Fuel Injection Strategy for Soot-Filter Regeneration

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Outline

• Regeneration of Soot Filters
• Causes of Soot Filter Failures
• Modeling of Active Regeneration and Drop-to-Idle events
• Injection Strategy
• Conclusion
Soot Filters in Diesel Exhaust Systems
As the soot accumulates in the filter, the backpressure of the exhaust increases. The soot needs to be removed continuously or periodically.

• Soot thickness increases with time
• Backpressure in the exhaust system increases = loss of engine power
• Overload can clog the filter

Comparison of delta P vs. time for PGM load & ratio & DPF washcoat during soot loading at C15 and 15 kPa exhaust BP

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Passive and Active Regeneration

The exhaust temperature is not always hot enough to regenerate passively the soot filter. Then, active regeneration becomes necessary.

Passive Regeneration (optimal at ≈300°C)

\[ \text{C}(\text{soot}) + 2 \text{NO}_2 \rightarrow \text{CO}_2 + 2 \text{NO} \]
\[ \text{C}(\text{soot}) + \text{NO}_2 \rightarrow \text{CO} + \text{NO} \]

Active Regeneration (>550°C)

\[ \text{C}(\text{soot}) + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 \]
\[ \text{C}(\text{soot}) + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \]
High Temperature is a Risk of Failure for Soot Filters

- Loss of catalytic activity
  - Sintering of PM particles
  - Alumina polymorphic transformation (1100°C)
- Ash reaction with cordierite
  - Solid-state reaction with cordierite (1200°C)
  - Filter-ash eutectic
- Mechanical stress
  - Thermal gradients
  - Fatigue
- Melting point of Cordierite (1450°C)
Drop-to-Idle:
Sudden drop of the exhaust gas flow rate during an active regeneration. The heat from the soot oxidation accumulates in the CSF and leads to a runaway reaction.

- Sudden drop of the exhaust flow rate
Active Regeneration Simulation
As the temperature increases in the CSF, the soot regeneration rate increases.

Speed = x 30

![Diagram of DOC and CSF with Fuel Injector]
Active Regeneration with Drop-to-Idle Simulation

The flow rate is too low to evacuate the heat created by the soot oxidation.

Speed = x 60

![Diagram showing exhaust system with DOC and CSF]
Filter Model (BASF CatSim) / Assumptions

CO, HC, NO, NH3,…

Heat and Mass Transfer

P, T, F

Soot Accumulation

CO2, H2O, N2, NO2, …

Axial conduction

Soot Regeneration

Thermal losses to ambient

• Soot oxidation yields equal amounts of CO and CO2 (CO is converted over the PM function of the catalyst)
• No axial motion of the soot from the cake
• 1D Model (no radial temperature gradients)
• Homogeneous soot distribution
• Uniform deactivation
Comparison of Model to Experimental Results. The model underestimates the maximum temperature in the CSF during an active regeneration (radial thermal gradients are not considered).

Active Regeneration - DOC+ CSF - 600C DOC out - 3.9g/l soot loading

Thick line: model
Thin line: experiments

Temperature (°C)

Time (s)

23K/hr
Fuel Injection Strategy: Objectives

• Propose an injection strategy for active regeneration with the following constraints:
  • The maximum temperature in the CSF during a drop-to-idle event must not be higher than 700°C.
  • Reach 90% regeneration.
  • Decrease the duration of the regeneration.
Experimental Conditions

- Initial soot loading: 3.5 gm/l
- Inlet Gas Temperature: 280°C
- Constant filter dry gain of 0.25 gm/in³
- Drop-to-Idle: 10 to 3 K/hr; 20 to 3 K/hr

DOC + CSF

- Uniform DOC, 300/8, 12”x8”
- PM: 60 gm/ft³ (4:1)
- Uniform CSF, 270/16, 13”x17”
- PM: 1.2 gm/ft³ (4:1)
Drop-to-Idle Test (DTI)
The maximum temperature in the CSF during drop-to-idle test has been calculated for variable injection rates and duration.

- The flow is decreased from 125 gm/s to 35 gm/s and the HC injection is decreased to 0 gm/s after a variable duration D.
- Several scenarios (different injection duration D) of drop-to-idle are considered in order to obtain the worst case.

10 to 3K/hr
Increasing the injection rate during the regeneration will allow to avoid high temperatures in case of DTI.

Drop-to-Idle Test (DTI)

CSF-in: 570°C

CSF-in: 560°C

CSF-in: 520°C

10 to 3K/hr

X: Injection (gm/min)

D(S)

Flow

HC Injection

Variable

Variable
Comparison between a Constant Injection and a Staged Injection.

As the soot is consumed, the injection rate can be increased. The following injection represent a 3 additional step injection respectively corresponding to 110, 120 and 130 % of the initial injection. The duration of the steps has been adjusted so that the maximum drop to idle temperature never reaches 700°C.
Constant VS Staged Injection: SV (10K/hr)

The staged injection shows a significantly shorter regeneration time and lower fuel consumption than the reference injection.

Constant VS Staged Injection: SV (10K/hr)

$d_0 = 260s$
$d_1 = d_2 = 100s$

10K/hr

38% fuel economy

42% time economy

90% Regeneration
16 minutes

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The staged injection shows a significantly shorter regeneration time and lower fuel consumption than the reference injection.

Constant VS Staged Injection : SV (20K/hr)

$d_0 = 260s$
$d_1 = d_2 = 100s$

20K/hr
Staged injection: DTI test
Drop-to-idle events have been simulated for variable injection duration during this stepped injection.
The staged injection strategy allows to keep the maximum temperature of the uniform CSF (with upstream DOC) below 700°C whenever the drop-to-idle event occurs.
Conclusions / Path Forward

Conclusions

• Staged injection strategy allows:
  • to respect a desired maximum temperature in the CSF when a drop-to-idle event occurs (700°C for this study).
  • to decrease the fuel consumption
  • to decrease the regeneration duration = decrease risk of DTI
• A better tuning of the steps duration or the addition of intermediary steps (or even using a continuous function) would allow further improvement of the regeneration.

Path Forward

• Experimental verification of the injection strategy (Model results validation)
• Steady-state → Transient
Acknowledgement

Florian Von Trentini
Dennis Anderson
Marius Vaarkamp
Sanath Kumar
Ken Voss
Alfred Punke
Kevin Hallstrom
Joe Patchett
Matt Larkin
Maurica Fedors
Thank you for your attention

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