Emissions Controls Technologies, Part 2

Factors Impacting EGR Cooler Fouling – Main Effects and Interactions

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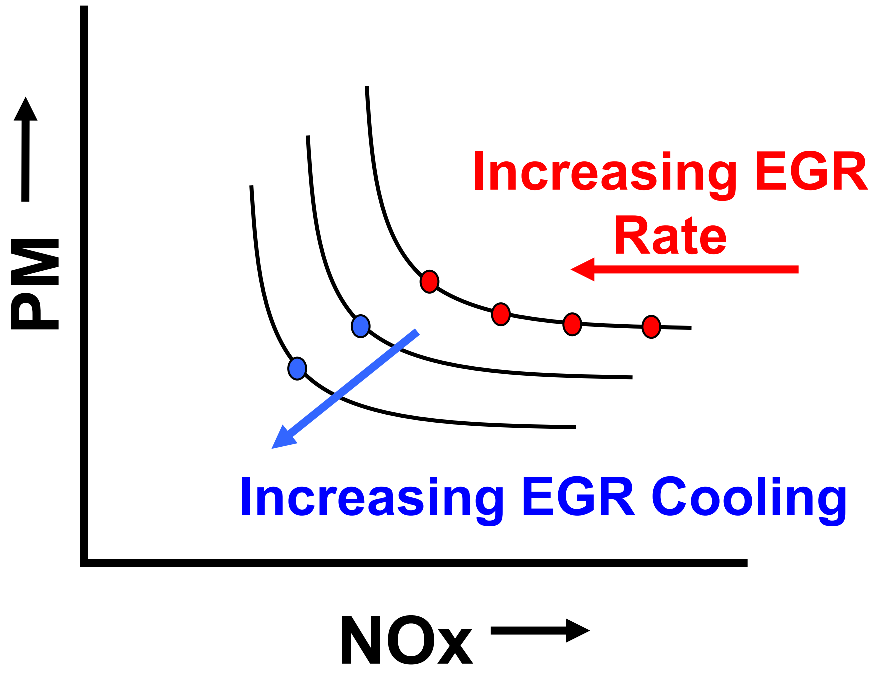
Benefits and Challenges of Cooled EGR

- Benefits
  - Enables more EGR flow
  - Cooler intake charge temp
  - Reduces engine out NOx by reduced peak in-cylinder temps

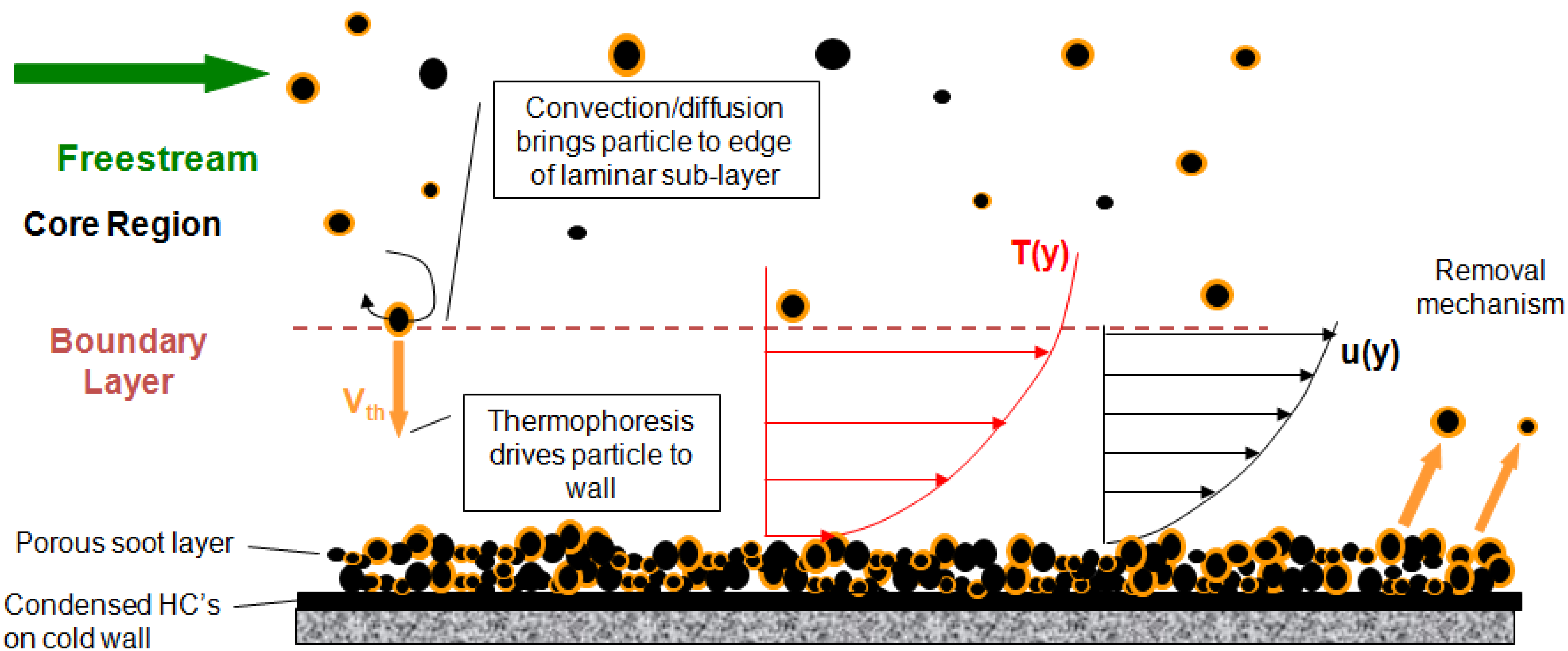


- Challenges
  - More HC's/SOF
  - More PM
  - More heat rejection
  - More condensation
  - HC/PM deposition in cooler (fouling) → degraded heat transfer and higher flow resistance

After 200 hr. Fouling Test

What is EGR Cooler Fouling?

- Deposition of Exhaust Constituents on EGR Cooler Walls
  - Decreases heat transfer effectiveness and increases flow restrictiveness



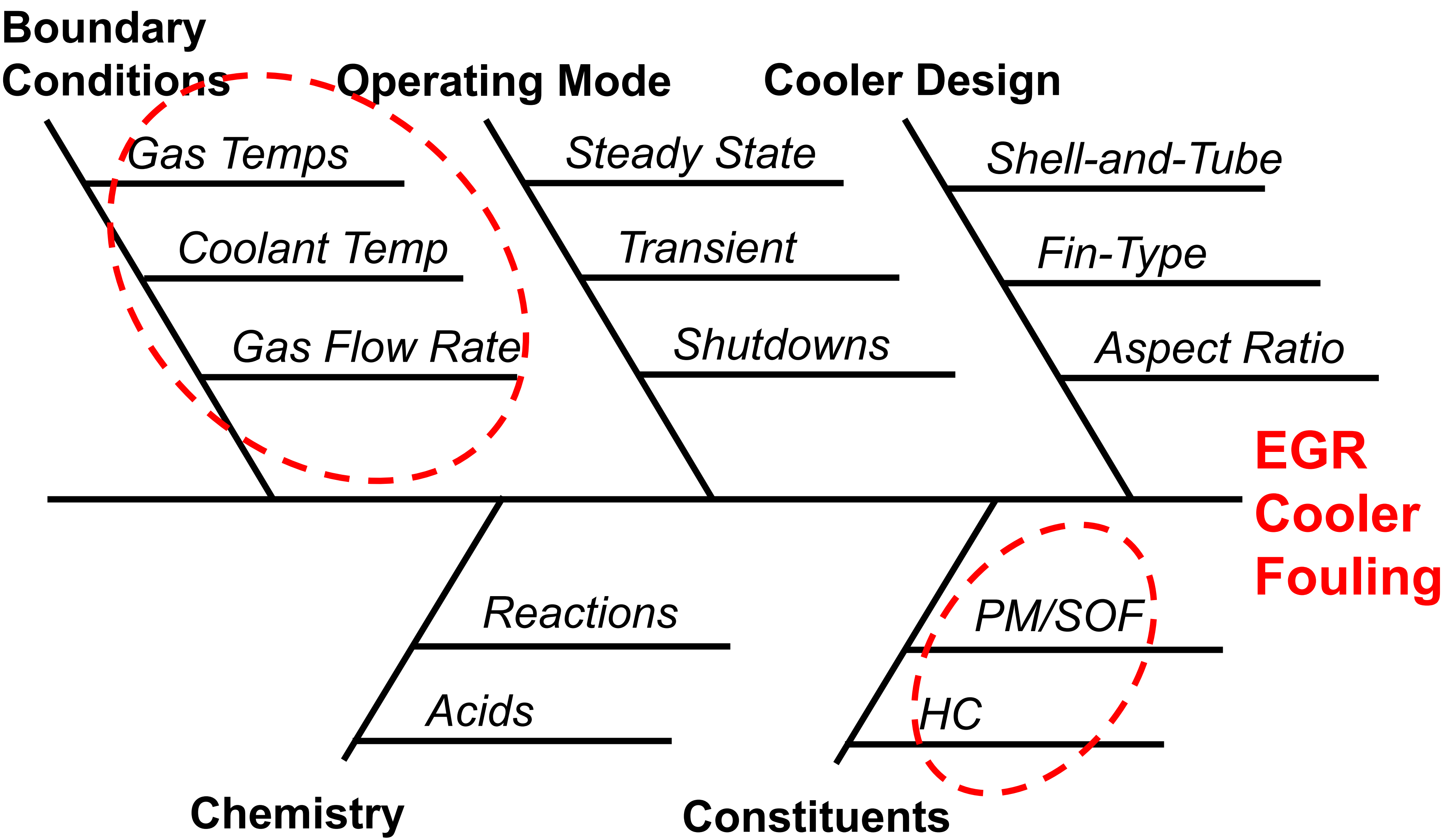
Previous DEER Conferences

- DEER 2007
  - Benefits of an EGR catalyst for EGR Cooler Fouling Reduction
- DEER 2008
  - Overview of EGR Cooler Fouling Literature Search
  - Results of initial controlled fouling experiment
    - High gas flow velocities reduce exhaust constituent trapping efficiency
    - Low coolant temperatures increase Hydrocarbon condensation
    - An oxidation catalyst is only marginally helpful at eliminating the heavier Hydrocarbons that are likely to condense in an EGR cooler
- DEER 2009
  - Further results from controlled fouling experiment
  - Complex interaction between PM and HC
  - HC's are more likely to increase mass of deposits
  - PM more likely to decrease heat transfer
  - Initial results of 1D EGR Cooler Fouling model

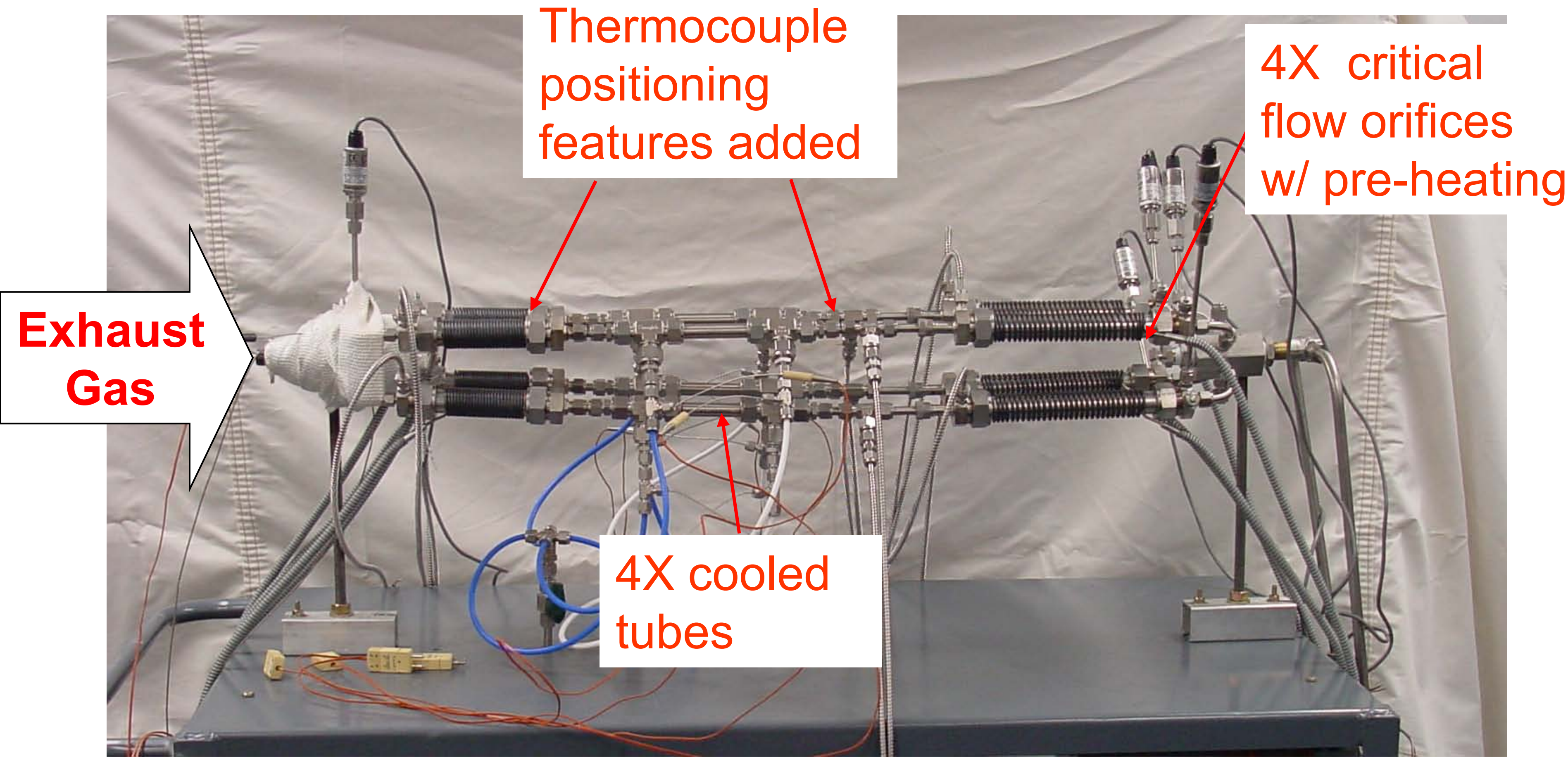
DEER 2010

- Present results of a large, full factorial DOE including key factors impacting EGR cooler fouling
  - Gas temperature
  - Coolant temperature
  - Gas flow rate
  - Hydrocarbon concentration
  - Particulate matter concentration
- Use an improved controlled EGR cooler fouling sampler that improves repeatability and accuracy of temperature and flow rate controls
- Experiments are short term (3 hours) and use simplified round Ø ¼” tubes
- Show updated modeling results

What Causes EGR Cooler Fouling?



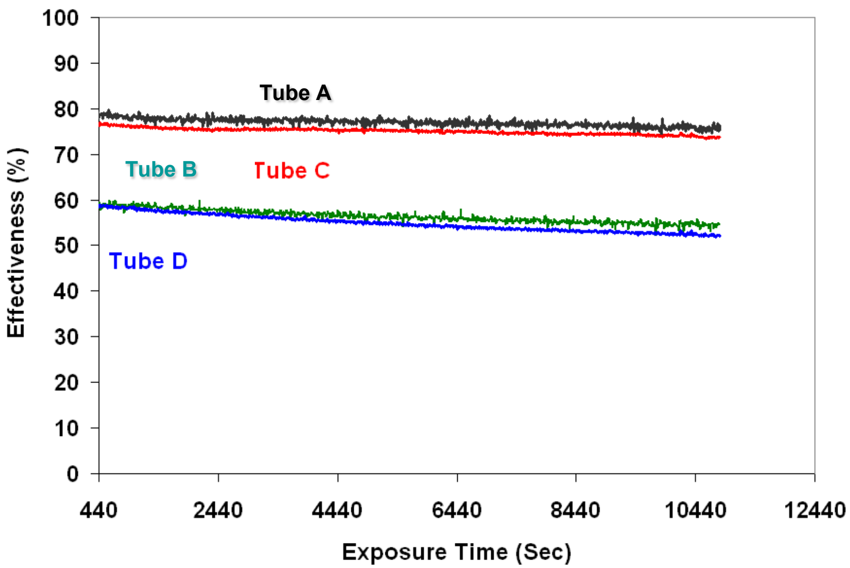
Improved EGR Cooler Fouling Sampler



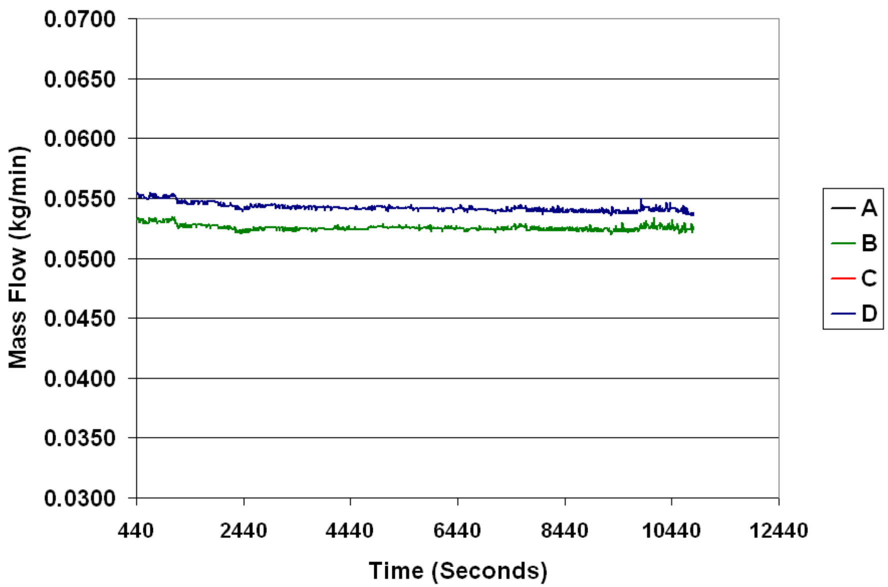
- Air pre-heating added to eliminate startup transients

Improved EGR Cooler Fouling Sampler, cont'd

More consistent positioning of thermocouples leads to close repeatability of effectiveness data for tube replicates

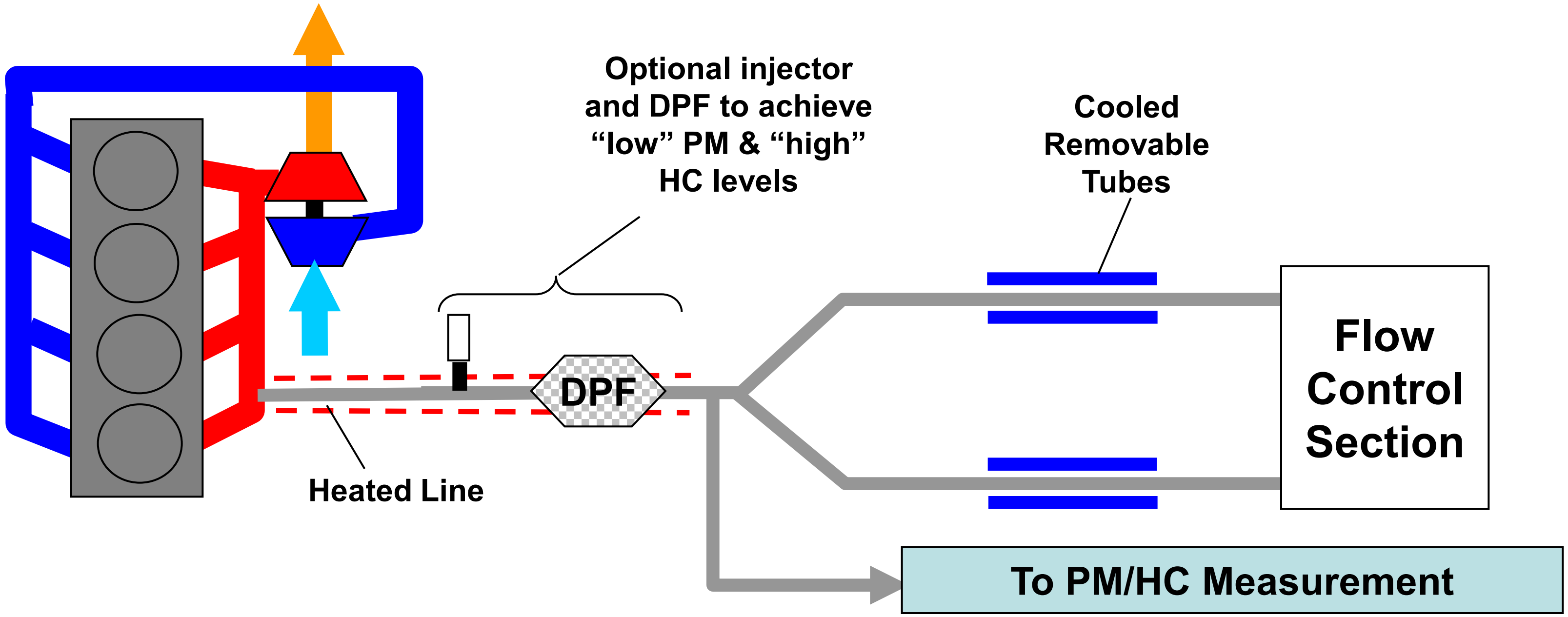


Less drop off in mass flow rate over time due to heating upstream of critical flow orifice



Test Engine and Conditions

- 2008MY 6.4L Turbo-Diesel
- 3 hours steady-state @ 2250 rpm / 300 ft-lbf
- 1.5 FSN
- 35 ppm C1 HC
- 385°C exhaust temperature
- CP Chem 2007 ULS Certification Diesel (≈ 47 Cetane)



Experimental Factor Levels

- Average Gas Velocity: 13.5 and 22 m/s via critical flow orifices (chosen to represent range of typical range)
- Gas Inlet Temperature: 220 & 380ºC
- Coolant Temperature: 40 & 90ºC
- PM Levels: 0.4 FSN (or 7.5 µg/l via uncatalyzed DPF) and 1.5 FSN (30 µg/l or natural level)
- HC Levels: 35 ppm C1 (natural) and 250 ppm C1 (achieved via downstream diesel fuel injector)
- Coating: An "anti-coking" tube coating was also included as a sixth factor in a fractional factorial DOE

- Note: Factor levels varied "outside of cylinder" to avoid confounding effects. Gas pressure constant ≈ 7 psig.

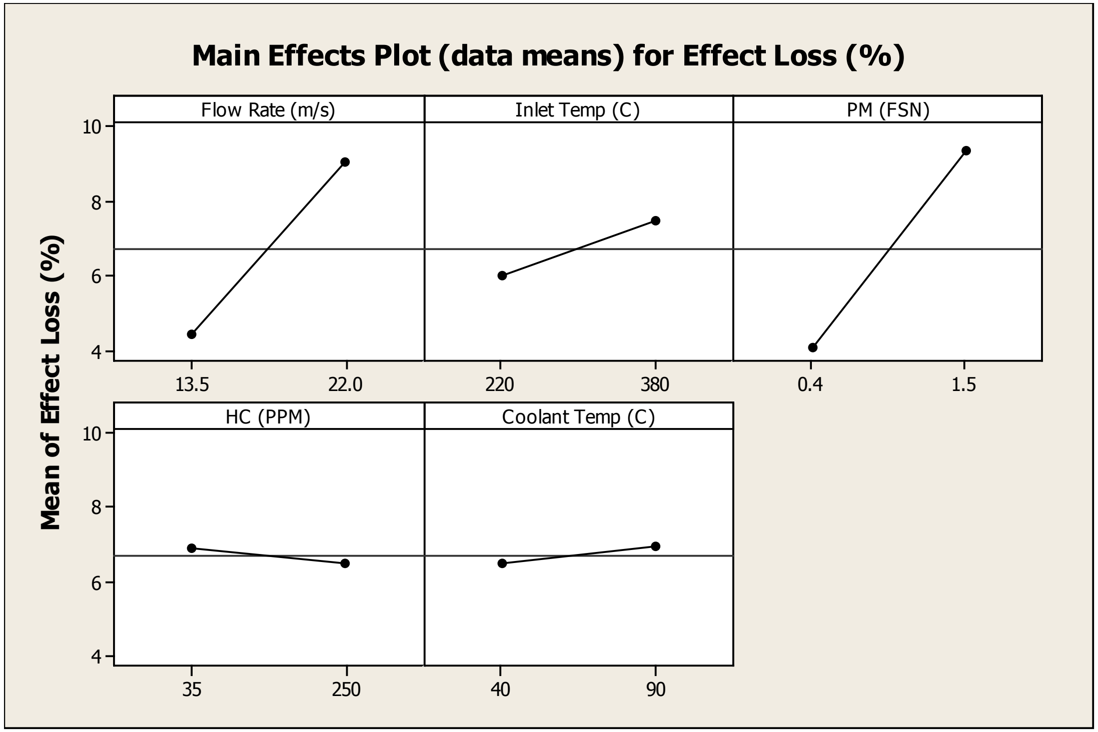
Experimental Structure and Response Variables

- Full factorial DOE with replicates
- 32 * 2 replicates / 4 tubes = 16 runs
- Response variables include
  - Absolute heat transfer effectiveness loss

$$\varepsilon = \frac{q_{actual}}{q_{max\ theoretical}} = \frac{T_{gas,in} - T_{gas,out}}{T_{gas,in} - T_{coolant}}$$

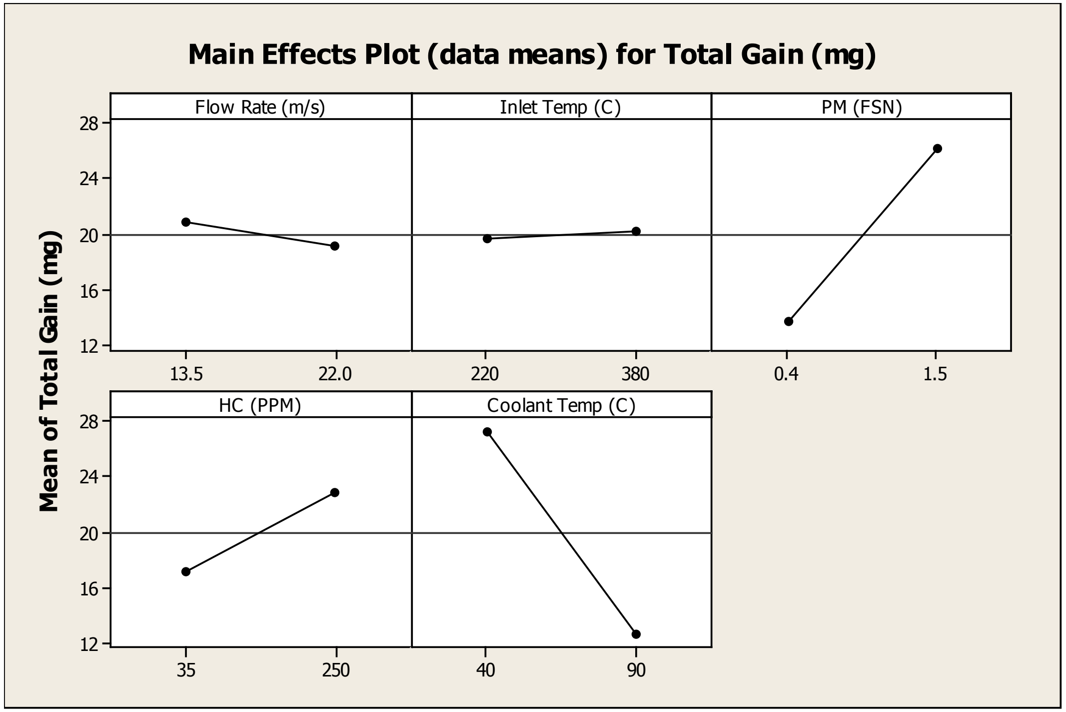
  - Deposit mass gain
  - Deposit "high level" speciation
    - Light volatile (fuel HC's, water)
    - Heavy volatile (oil)
    - Non-volatile (soot, ash, inorganics)
  - Deposit layer sectioning, microscopy, thickness

Effectiveness Loss Main Effects



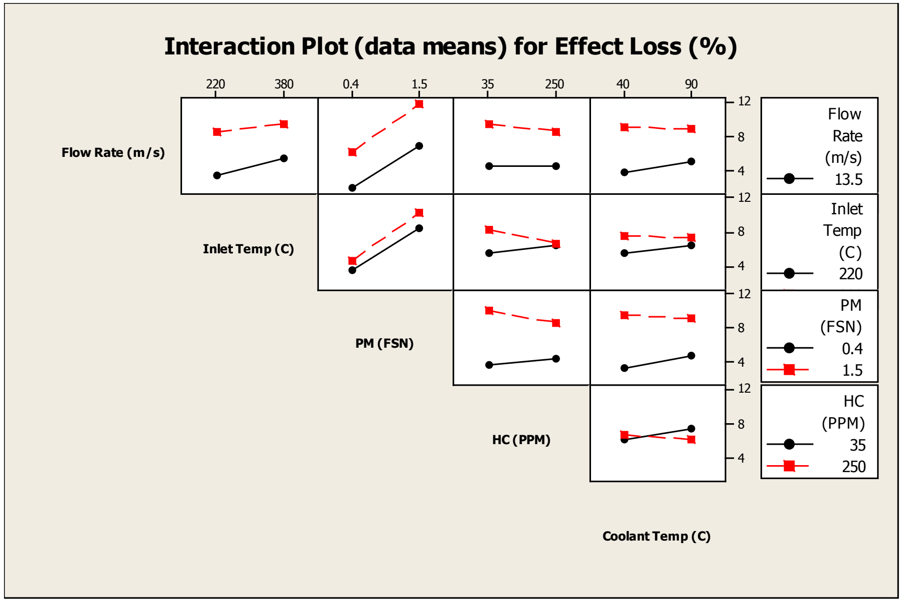
- ✓ Higher inlet temperatures → more thermophoresis
- ✓ More thermophoresis → more PM deposition
- ✓ More PM deposition → more effectiveness loss
- ✓ Also, higher flow rate → double mass flow → higher effectiveness loss

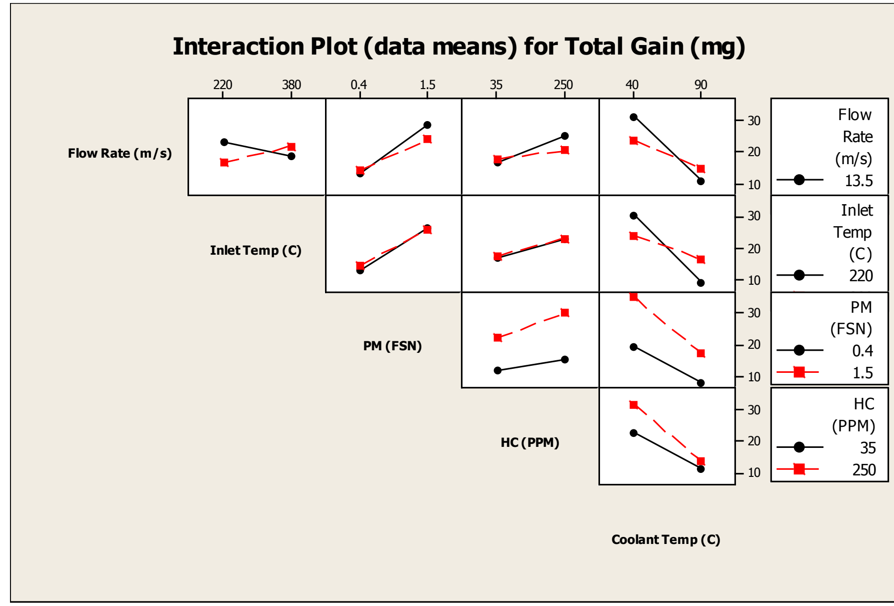
Deposit Mass Accumulated Main Effects



- Lower coolant temperatures → more Hydrocarbon condensation
- More Hydrocarbon condensation → more mass gain
- Higher PM levels also resulted in higher mass gains, but not higher flow rate (double mass exposure) and higher inlet temperature!
- Interesting interactions ….

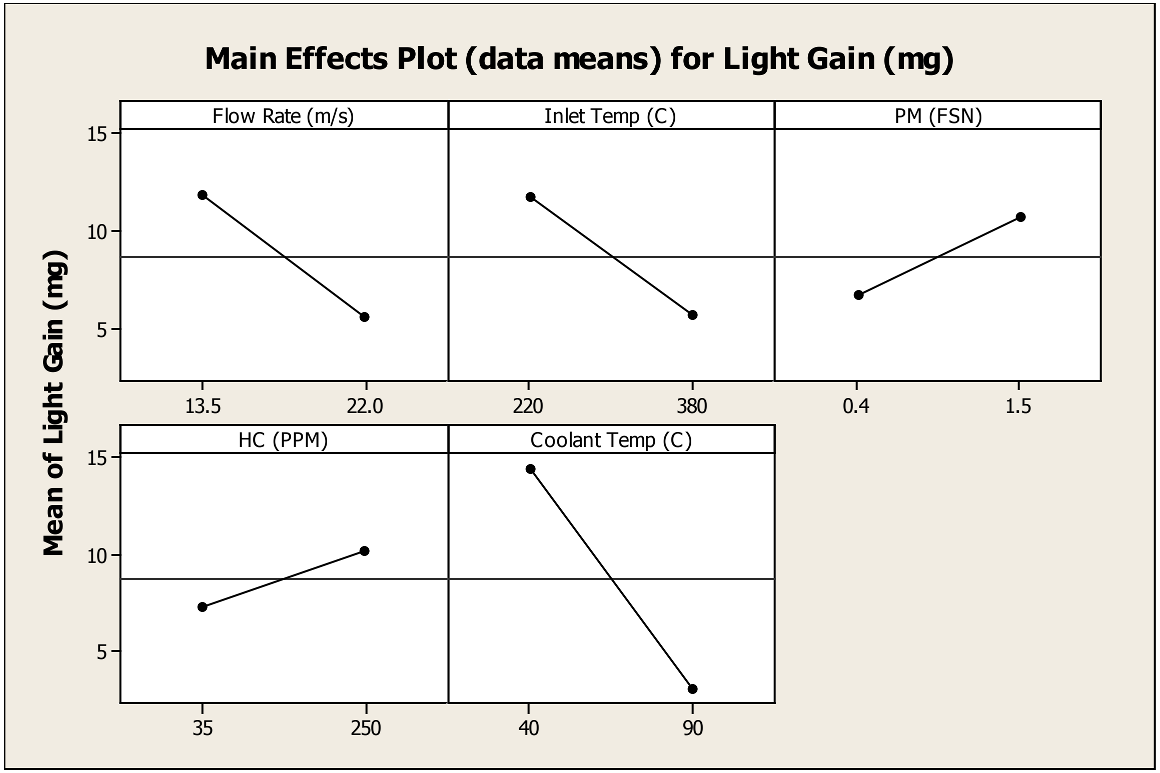
Interactions





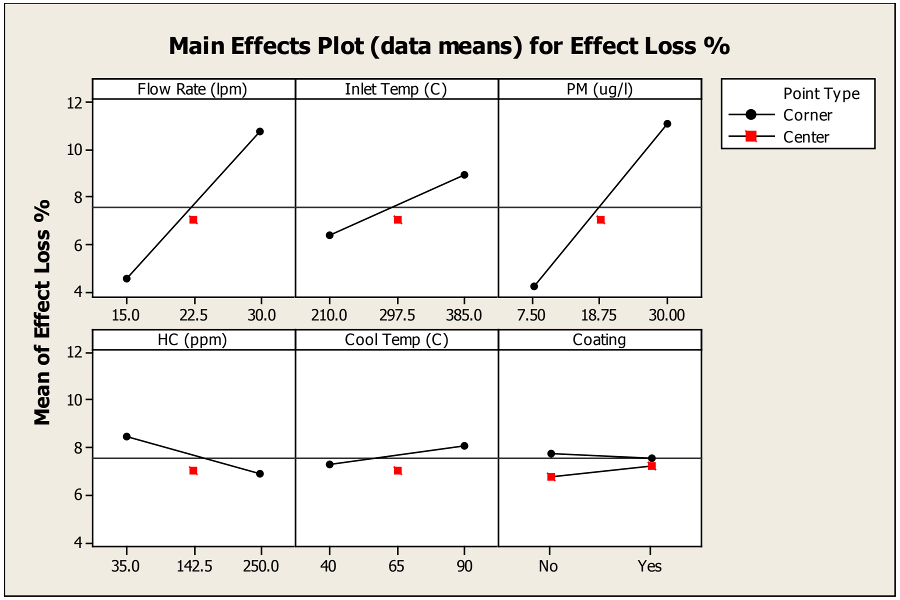
- ✓ Non-parallel lines indicate an interaction between factors
- ✓ Intersecting lines indicates a strong interaction between factors
- ✓ For example: For total deposit mass accumulated several 2-way and higher interactions are statistically significant!
- ✓ The physics are complicated!

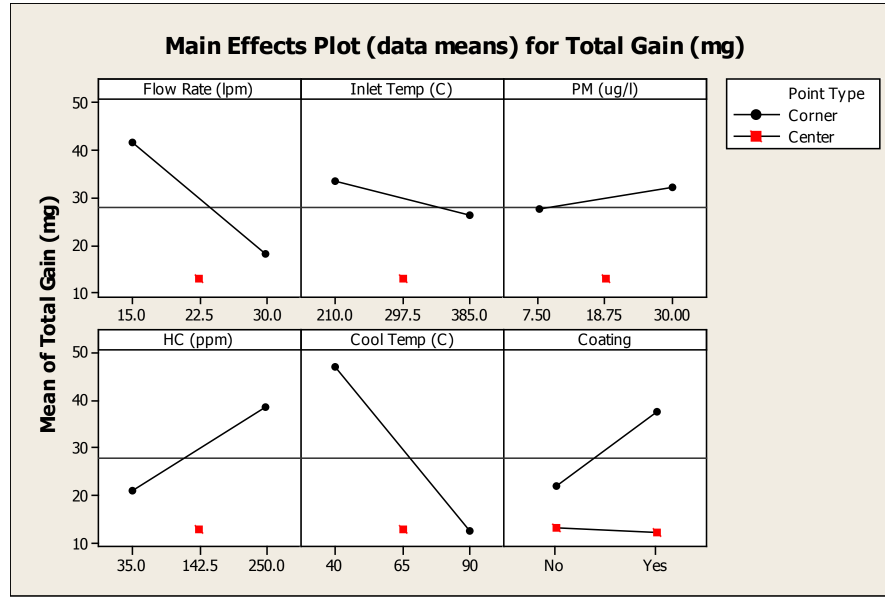
Light Volatile Mass Accumulated Main Effects



- Sources are diesel fuel, other light volatiles. Accounts for ½ mass gain.
- Some trends as expected (HC concentration, coolant temperature).
- Others puzzling (half the mass gain with double the exposure)!
- Key point: Deposit layer thermal conductivity variable & important.

Impact of Tube "Anti-coking" Coating

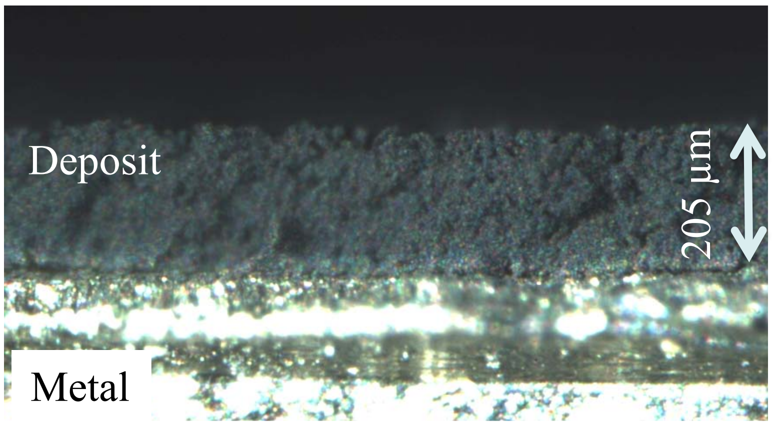




- ✓ ½ fraction factorial with added factor of anti-coking coating.
- ✓ No impact on effectiveness loss. "Center-points" indicate linear responses.
- ✓ Coating increases mass gain? Responses are not linear between factor levels.

Cooled Tube Microscopy, Sectioning

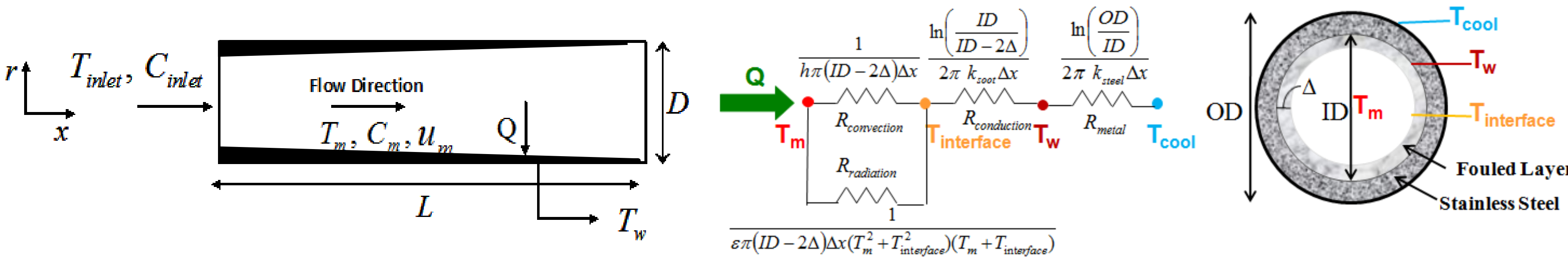
6 hours, 30 SLPM, High HC, Low Coolant Temp



Exposure Time (hr)	Flow Rate (SLPM)	HC	Coolant Temp	Density (g/cc)	StDev (g/cc)
0.5	15	High	Low	0.069	0.041
1	15	High	Low	0.104	0.034
6	15	High	Low	0.077	0.038
12	15	High	Low	0.054	
0.5	30	High	Low	0.050	0.027
3	30	High	Low	0.056	0.010
6	30	High	Low	0.064	0.016
0.5	30	Low	High	0.037	0.025
4	30	Low	High	0.043	0.008
12	30	Low	High	0.032	

- **Deposit thicknesses were measured by milling the tube metal to ~2 mils and then breaking it open thereby revealing the deposit cross-section.**
- **From this and the mass measurement, the density of the deposit was determined.**
- **High HC and low coolant temperatures increased the deposit density.**

Modeling Overview



A schematic of the surrogate tube and the heat transfer model

Model features:

- Subroutines for EGR properties calculation
- Calculating of density, viscosity, thermal conductivity of a mixture including four components (CO_2, H_2O, N_2, O_2)
- Variable thermal conductivity of deposit layer
- Variable sticking and removal coefficients
- Radiation, convection, and conduction heat transfer mechanisms included

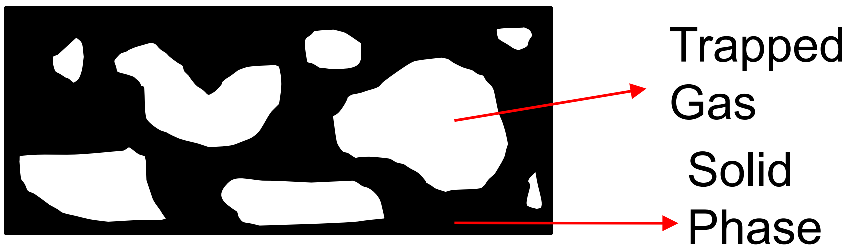
Key Physics:

- Thermophoresis, the only dominant deposition force on soot particles
- No physical verification for deposit stabilization in long exposures
- Possible hypotheses for stabilization:
  - **Kinetic theory removal mechanism**
  - **Variable deposit thermal conductivity**

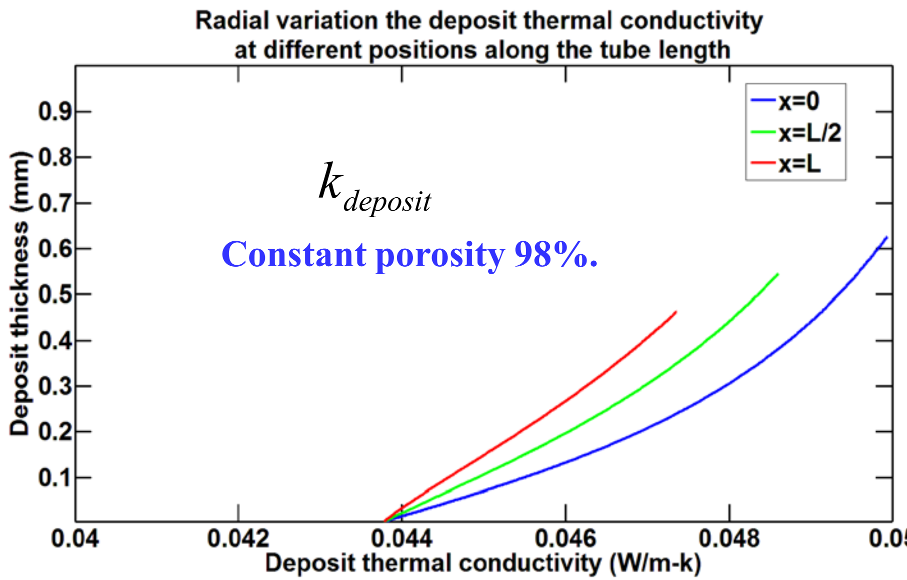
Variable Thermal Conductivity of Layer

The equivalent thermal conductivity is calculated as:

$$k_{cluster} = (1-\varphi)^{1.5} k_{Solid} + \varphi^{0.25} k_{Fluid}$$



$$\varphi = porosity$$

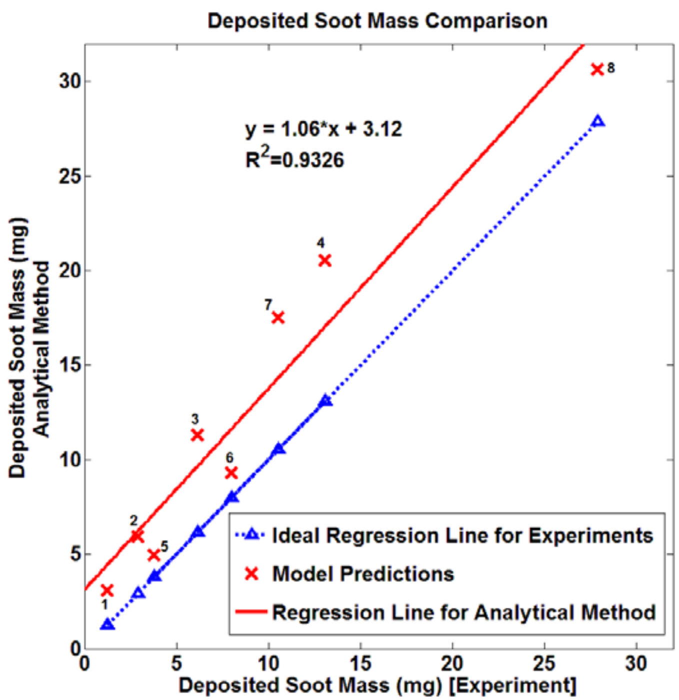


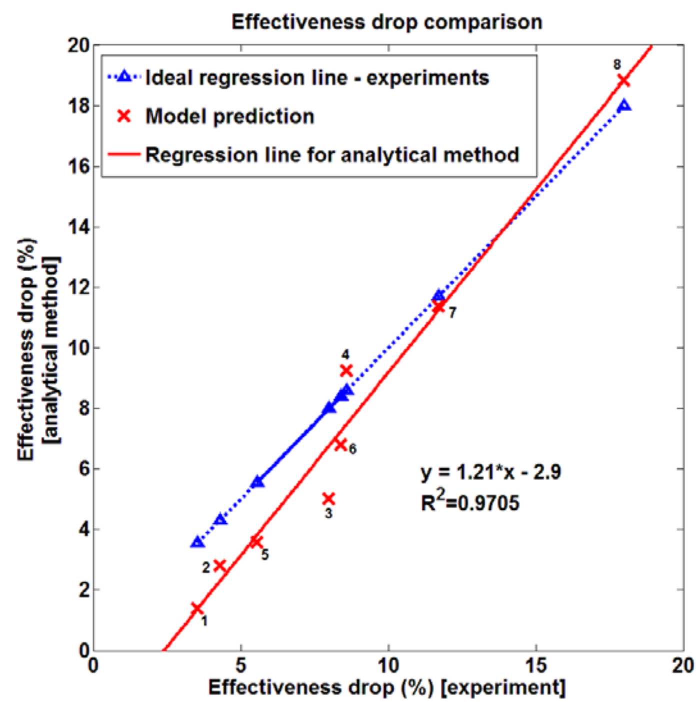
In our study, the solid can be assumed as Graphite and EGR as the fluid:

$$\boxed{k_{deposit} = (1-\varphi)^{1.5} k_{Graphite} + \varphi^{0.25} k_{EGR}\Big|_{T_{avg}}}$$

Short Exposure Time

- Different thermo-hydraulic conditions.
- The comparison for soot mass gain along the tubes and the effectiveness drop of the surrogate tubes after 3 hours (short exposure) are in a reasonable agreement with ORNL data.
- Comparable results for short exposure times with no removal and variable deposit properties.





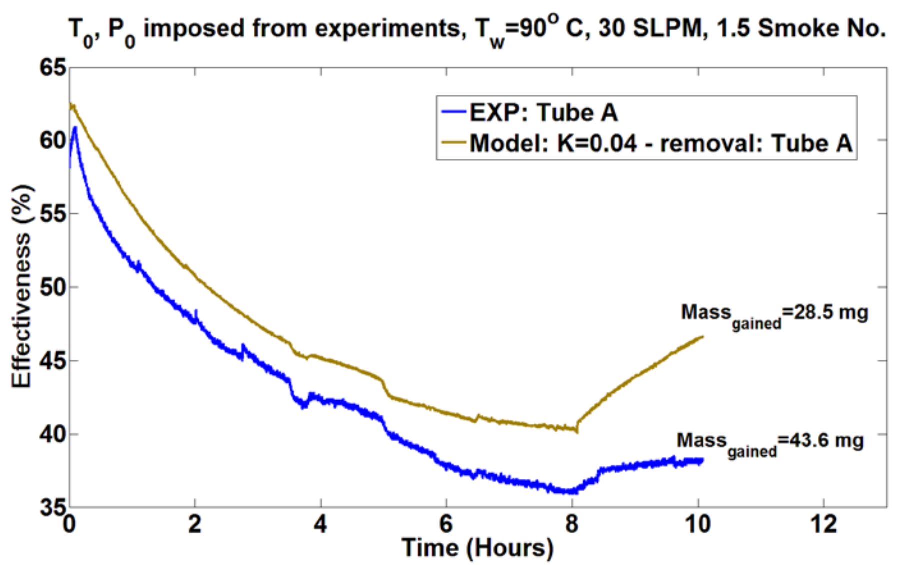
Long Exposure Time

- No physical verification yet for removal mechanisms! Matching the data with the proposed kinetic theory.

Criterion for removal: Kinetic Energy > Van der Waals Energy

Literature: removal coefficient proportional to drag/ bond force ratio.

- Literature: the sticking probability of soot nanoparticles is assumed 100%!
- The removal rate to match the data in first 8 hours is too much for the second phase when deposition stops!



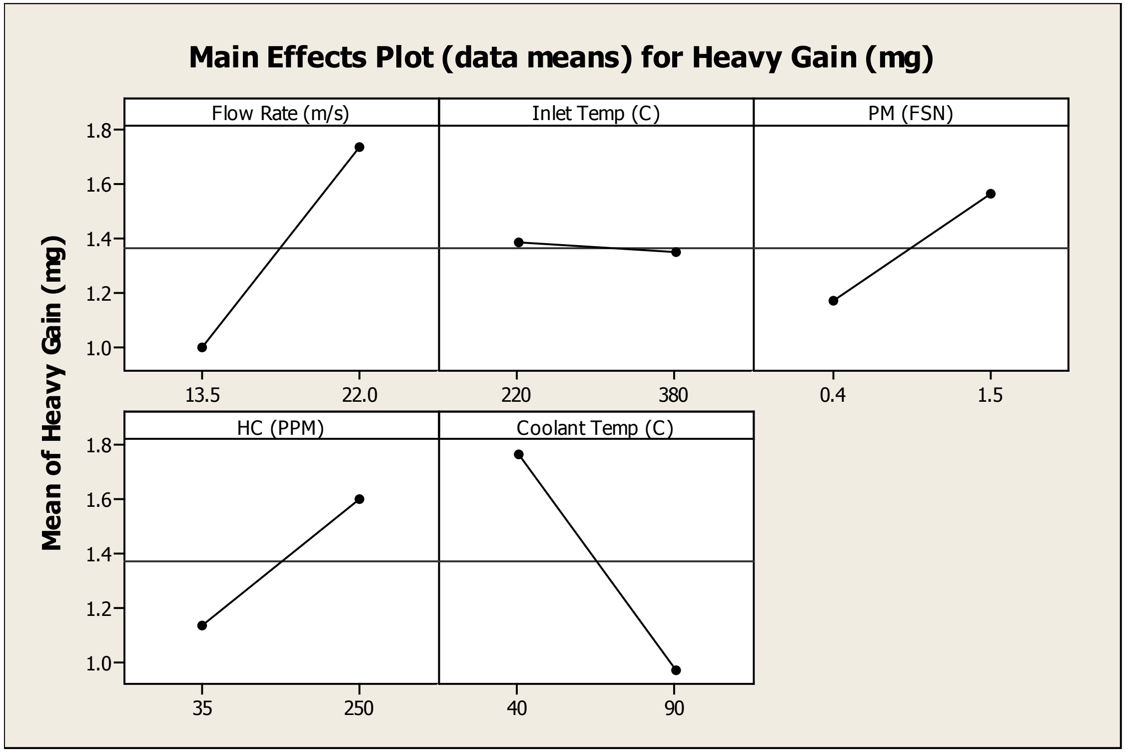
Key Conclusions

- Thermophoresis substantiated as key PM deposition mechanism.
- PM is penalizing to heat transfer effectiveness.
- HC’s are more penalizing to deposit mass accumulation.
- There are several statistically significant interactions between the key factors impacting cooler fouling.
- The physics are complicated.
- Capturing deposit layer thermal conductivity changes due to key factors such as flow velocity, gas temperatures, HC levels, etc. is key to any successful modeling exercise for EGR cooler fouling.
- The deposits in these shorter-term experiments consisted of light volatiles and non-volatiles in roughly equal proportions on average (mass basis).
- The effect of the anti-coking coating is inconclusive.

Thanks for Your Attention

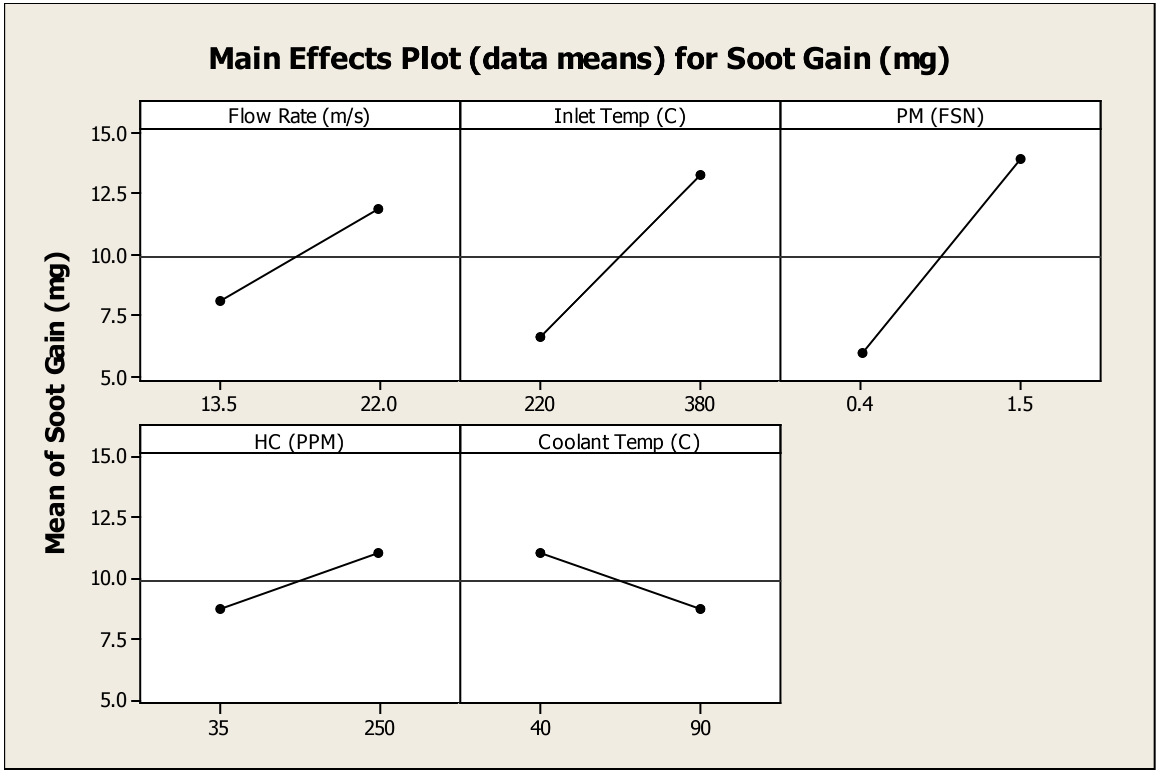
- Questions?

Heavy Volatile Mass Accumulated Main Effects



- ✓ Sources are lube oil and partially oxidized productions of combustion
- ✓ Levels are small relative to light volatile and non-volatile.
- ✓ Trends as expected. Higher flow rates, higher PM (SOF), higher HC levels, lower coolant temperatures.

Non-volatile Mass Accumulated Main Effects



- ✓ Trends as expected … higher flow rates, inlet temperatures and PM levels increase non-volatile mass gain.
- ✓ Higher HC's and lower coolant temperatures increase HC condensation … and PM sticking.