Emissions Controls Technologies, Part 1

EGR Cooler Fouling – Visualization of Deposition and Removal Mechanisms

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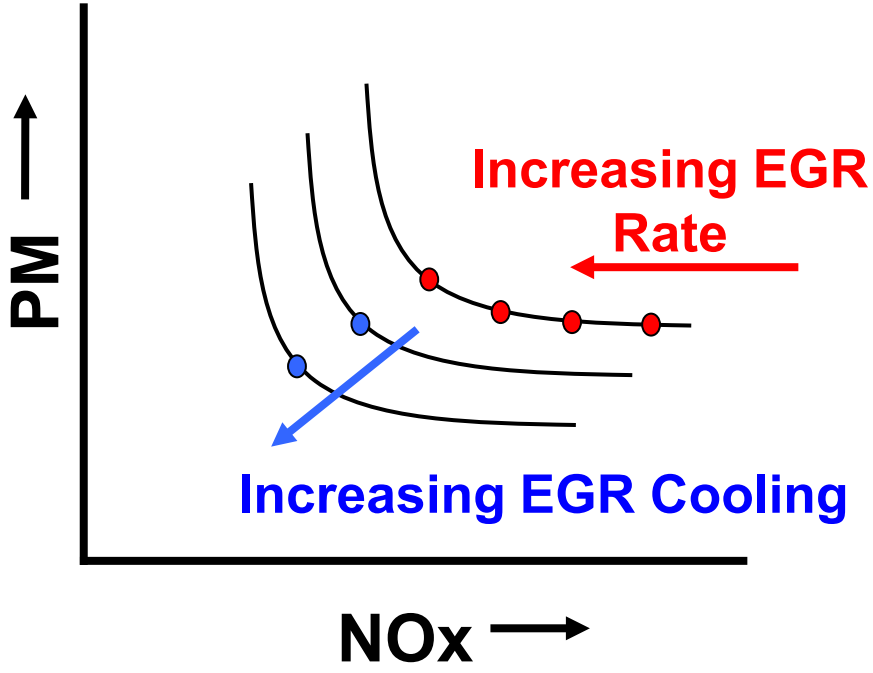
Benefits and Challenges of Cooled EGR

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

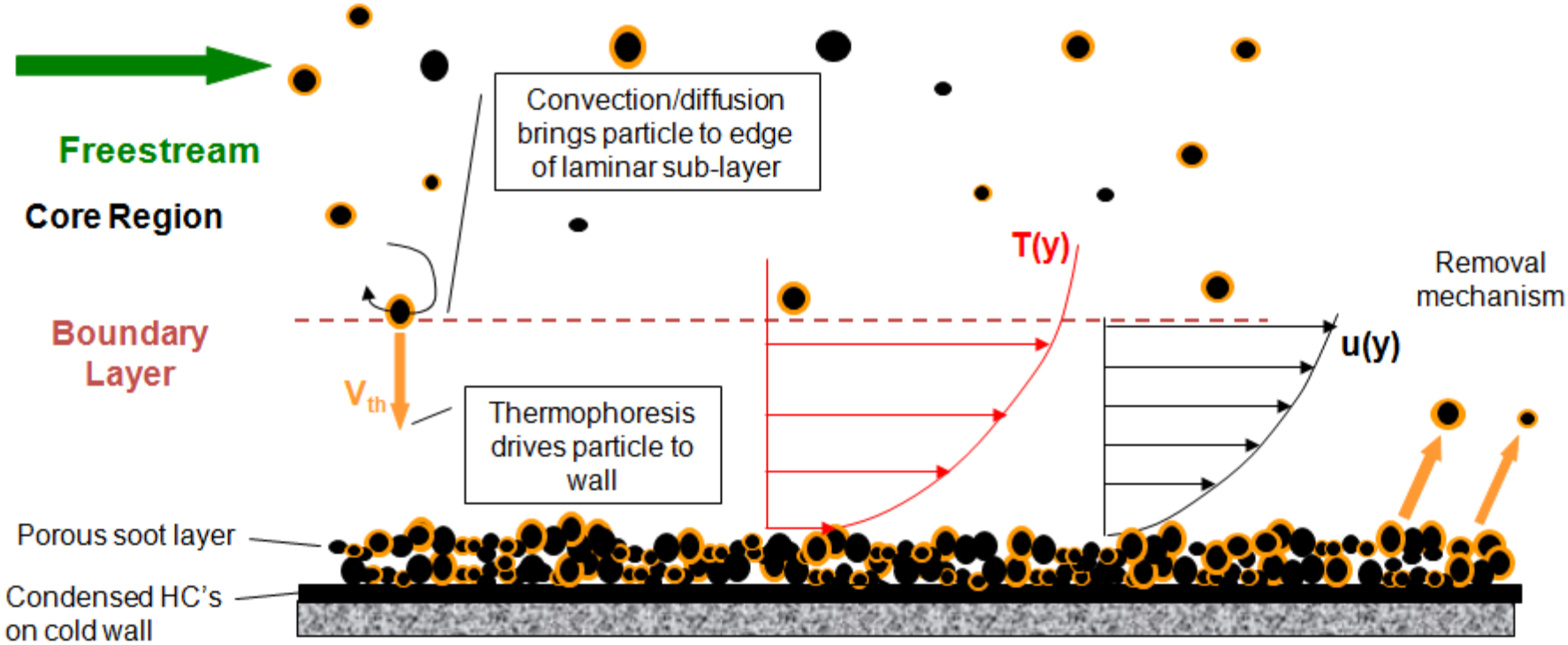


- Challenges
  - Future emissions standards
    - ✓ Higher EGR rates
    - ✓ More cooling
  - More HC's
  - More likely HC condensation
  - Potentially more PM/SOF
  - HC/PM deposition in cooler or FOULING

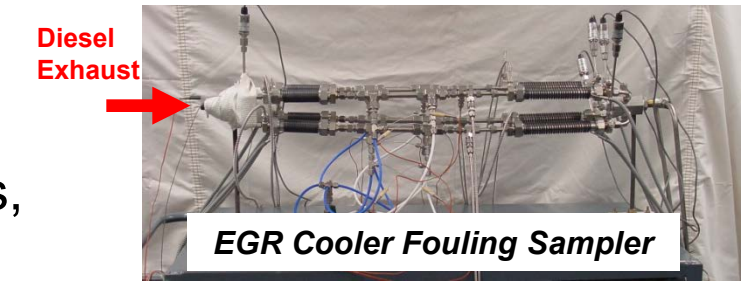
After 200 hr. Fouling Test

What is EGR Cooler Fouling?

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



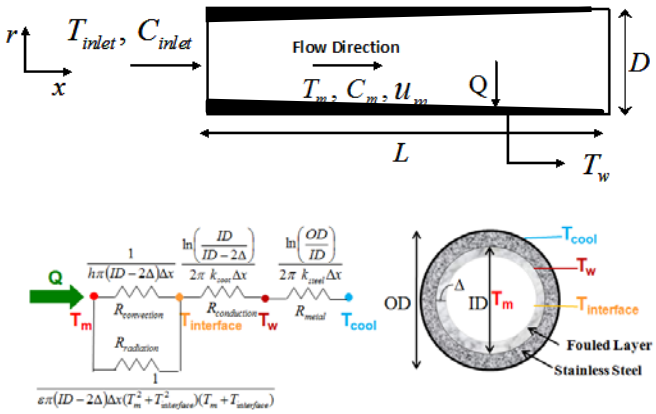
Previous DEER Conferences

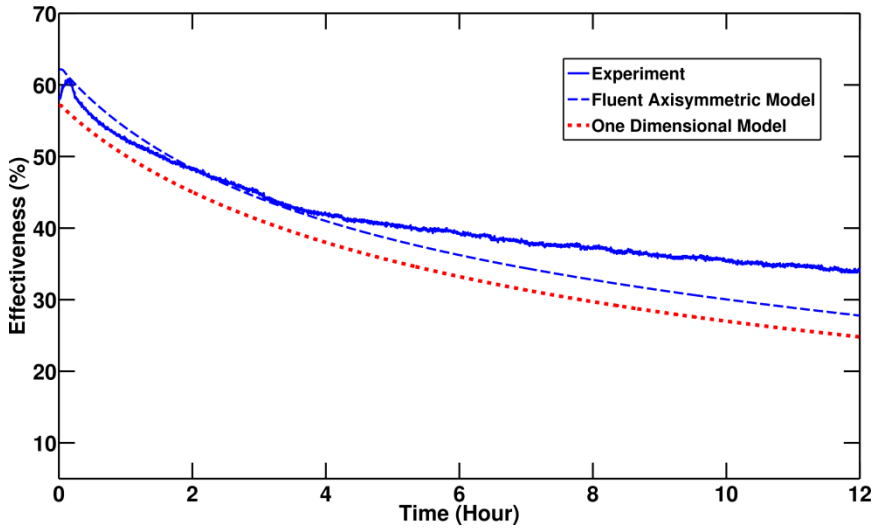


- Focus on physics of deposition
  - Key factors: gas/coolant temperatures, gas velocities, exhaust constituents
  - Controlled experiments at Oakridge National Laboratory (ORNL) using fouling "sampler" for good test repeatability and separation of variables.
  - Key findings:
    - ✓ High gas flow velocities reduce trapping efficiency
    - ✓ Lower coolant temperatures lead to higher HC condensation → more deposit mass accumulated
    - ✓ Higher gas temperatures lead to thermophoretic soot deposition → greater loss of heat transfer "effectiveness"
    - ✓ Importance of deposit layer composition → thermal conductivity
  - Benefits of an EGR catalyst for EGR Cooler Fouling Reduction

Previous DEER Conferences, continued

- Model of EGR Cooler Fouling
  - Analytical, 1D and 2D models
  - Variable layer thickness
  - Variable layer thermal conductivity
  - Thermophoresis and condensation
  - More details tomorrow at 8:30!

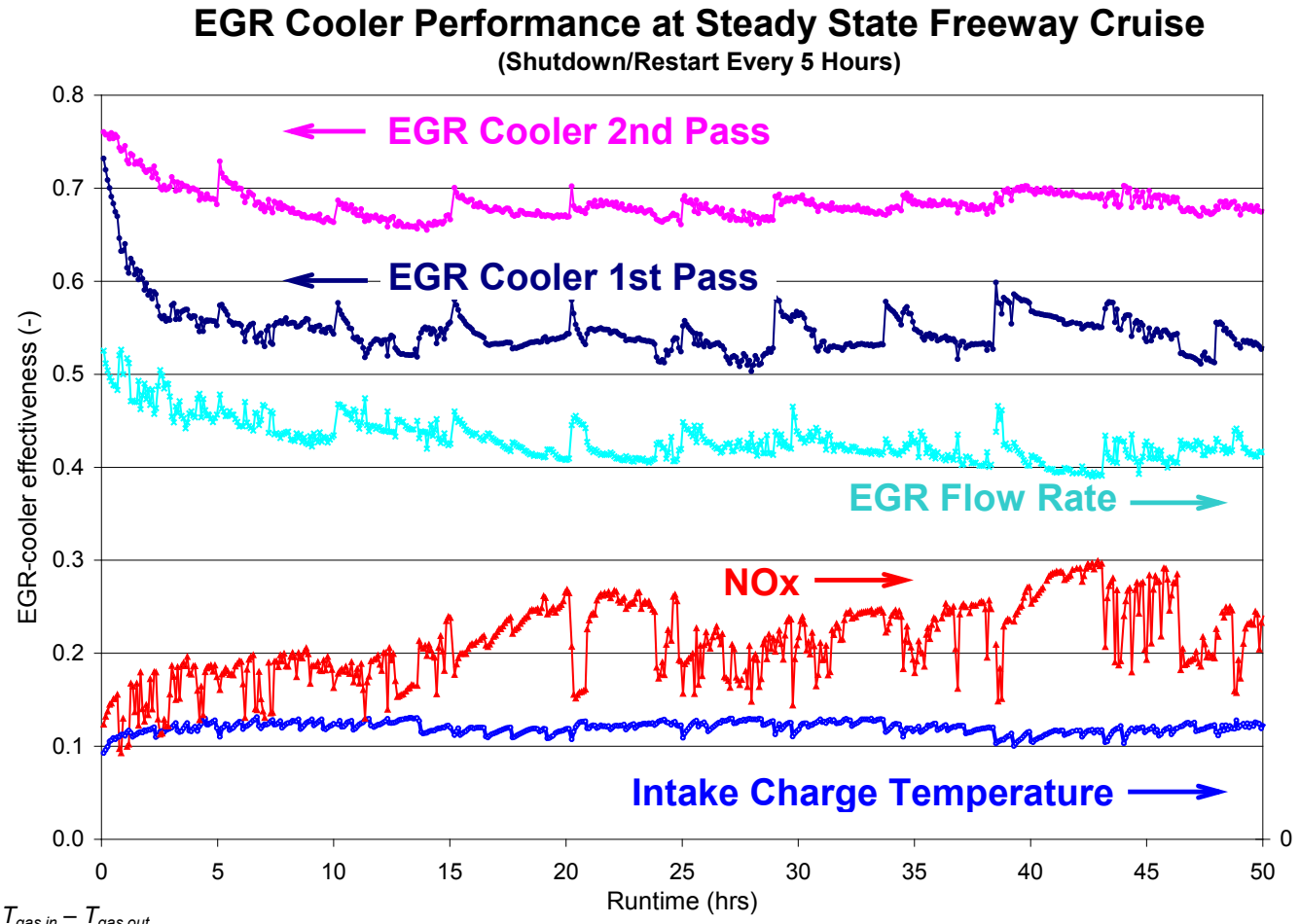




- Good correlation for first 3 hours
- Longer term experiments → model over-predicts effectiveness loss
- Missing physics
  - ✓ Removal mechanism
  - ✓ Sticking coefficient < 100%
  - ✓ Thermal conductivity change

The Impact of EGR Cooler Fouling

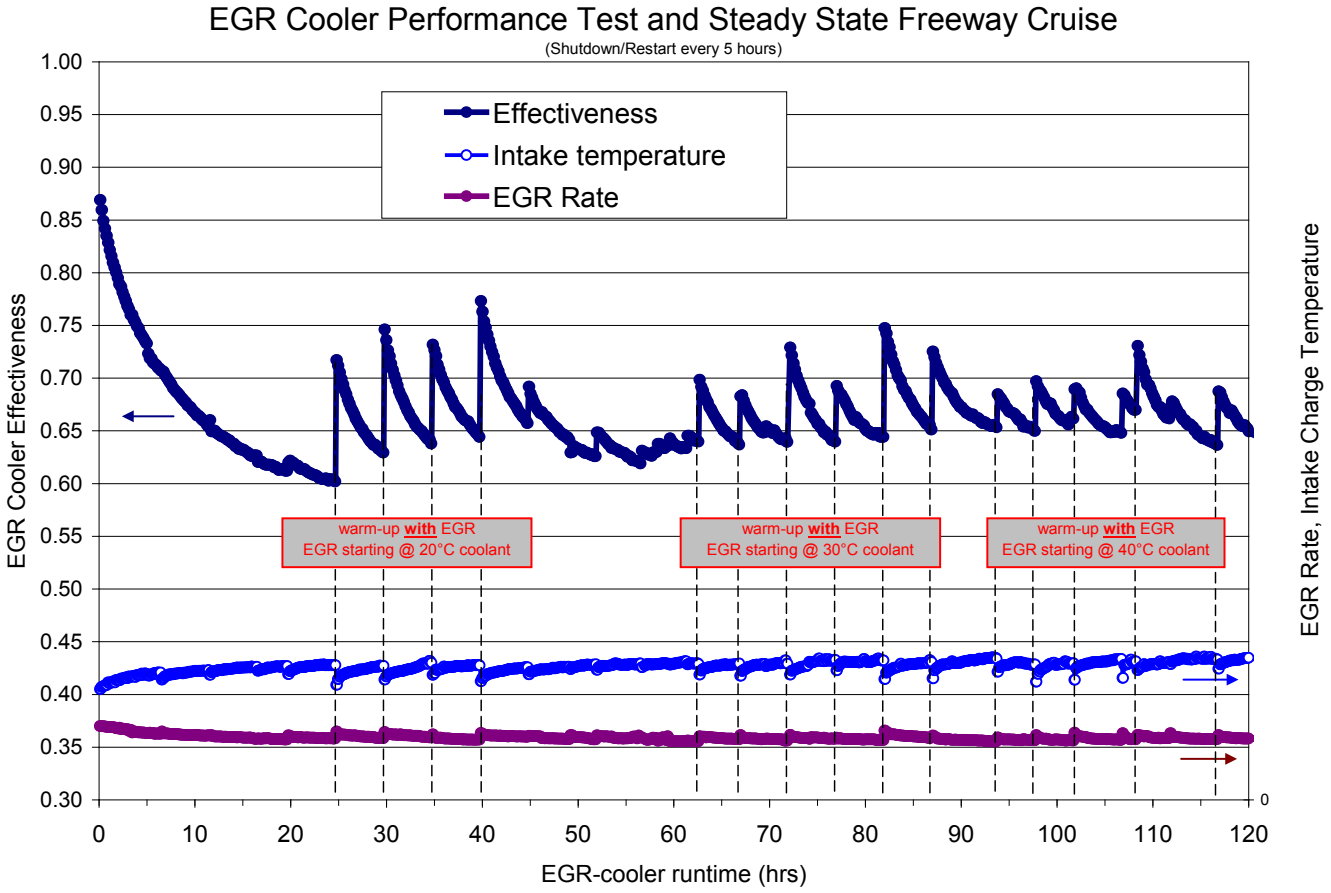
- Note stabilization and “recoveries” of effectiveness loss



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

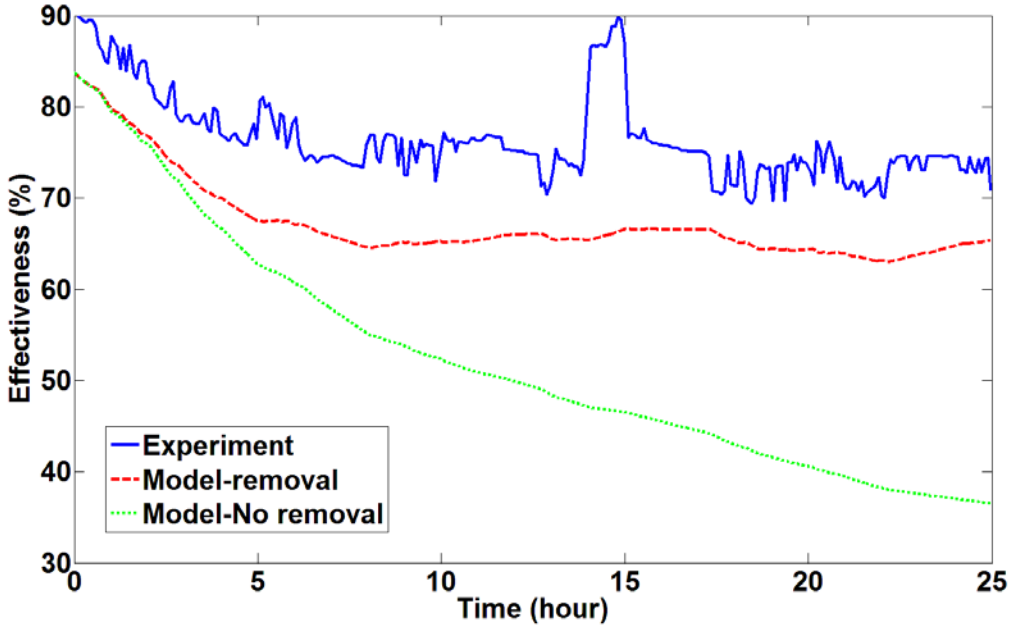
EGR Cooler Recoveries

- Shutdown/restart recoveries correlated to coolant temperature. Water condensation?



Steady State Stabilization

- Longer term “steady state” experiments require removal mechanism match slope of effectiveness degradation.
- Predicted soot gain mass gain is 45.1 mg (no removal) vs. 13.2 mg (removal)
- What is the mechanism?



Fin type EGR cooler.

Gas inlet temperature = 330ºC

Gas inlet pressure = 190 kPa

Coolant temperature = 90ºC

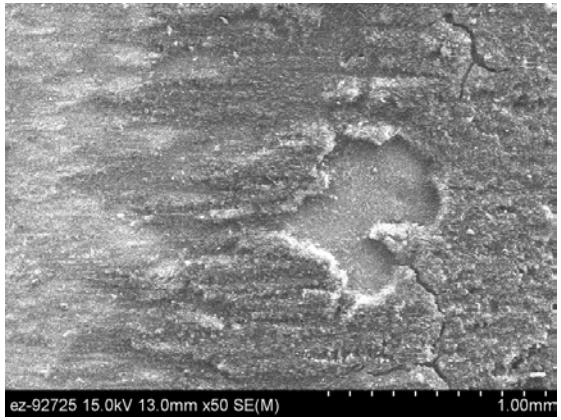
FSN ≈ 1

Deposit Removal Mechanisms

- Flow force removal
  - Drag
  - Lift
  - Turbulent burst
- Deposit layer loosening
  - Water condensate “washing”
  - Mechanical vibrations
  - Flow/pressure pulsations
  - Thermal stress cracking
  - Particle scrubbing
  - Flaking
  - Spallation
- Deposit layer change
  - Layer wetting
  - Layer collapse
- Reactions
  - Evaporation
  - Chemical reactions

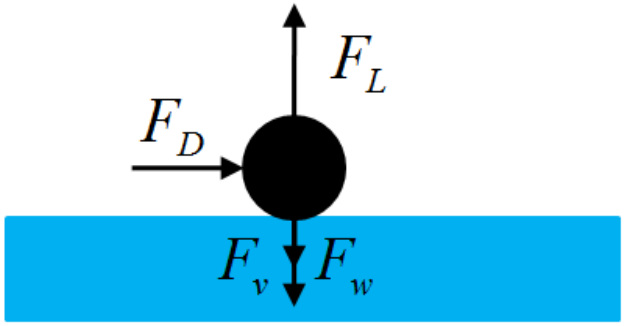
Deposit Erosion at Leading Surface/Peak of Wavy Fin

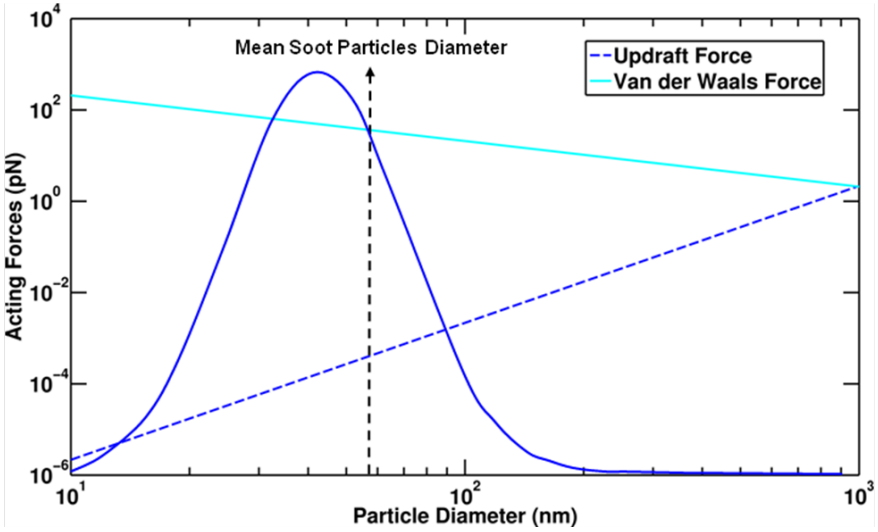
(courtesy Michael Lance – ORNL)

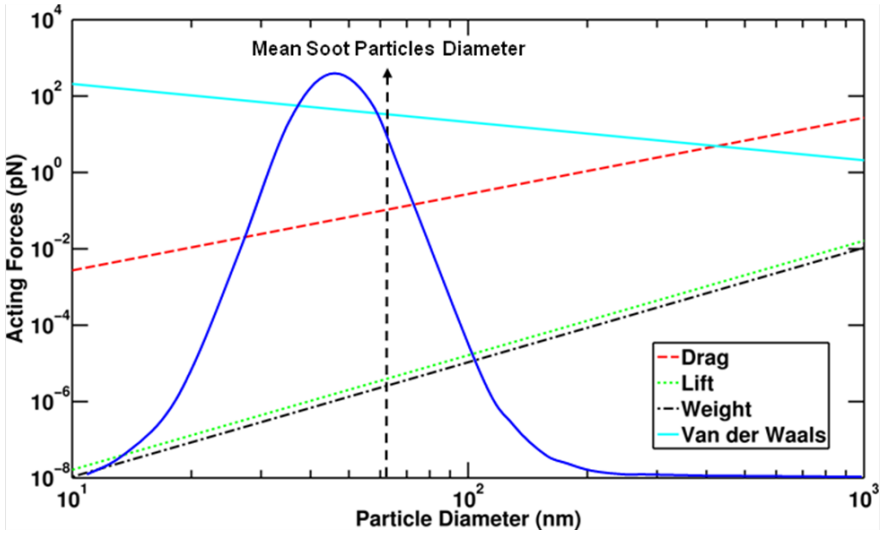


Deposit Removal Scaling Exercise

- Removal mechanisms allowing for analytical formulation are insignificant relative to “sticking” mechanism
  - Drag $F_D = 8\rho v^2 (u^* d_p / v)^2$
  - Lift $F_L = 0.076\rho v^2 (d_p u^* / v)^3$
  - Weight $F_w = \frac{\pi}{6}(\rho_p - \rho_g) g d_p^3$
  - Vander Waals $F_v = A_H d_p / 12 Z_0^2$
  - Updraft force $F_C = 10.1\rho v^2 (d_p u^* / v)^3$

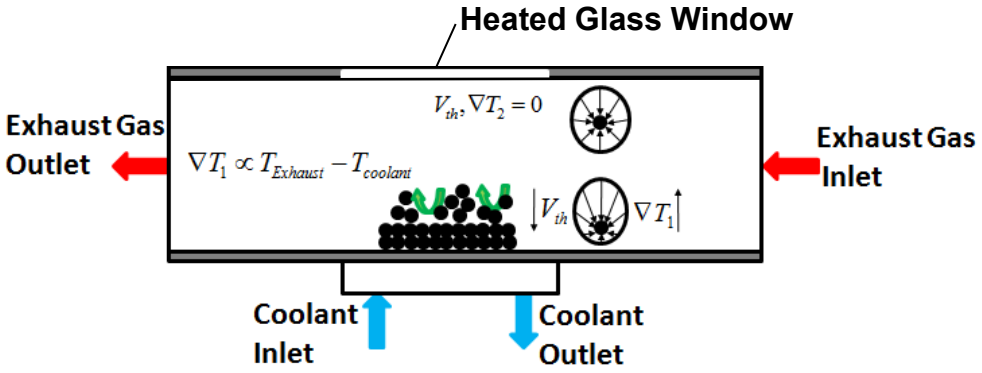






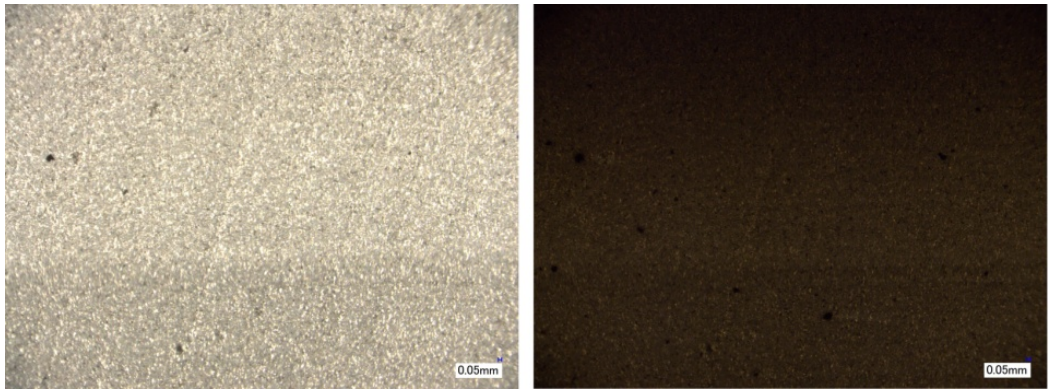
Deposit Visualization Rig

- Test rig developed at University of Michigan allowing for direct optical access to deposition process
  - Can observe fouling/removal in real time
  - Diesel engine producing exhaust gas
  - Confidential method to keep “window” clean
  - Digital video microscope
  - Cooled surface produces deposition
  - Hot air stabilization

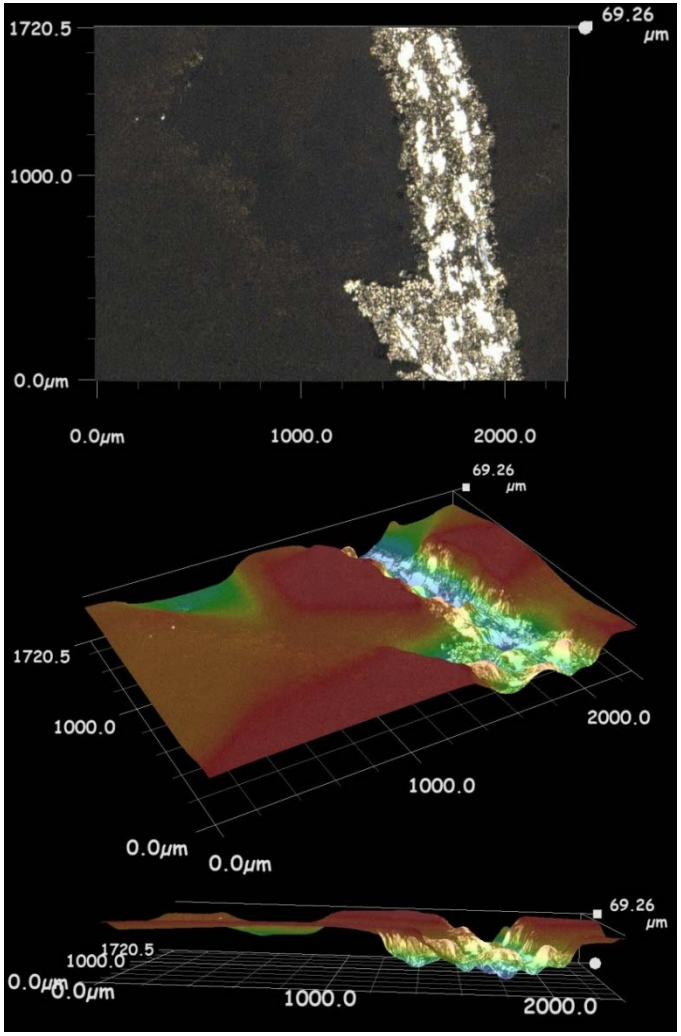


Initial Tests

- Rig creates deposits similar to EGR coolers
- Deposit build up in fairly short time frame
- Several initial observations
- Gouges or flakes observed



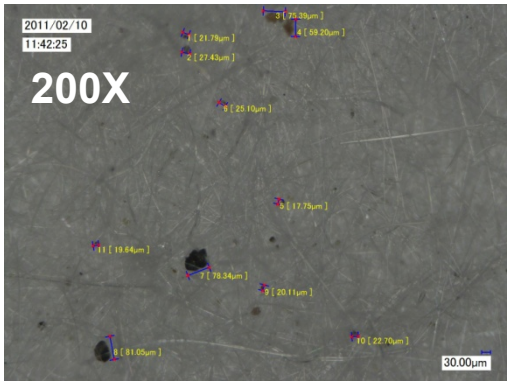
Before and after deposition in a 2 hour test

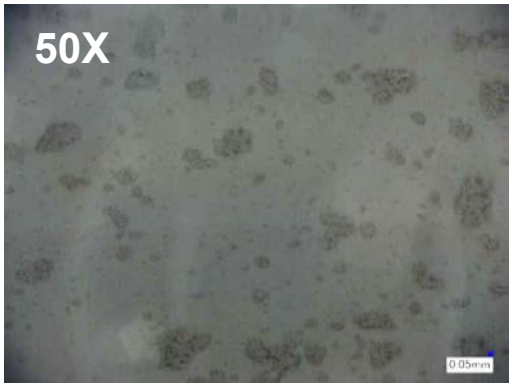


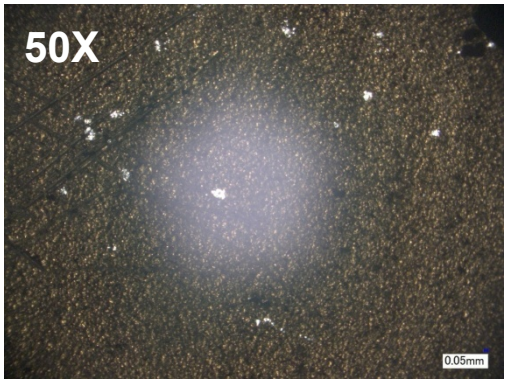
150x Magnification
Deposit thickness after 3 hours

Particle Bombardment

- Larger particles measured traveling in engine exhaust
  - 10-80 μm sized particles
- Appear to be associated with “flakes” or “grooves” removed from deposit layer
- Further results planned for upcoming conference

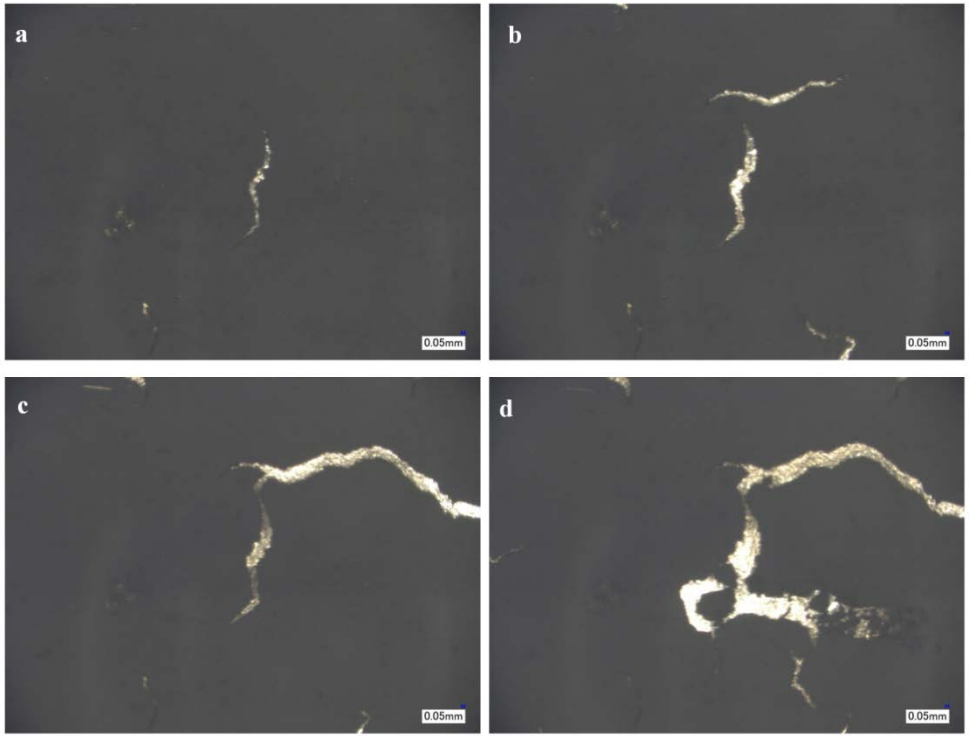






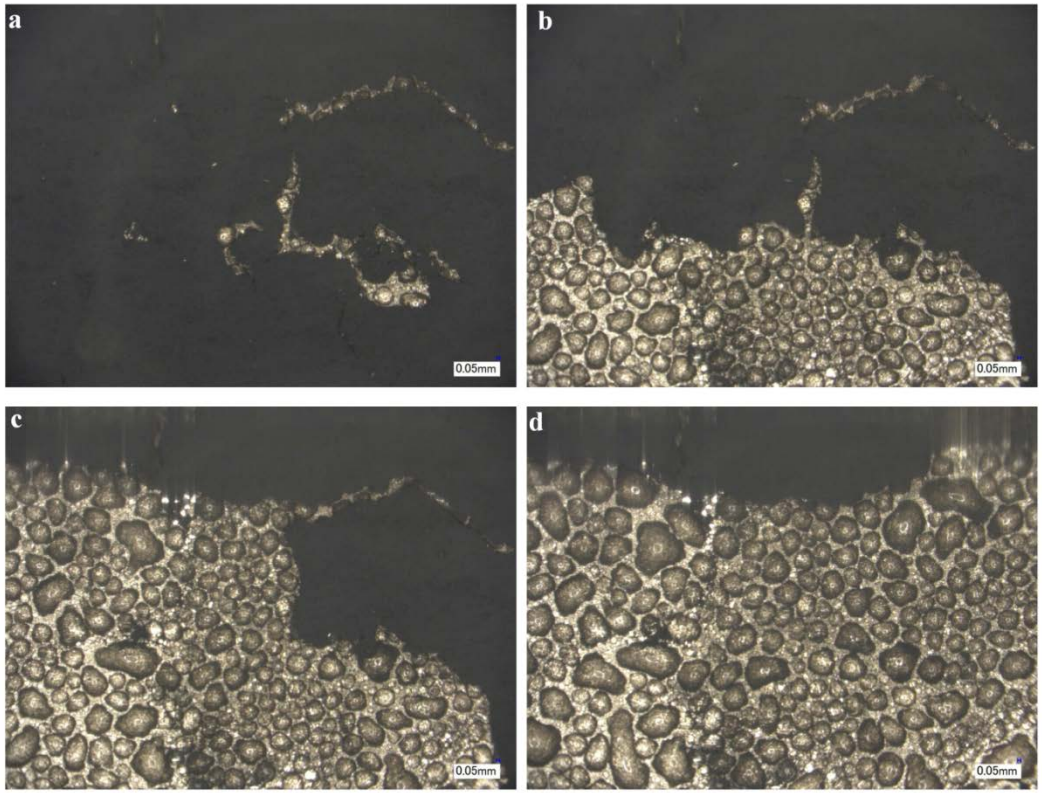
Confirmation of Water Condensate Removal

- 18 hour deposition test at 80ºC coolant
- Coolant temperatures switched to 40ºC
- Evidence of water condensate fracturing deposit layer



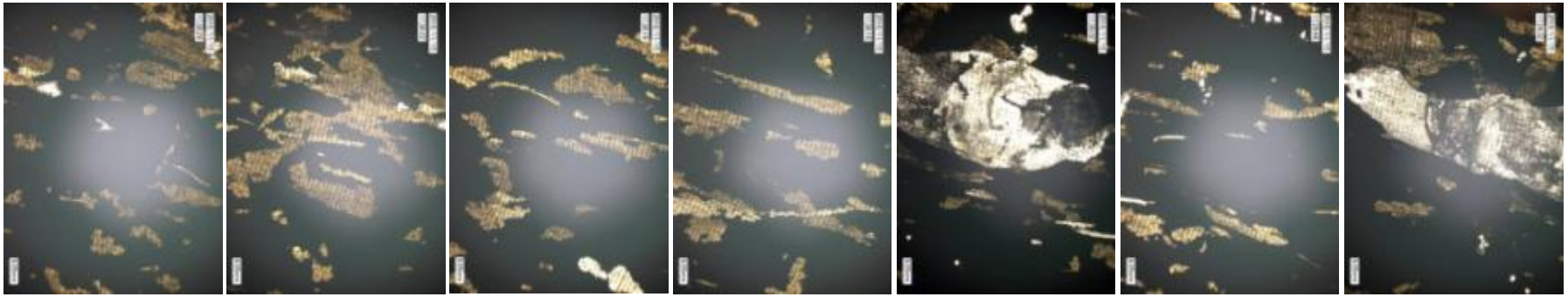
Water Condensate Removal

- Coolant temperature lowered to 20ºC with hot air stabilization
- Switch to exhaust gas resulted in immediate condensation
- Condensate appears to form below deposit layer and carry away



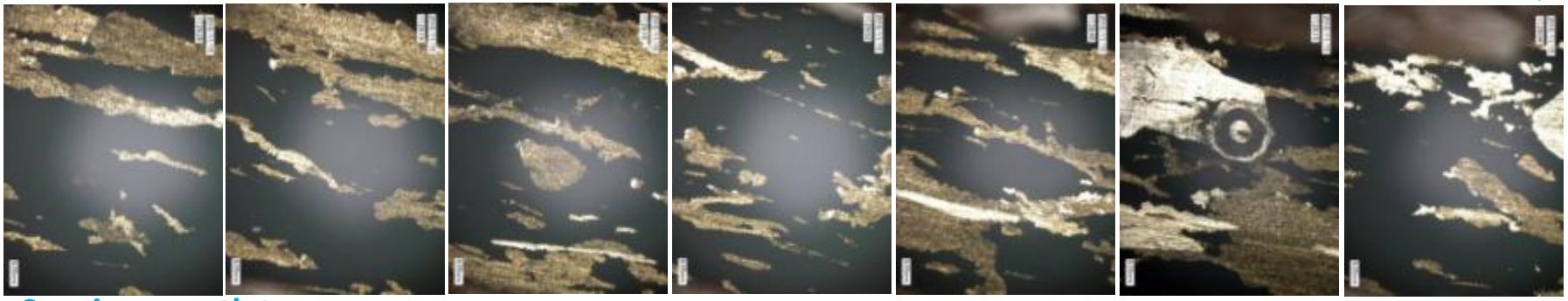
Other Removal Mechanisms

Specimen inlet

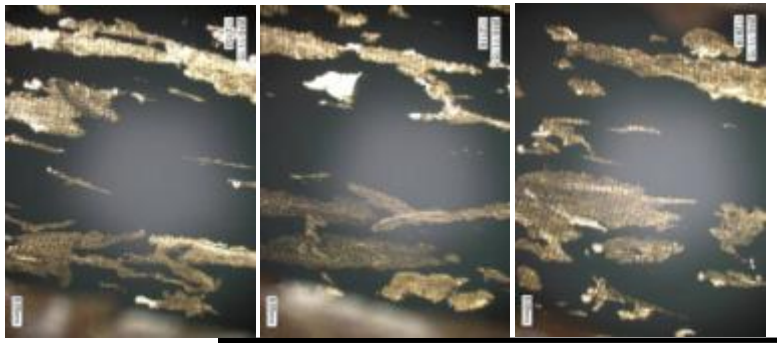


Specimen – Middle Section

Flow Direction



Specimen outlet



- Other removal mechanisms observed
- Currently under investigation
- 50X magnification

Key Conclusions

- Cooled EGR is an increasingly important NOx reduction technology for current and future diesel engines.
- Higher EGR flow rates and cooling levels required by future emissions regulations exacerbate fouling, or the deposition of soot and HC exhaust constituents, degrading EGR cooler performance.
- An EGR cooler fouling model is developed and correlated to shorter term controlled EGR cooler fouling experiments.
- Longer term EGR cooler fouling experiments appear to require a “removal mechanism” to achieve correlation.
- A deposit visualization rig has been developed and is running experiments to observe these suspected removal mechanisms in real time.
- Water condensation and large particle bombardment appear to be important removal mechanisms. Other removal mechanisms are under investigation.

Thanks for Your Attention

- Questions?