Soot trapping both in the wall and on the surface of diesel particulate filters: effect of particles size distributions and material properties

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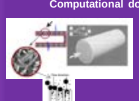
Introduction: Wall-flow diesel particulate filters are widely used for soot removal from engine exhausts. The exhaust gas flows through the porous walls from the inlet channel into the outlet ones. Soot particulates deposit both in the pores of the wall and on its surface in the inlet channels. The efficiency of the further oxidation of accumulated soot depends on the ratio of soot captured inside the wall to one collected on the wall surface, because soot inside the pores has more close contact with catalyst. In theoretical investigations devoted to soot capturing in diesel particulate filters, authors usually take into account soot trapping either inside the porous material of filters or on the wall surface. Besides, they assume a constant particulates size in mathematical models.

Aim. The paper is devoted to the development of the unsteady-state mathematical model, which takes into account the simultaneous soot accumulation both inside the wall and on its surface as well as to the investigation of the influence of particle size distributions and material properties on both amount of accumulated soot inside the wall and height of soot layer in the channel wall.

Mathematical model

Scheme of the catalytic trap for diesel particules

Computational domain



Balance equations

Soot particles of j-th size in gas phase: $\varepsilon \frac{\partial c_j^{soot}}{\partial t} + v \frac{\partial c_j^{soot}}{\partial x} = -v\varphi\eta(d_p^j) c_j^{soot},\ j = 1, N$

Soot deposited inside the wall of the filter channel: $\frac{\partial m}{\partial t} = v\varphi \sum_{j=1}^{N} \eta(d_p^j) c_j^{soot}$

Volume of filtered gas: $\frac{\partial V_{gas}}{\partial t} = \upsilon \cdot S$

Height of soot layer on the surface: $h_D = X_0 \frac{V_{gas}}{S}$

Volume ratio of soot layer to filtered gas: $X_0 = \frac{(\sum_{k=1}^{N}(\overline{C_k^{in}} - \overline{C_k^{out}}) - \overline{m} - \sum_{k=1}^{N}\overline{C_k})\rho_{gas}}{V_{gas} \cdot \rho_{soot}(\rho_{soot+gas} - \sum_{k=1}^{N} C_k^{in})}$

Pressure drop across the filter: $\Delta P = \frac{\upsilon}{S}\mu\left[K_D \frac{(1-\varepsilon_D)^2}{d_D^2 \cdot \varepsilon_D^3} h_D + K_F \int_0^L \frac{1}{d_F^2} \cdot \frac{(1-\varepsilon_F)}{\varepsilon_F^3} dx\right]$

Boundary conditions:

x=0: $c_j^{soot}(0,t) = \left(c_{in}^{soot} / \sqrt{2\pi}\ln\sigma_p\right)\exp\left[-0,5\left(\left(\ln d_p - \ln\mu_p\right)/\ln\sigma_p\right)^2\right],\ j = 1, N$

Initial conditions: $t = 0: m(x,0) = 0,\ c_j^{soot}(x,0) = 0,\ j = 1, N$

Particle collection mechanisms by a single fibre and the expressions of collecting efficiency

$\eta = \eta_1 + \eta_2 + \eta_3 + \eta_{23} + \eta_{stick};\quad \eta_1 = 3,2\cdot 10^{-4}\exp\left[10,5(Stk)\right]$

$\eta_2 = \frac{1}{2k}\left[\frac{1}{(1+R_i)} - (1+R_i) + 2(1+R_i)\cdot\ln(1+R_i) + 2,86Kn(1+R_i)\frac{R_i}{(1+R_i)}\right]$

$\eta_3 = \frac{2,7}{Pe^{2/3}}\left(1 + 0,39k^{-1/3}Pe^{1/3}Kn\right) + \frac{0,624}{Pe}$

$\eta_{23} = \frac{1,24\cdot R_i^{2/3}}{k^{1/2}\cdot Pe^{1/2}},\ \eta_{stick} = 1 - \exp(-Fr')$

$R_i = \frac{d_p}{d_f};\quad k = -0,5\ln(1-\varepsilon_F) - 0,52 + 0,64(1-\varepsilon_F) + 1,43\cdot\varepsilon_F\cdot Kn$

$\varepsilon_F = \varepsilon_{F0}\frac{(\rho'_s - m)}{\rho'_s},\quad \varphi = \frac{4(1-\varepsilon_0)}{\pi d_{f_0}^2} d_f,\quad d_f = d_{f0}\sqrt{1 + \frac{2m}{\rho'_S(1-\varepsilon_{F0})}}$

Stk – Stokes number, Kn – Knudsen number, Pe – Peclet number,
Fr' – modified Froude number,
d_p – soot particle diameter from log-normal particles size distribution,
d_f – diameter of the fibre, $\rho_{soot}, \rho'_s, \rho_{gas}$ – density of soot, deposited soot and gas,
$d_{D(F)}$ – pore diameter, x – channel wall coordinate, υ - linear velocity,
a, b - coefficients, ε – porosity, μ_p – median particle diameter,
σ_p – standard deviation of particle size distribution, K – coefficient,
S – surface area, index: $_0$ - clean filter, $_D$ - soot layer on the surface of the channel, $_F$ - filter

Results & Discussion:

Unsteady-state mathematical model with accounting for the simultaneous soot accumulation both inside of the wall pores and on its surface was developed. It is assumed that the soot particulates are captured in the pores by inertial impaction, interception, Brownian diffusion and interactions between interception and Brownian diffusion. We consider also particulate size distributions in the model. Besides, it is assumed in the model that soot collects on the solid part of the wall surface firstly by inertial impaction, after the soot amount near the inlet of the wall exceeds a certain level, the pores are bridged by soot and all soot deposits on wall surface. Height of soot layer becomes equal to H* in this case.

We investigate the influence of particle size distributions and material properties on both amount of accumulated soot inside the wall and height of soot layer in the channel wall.

Conclusions:

Dynamics of pressure drop across the filter is shown to depend on the soot amount both inside the channel wall and on the wall surface. At the beginning of the process, ΔP increases better due to soot accumulated inside the wall. Then ΔP increases better due to soot collected on the wall surface. Filtration efficiency is equal to 34% at the beginning of the process while height of soot layer is low (< H*). When height of soot layer becomes equal H*, the filtration efficiency reaches approximately 100%.

Mass of accumulated soot inside the wall in the case of fiber quarts is smaller than one in the case of SiC, but height of soot layer increases faster. So filtration efficiency reaches 100% earlier.

Mass of accumulated soot inside the wall in the case of Opel exhaust is larger than one in the case of acetylene burner and height of soot layer increases faster due to the soot particles from diesel exhaust are larger than ones from acetylene burner.

Process parameters:

$v = 0.1\, m/s,\ c_{in}^{soot} = 0.13\, g/m^3,\ d_D = 1.7\cdot 10^{-5}\, m,\ \varepsilon_D = 0.9,$
$\rho'_s = 60\, kg/m^3,\ H^* = 1\,\mu m,\ L = 0.4\, mm,\ t = 10\, min$

Material properties:

Fiber quartz: $\varepsilon_{F0} = 0.86,\ d_{F0} = 10^{-5}\, m,\ d_f = 0.44\cdot 10^{-5}\, m$

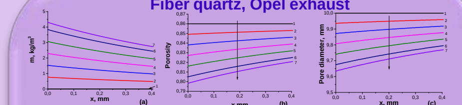
SiC: $\varepsilon_{F0} = 0.37,\ d_{F0} = 1.03\cdot 10^{-5}\, m,\ d_f = 1.02\cdot 10^{-5}\, m$

Particle size distributions:

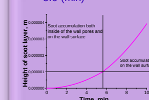
Opel exhaust: $\mu_p = 0.17\cdot 10^{-6} m,\ \sigma_p = 1.74$

Acetylene burner: $\mu_p = 0.144\cdot 10^{-6} m,\ \sigma_p = 1.242$

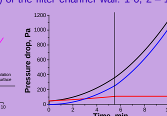
Fiber quartz, Opel exhaust



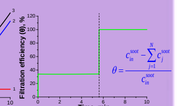
Dynamics of the amount of accumulated soot inside of the wall pores (a), porosity (b) and pore diameter (c) of the filter channel wall: 1-0, 2 – 1, 3 – 2, 4 – 3, 5 – 4, 6 – 5, 7 – 5.6 (min)



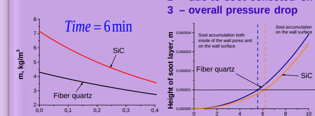
Height of soot layer on the wall surface vs time



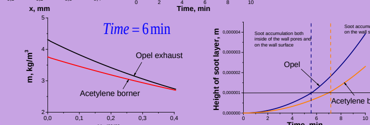
Pressure drop vs time:
1 – due to soot accumulated inside the wall
2 – due to soot collected on the wall surface
3 – overall pressure drop



Filtration efficiency vs time



Comparison of fiber quartz and SiC, Opel exhaust



Comparison of Opel exhaust and acetylene burner, fiber quartz