLEIGH SCATTERING/BACKGROUND LEVEL ~0.2 - 0.5
  - 1.3% PRECISION FOR 0.1 ms INTEGRATION AT 10 atm 580 K
    0.3% PRECISION FOR 0.1 ms INTEGRATION AT 5000 psi, 1600 K
    (ASSUMING 1.5 W Ar ION LASER AT 488 nm)

CONCLUSIONS

- DUAL-LINE DETECTION RAYLEIGH SCATTERING MEASUREMENT TECHNIQUE ALLOWS TEMPERATURE AND DENSITY MEASUREMENTS TO BE PERFORMED WITH BACKGROUND LEVELS AS HIGH AS 2 - 5 TIMES THE RAYLEIGH SCATTERING SIGNAL LEVEL.

- RAYLEIGH SCATTERING/BACKGROUND RATIOS ON THE ORDER OF 0.5 - 1 OR HIGHER FOR ENCLOSED ENVIRONMENTS CAN BE OBTAINED WITH CAREFUL PROBE DESIGN.