STAR: Real-time Soot Emissions Instrument for Gas Turbine and Diesel Engines

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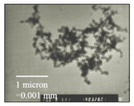
1.0 Objective

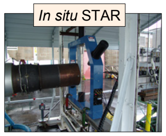
Measure engine exhaust soot mass concentrations in real time

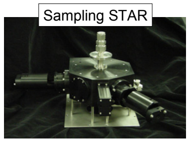
- Soot Mass Concentration (.001 – 1000 mg/m^3)
- Mean agglomerate Diameter: (50 – 500 nm)



Mass is mostly tied up in soot agglomerates, composed of small (25-35 nm) spherical carbon particles.

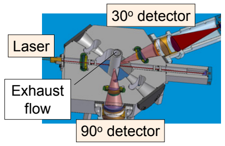
Method: Light Scattering by Two Angle Ratio, STAR





2.0 RDG/PFA scattering theory

Measure scattered light at two angles, (e.g. 90° & 30°), from soot passing through laser beam



- Start with Rayleigh analysis of light scattering from uniform and well defined spherical primary particle, d_p (25-35 nm), density, ρ_p, and refractive index function, f(m), giving a soot property, S_p.
- Use Particle Fractal Aggregate (PFA) concept of fractal dimension, D_f, to quantify the number of primary particles in a soot agglomerate with diameter, d_g.
- Compute the mass concentration, C_m and light scattering, $P_{T\theta}$ from agglomerate using Rayleigh-Debye-Gans (RDG) theory and integrate scattering over known agglomerate size distribution.
- Obtain fundamental formulas for mass and mean agglomerate size that do not rely on empirical calibration:

$$R_{\theta 1/\theta 2} = \left(\frac{M_{2\theta 1}}{M_{2\theta 2}}\right)\left(\frac{S(q_{\theta 1} d_{go})}{S(q_{\theta 2} d_{go})}\right)$$

: Agglomerate size is function of scattering ratio, $R_{\theta 1/\theta 2}$ only.

$$\frac{C_m}{P_{T\theta}} = \left(\frac{\rho_p}{(d_p/\lambda)^{3-D_f} f(\underline{m})}\right)\left(\frac{\lambda}{P_l I \Omega}\right) C_m\#(q d_{go})$$

$$\frac{C_m}{P_{T\theta}} = S_p \cdot I_p \cdot C_m\#(R_{\theta 1/\theta 2})$$

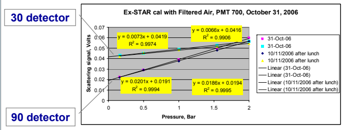
: Soot mass concentration. $C_m\#$ is function of scattering ratio, $R_{\theta 1/\theta 2}$ only.

3.0 Air Rayleigh scattering for calibration of instrument properties, I_p

$I_p = \lambda/(P_l I \Omega) = \lambda/(3\sigma_g N/8\pi P_r)$

P_r = Measured scattering at air pressure

$\sigma_g N$ = Rayleigh scattering cross-section at pressure, (±2% accuracy)



4.0 S_p depends only on primary particle properties:

$$S_p = \left(\frac{\rho_p}{d_p^{3-Df} f(\underline{m}_p)}\right)$$

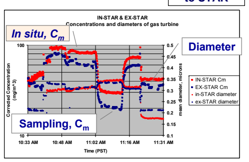
S_p is near invariant!

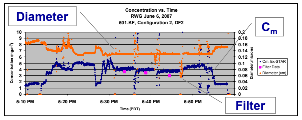
5.0 Gas turbine measurements

- *In situ* STAR compared with sampling STAR:

  Line loss is 20% over 8m line

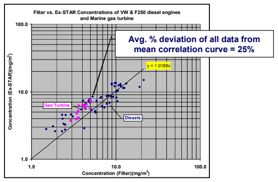
- STAR also gives good comparison with filter measurements



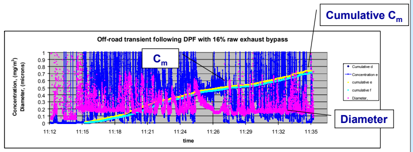


6.0 Diesel engine measurements

STAR vs. filter measurements for diesels (and gas turbines) @ exhaust

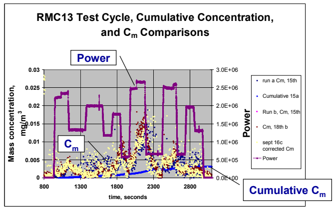


Transient STAR concentration and diameter after diesel particulate filter (DPF); 3 cycles

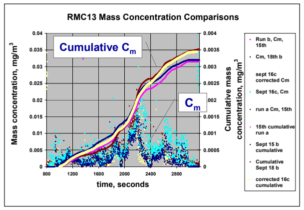


7.0 Diesel transient cycle (RMC13) with STAR after DPF & BG-3 dilution

STAR sensitivity to 0.5 µg/m^3

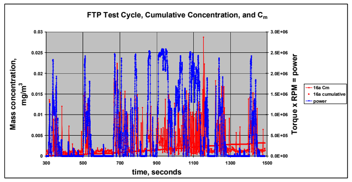


Repeatability within 3-10%

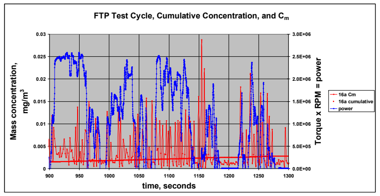


8.0 Diesel transient cycle (FTP) with STAR after DPF & BG-3 dilution

FTP cycle (rapid accelerations) gives large transient peaks in mass concentration, C_m



FTP cycle and STAR response detail



9.0 Summary:

- STAR (Scattering by Two Angle Ratio):
  - Based on fundamental theory for soot mass and diameter from light scattering
  - Use room air to verify calibration
- Gas turbine measurements:
  - In situ and sampling comparisons show 20% line loss for 8m line
- Transient diesel measurements:
  - Sensitivity to 0.5 µg/m^3
  - Repeatability of 3-10%
- STAR agrees with filter measurements within ±25% using primary particle property values from literature

10.0 Acknowledgments:

- We appreciate the assistance of Prof. R. Dibble at UC Berkeley, and Jessica Chapman of Process Metrix
- STAR development was supported by the Navy and Air Force Small Business Innovation Research (SBIR) program