Comparison of Experimental and First Principles Modeling Results for the PMTrac® Electrostatic Soot Sensor

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1. Presenter
Presentation Outline

1) PMTrac® Sensor Design & Correlation Review
2) Sensor First Principles Model
3) Comparison to Experimental Results
PMTrac Sensor Design

- Venturi draws exhaust gas through sensor
- Gas flows between electrodes at high electric field (~1KV)
- Charged particles (+/-) are electrostatically collected on respective (-/+ ) electrode surfaces
- Field-induced breakoff of charged soot agglomerates carries charge from one electrode to another generating an amplified current
HD Engine Dynamometer Test Results: PMTrac Sensors Correlate Well with AVL MSS

PMTrac Raw Signal vs. Concentration From MSS
155 Tests, Average of 6 sensors, No Omissions

PMTrac Raw Signal vs. Concentration at Sensor
155 Tests, Average of 6 Sensors, No Omissions

Actual Sensor Concentration mg/m³ (MSS mg/m³ * 273/K/sensor T [K])

Ideal Gas Law Correction

R² = 0.8717

R² = 0.9506
Sensor Variability

- **Multiple sensors in good agreement** ($R^2=0.99$, 900+ Test Runs).
- **Divergence from MSS in unison**, implying predictable variance in measurement principle.
PMTrac® Electrostatic and Particle Physics Model: Overview

**Calculations**

<table>
<thead>
<tr>
<th>1) Exhaust Gas Properties</th>
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<tbody>
<tr>
<td>a) Mean free path length</td>
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<td>b) Dynamic viscosity</td>
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<td>c) Cunningham slip factor</td>
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<th>2) Electrostatic Particle Physics Properties</th>
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<td>a) Electrical particle mobility</td>
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<td>b) Capture efficiency</td>
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<td>c) Captured particle mass</td>
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<th>3) PMTrac Sensor</th>
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<td>a) Break-off agglomerate mobility</td>
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**Diagram:**
- EGV & EGT
- Sensor Flow Model (CFD)
- Heat Transfer Model (FEA)
- Actual Electrode and Gas T and Flow Rate Through Sensor
- PMTrac Electrostatic Particle Mobility & Agglomeration Model
- PMTrac Output (mg/m3)
- Exhaust Soot Characteristics
- Sensor Break-off Agglomerate Characteristics
- Sensor Design and Calibration Characteristics
PMTrac® Electrostatic and Particle Physics Model: Inputs

1) Exhaust Gas Parameters
   a) Exhaust gas temperature (EGT (300 °C))
   b) Exhaust gas velocity (EGV(30 m/s))

2) Exhaust Soot Parameters
   a) Charge distribution (CHARGEA, CHARGE B)
   b) Particle size distribution (MEAN, SIGMA)
   c) Mass-mobility exponent (MASSEXP)

3) Break-off Agglomerate Parameters
   a) Charge distribution (AGGLCHARGE)
   b) Agglomerate size distribution (AGGLDP)
   c) Fraction of charged agglomerates from HVE (AGGLFRAC T)

4) Sensor Parameters
   a) Current (ISENSE(nA))
   b) Gain (GSENSE (nA/(mg/m3) during calibration at 300 C, 30 m/s)
Sensor Measures Charged Particles, Not Neutral Particles

SMPS = Scanning Mobility Particle Sizer
ELPI = Electrical Low Pressure Impactor
ESP = Electrostatic Precipitator
CPC = Condensation Particle Counter
DMA = Differential Mobility Analyzer

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Flow Influence: Soot Flux Increase Offsets Capture Efficiency Decrease

- At low flows, charged soot captured by sensor and sensor signal both increase linearly with flow.
- At higher flows, the increase in charged soot entering starts to be cancelled by the lower trapping efficiency of the sensor. Both the trapped soot current and the sensor response level off, but more rapidly in the sensor signal.
APS and SMPS Consistently Detect 0.3 to 10 um Break-off Agglomerates Exiting The PMTrac Sensor
SEM Images Confirm Agglomerates Exiting the Sensor

- 30-50nm particles evident in early stages on new HV electrodes
- 2-5 micron agglomerates evident on HV electrode at later stages and exiting sensor via SMPS and APS
- Consistent with electrostatic force directed assembly (ESFDA) and break-off agglomerates
In Situ (Field Applied) SEM Imaging Work
Comparison of First Principles Model with PMTrac Sensor Output for mini-CAST Soot

**Particle parameters**

- **DTYPE**: D
- **MEAN**: 6.30E-08
- **SIGMA**: 1.55297
- **NTOTAL**: 1.61E+13
- **CHARGEA**: 3.7337
- **CHARGEB**: 0.3021
- **MASSEXp**: 2.3311
- **ZTEMP**: 293.15
- **PDENSITY**: 1
- **AGGLDP**: 1.00E-06
- **AGGLCHARGE**: 100
- **AGGLFRACT**: 0.55
- **Masscorr**: 2.57E+00

- **Normalized PMTrac Signal (nA/nA(1 LPM))**
- **Percentage Difference**

- **Sensor Flow (LPM)**

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PMTrac Sensor Model Transfer Function

PMTrac Mass Correlation, Model-based Transfer Function Applied

\[ R^2 = 0.975 \]

Sensor Correction Factor Table

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A first-principles-based model and transfer function that converts the PMTrac sensor’s signal (nA) to soot mass concentration (mg/m³) as a function of EGT, EGV, soot characteristics, and sensor characteristics has been developed.

SMPS was used to characterize particle size and charge distribution of soot entering and leaving the sensor. The influence of PSD, charge distribution, applied voltage, and sample flow rate on sensor output was characterized.

PMTrac sensor measures charged particles (and not neutral particles).

SMPS, APS, and SEM results confirm that larger (0.4 to 10 um) particles exit sensor and verifying ESFDA and signal amplification.

The PMTrac sensor signal is amplified several orders of magnitude higher than expected if the observed current were solely caused by combustion-generated charged particles depositing their charge.

These tests have enabled us to gain a better understanding of the sensor’s operating principle, validate our unified sensor model, and confirm our signal amplification mechanism.