Improving GPF Filtration Performance through Modeling Analysis

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Need for High Performance GPF

- **Target:** high efficiency, low backpressure
- **High efficiency for stringent particle matter (PM) standard**
  - **US** (California LEVIII 3 mg/mi phase in 2017 → 1 mg/mi phase in 2025)
  - **Europe** (Euro 6b WLTP cycle $6.0 \times 10^{11}$#/km in 2017 → Euro 6d Real Driving Emissions Test or RDE)
  - **China** (China 5 WLTP cycle $6.0 \times 10^{11}$#/km phase in 2016 → China 6 RDE phase in 2023)
- **High efficiency could enable GPF size reduction**

Particle emission of GDI engine during WLTP cycle, GPF efficiency >90%
Filtration Models

- **Unit collector model** for GPF is inherited from DPF model proposed in 80s.
- Several recent model improvement includes pore size distribution.
- Filter media is modeled as a packed particle bed.

- **Capillary tube model** has been used for decades for membrane filters.
- Filter media is modeled as an assembly of straight capillary tubes.
- It can be used to represent the filtration path through GPF wall.

Packed ceramic particle bed

Assembly of straight tubes
Unit Collector Model

- **Filtration Efficiency Model**
  - Diffusion mechanism
    \[
    d_c = \frac{3}{2} \frac{1-\varepsilon}{\varepsilon} d_{pore}
    \]
  - Interception filtration
    \[
    \eta_d = 3.5g(\varepsilon) Pe^{-2/3}
    \]

- **Backpressure Model**
  - Backpressure is accumulative resistance around spherical collectors
    \[
    \Delta P_w = \frac{\mu \bar{U} w}{k} \quad k = \frac{K_u d_c^2}{18(1-\varepsilon)}
    \]

Unit collector size and number depend on
- \(\varepsilon\), porosity
- \(d_{pore}\), pore size
Capillary Tube Model

- Filtration Efficiency Model
  - Diffusion mechanism
    \[
    \mu = \frac{4DL}{\pi d_t^2 U} = \frac{DL}{Q_t}
    \]
    \[
    \eta_{\text{diff}} = 5.5\mu^3 - 3.77\mu \quad (\mu < 0.007)
    \]
    \[
    \eta_{\text{diff}} = 1 - 0.819 \exp(-11.5\mu) - 0.0975\exp(-70.1\mu) - 0.0325\exp(-179\mu) \quad (\mu > 0.007)
    \]
  - Interception filtration
    \[
    \eta_{\text{inter}} = 1 - (1 - d_t / d_p)^2f
    \]
- Backpressure Model
  - Backpressure is resistance across the tube length
    \[
    \Delta P_w = \frac{\mu U_w}{k} \quad k = \varepsilon d_t^2 / 64
    \]
Capillary Tube Model

• **Single tube**
  - Deposition parameter $\mu$, $\mu = \frac{4DL}{\pi d_t^2 \bar{U}} = \frac{DL}{Q_t}$
    - $d_t$ tube diameter
    - $L$ is the length
    - $D$ particle diffusion coefficient
    - $\bar{U}$ is the average velocity
    - $Q_t$ is the flow rate through tube

• **Assembly of tubes**
  - Flow rate $Q_t$ depends on number of tubes or size distribution
    \[ Q_t = \frac{Q_{total}}{N_t} \text{ (same tube size)} \text{ or } Q_t \sim d_t^4 \text{ (tube size distribution)} \]

Filtration efficiency through a single tube changes with flow rate and length
NOT tube diameter
Tube model vs. Unit Collector Model

Tube model and unit collector predict similar filtration efficiency of diffusion mechanism for typical porosity range.

Porosity = 0.6

- Tube model
- Unit collector model
Model Analysis on Different Approaches

- Possible approaches to improve filtration performance
  - **Substrate structure**
    - Porosity, pore size and distribution
  - **Washcoat**
    - In-wall coating, on-wall coating
  - **Artificial ash layer**
    - A top layer to provide additional filtration efficiency

- **Modeling Condition**
  - Filtration efficiency (SV~30k hr\(^{-1}\), 20 °C for 80 nm soot particle)
  - Backpressure (SV~400k hr\(^{-1}\), 750 °C)
Model on Substrate – Narrower Pore Size Distribution

Blank substrate follows a lognormal pore size distribution

Narrow pore size distribution increases filtration efficiency
Model on Substrate – Pore Size and Porosity

Higher porosity, smaller pore size give higher efficiency

- Increase porosity from 45% to 55%
- Decrease pore size from 20 μm to 10 μm

Filter wall by tube model
- Increasing porosity gives more filtration path with same tube size
- Decreasing pore size also gives more filtration path
In-wall coating could decrease efficiency with some backpressure penalty

- In-wall coating doesn’t create additional filtration path, and potentially block filtration path.
- Washcoat should avoid blocking filtration path to minimize negative impact on efficiency
Model on Washcoat – On-wall Coating

- On-wall coating could increasing efficiency but with higher backpressure penalty

- Good Particle size from 15 μm to 4 μm

- Model assuming 20 μm top layer with 50% porosity and particles with size varying from 4 μm to 15 μm

On-wall coating could increasing efficiency but with higher backpressure penalty
Artificial Ash Layer

- Artificial ash layer significantly increases filtration efficiency

GPF loaded with fine Al₂O₃ particles

Filtration efficiencies with different artificial ash loading

SV=23k hr⁻¹
A highly porous top layer could boost up filtration efficiency.

Model on Artificial Ash Layer

- Model assuming 6 μm top layer with 80% porosity and particles with size varying from 0.5 μm to 3 μm

High porosity fine particle layer

Finer particle size from 3 μm to 0.5 μm

Predicted Filtration Efficiency vs. Predicted Backpressure (kPa)
Model Analysis on Different Approaches

- Possible approaches to improve filtration performance
  - **Substrate structure**
    » Narrow pore size distribution
    » Large porosity
    » Small pore size
  - **Washcoat**
    » In-wall coating, on-wall coating
  - **Artificial ash layer**
    » High porosity
    » Small particles
Summary

- A tube model was used to predict GPF substrate filtration efficiency.

- Approaches to improve filtration performance was analyzed through the tube model and unit collector model.

- Model analysis indicates optimizing porous structure of substrate and using artificial ash layer increase efficiency with best backpressure tradeoff.

- If needed, in-wall coating should avoid blocking the flow path to minimize impact on filtration efficiency.