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Analysis of flow distribution and heat transfer in a diesel particulate filter

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HIGHLIGHTS

- A criterion is developed for obtaining uniform filtration in a DPF.
- Formulas are presented for estimating the width and speed of temperature fronts.
- Formulas are presented for estimating the heat-up time and pressure drop.
- A long DPF leads to non-uniform filtration and sharp temperature front.
- A short DPF leads to uniform filtration and temperature.

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ABSTRACT

Analysis of limiting models of a Diesel Particulate Filter (DPF) provides insight on its design and operating conditions. Analytical expressions for predicting the filtration velocity, pressure drop, filter heat-up time and speed and width of the temperature front in a DPF are presented. A more uniform filtration velocity with a lower pressure drop can be obtained by either decreasing the inlet velocity, increasing the channel hydraulic diameter or by increasing the DPF aspect ratio (D/L) under constant DPF volume and flow rate. The DPF heat transfer properties depend on the heat capacitance ratio (σ) and the effective heat Peclet number ($Pe_{h,e}$) as well as on the hydraulic parameters. The speed of the temperature front can be increased by decreasing the DPF substrate thickness and volumetric heat capacitance. Higher value of $Pe_{h,e}$ decreases the DPF front heat-up time and sharpens the temperature front. When $Pe_{h,e}$ is smaller than 8, the temperature front covers the whole DPF length. When it is larger than 128, a sharp front forms covering less than 25% of the DPF length. The effective heat Peclet number attains a maximum value at an intermediate inlet velocity and channel hydraulic diameter. Increasing the DPF aspect ratio (D/L) under constant DPF volume and flow rate can help achieve two important design targets, low pressure drop and a wide temperature front.

1. Introduction

High efficiency and long durability diesel engines have motivated their world-wide use in passenger cars, heavy-duty trucks and non-road vehicles. An additional advantage is the lower emission of "greenhouse gases" and hydrocarbons than by gasoline engines. The main drawbacks of diesel engines are the emissions of NO_x, which has adverse respiratory effects and forms ground-level ozone, and particulate matter (PM), which is a potential carcinogen [1–3]. More than 95% of the PM emitted by a diesel engine is collected and then burned in a Diesel Particulate Filter (DPF). The DPF consists of many parallel square channels with the opposite ends of adjacent inlet and outlet channels being plugged. The exhaust gas passes through the filter porous walls from the inlet to the adjacent outlet channels. A schematic of a pair of inlet-outlet channels and of short and long DPFs are shown in Fig. 1. Recently developed catalytic DPFs [4–7] can simultaneously remove the PM and oxidize the effluent organic compounds. New DPFs coated with SCR catalysts [8–11], which reduce both PM and NOx emissions, are the subject of intense current research.

The main objectives in the design and operation of a DPF are (i) low pressure drop and operating costs (fuel penalty), (ii) limiting the maximum local temperature rise during regeneration below the melting point of the substrate and (iii) avoiding large temperature gradients that can crack the support. As in many chemical reactors, designs that lead to low operating costs may lead to unsafe operation. Previous extensive numerical studies did not identify the operating windows of design and

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Nomenclature

Roman letters

A_o	adjusted pre-exponential factor, m/s
B	dimensionless adiabatic temperature rise, defined by Eq. (15)
C_{pg}	gas specific heat capacity, J/(kg K)
C_{ps}	solid wall specific heat capacity, J/(kg K)
C_{pp}	particulate matter specific heat capacity, J/(kg K)
d	hydraulic diameter of clean channel, m
D	DPF diameter, m
Da	Damköhler number, defined by Eq. (15)
E	adjusted activation energy, kJ/mol
$\hat{f}$	adjusted asymptotic friction factor in square channel
F_{in}	volumetric inlet flow rate, m^3/s
h	heat transfer coefficient, $W/(m^2 K)$
$k(T_{ref})$	reaction rate constant under reference temperature, m/s
K_p	particulate layer permeability, m^2
K_s	ceramic wall permeability, m^2
L	filter length, m
M_a	air molecular weight
M_p	particulate molecular weight
M_{o_2}	oxygen molecular weight
Nu_Ω	Nusselt number, defined by Eq. (15)
p	pressure, Pa
$\hat{P}$	dimensionless pressure, defined by Eq. (15)
p_{amb}	atmosphere pressure, Pa
Δp	backpressure, Pa
$\Delta\hat{p}$	dimensionless backpressure
P	transverse Peclet number, defined by Eq. (15)
Pe_h	axial heat Peclet number, defined by Eq. (15)
Pe_{hp}	particulate layer heat Peclet number, defined by Eq. (15)
r_{o_2}	oxygen reaction rate, mole/(m^3 s)
R_g	gas constant, J/(mol K)
R_Ω	hydraulic radius of a clean channel, m
s_p	specific area of PM deposit layer, m^{-1}
t	time, s
T	temperature, K
u	dimensionless velocity
u_w	dimensionless filtration velocity, defined by Eq. (15)
V	velocity, m/s
V_w	filtration velocity, m/s
w	particulate layer thickness, μm
$\overline{w_o}$	average thickness of initial PM deposit, μm
$\hat{w}$	dimensionless particulate layer thickness, defined by Eq. (15)
w_s	substrate layer thickness, μm
x	dimensionless axial position, defined by Eq. (15)
y	oxygen concentration of the exhaust gas (mass fraction)
z	coordinate/axial direction, m

Greek letters

α	oxidation reaction index
β	ratio of moles of oxygen to PM in the channel, defined by Eq. (15)
γ	dimensionless activation energy, defined by Eq. (15)
ΔH	heat of reaction, kJ/mol
λ	conductivity, W/(m K)
θ	dimensionless temperature, defined by Eq. (15)
μ	exhaust gas viscosity, kg/(m s)
ν	kinematic exhaust gas viscosity, m^2/s
ρ	density, kg/m^3
τ	dimensionless time, defined by Eq. (15)
Λ_1	flow resistance ratio, defined by Eq. (15)
Λ_2	flow resistance ratio, defined by Eq. (15)
Λ_3	dimensionless pressure drop ratio, defined by Eq. (15)
σ	dimensionless heat capacity ratio, defined by Eq. (15)
ϵ	dimensionless heat conductivity, defined by Eq. (15)
ΔT_{ad}	adiabatic temperature increase, K, defined by Eq. (15)

Subscripts

e	effective
f	DPF front heat-up
g	exhaust gas
in	DPF inlet
p	particulate layer
s	substrate layer
$T,heat$	total/whole DPF heat-up
V	temperature wave traveling time
w	filtration through the filter wall

operating conditions leading to optimal operation. Our goal is to determine these using several limiting models of the DPF that provide analytical predictions and physical insight on the filtration velocity, pressure drop and heat transfer in a DPF. The flow analysis enables an efficient optimization of the DPF design and operating conditions that lead to a more uniform PM deposition profile and a decrease of the pressure drop. The heat transfer analysis enables estimation of the DPF heat-up time and speed and width of the temperature front. The heat transfer analysis will be utilized in subsequent publications to minimize the PM light-off temperature and time [12] and temperature excursions during regeneration [13] and to suggest new DPF regeneration procedures.

This paper is organized as follows: a dimensionless DPF model is presented in Section 2 along with identification of the dimensionless groups that determine the hydrodynamic and heat transfer characteristics. Various limiting models are used in Section 3 to predict the filtration velocity distribution and pressure drop across the DPF. The transient heating of a cold DPF by hot exhaust gas and the corresponding heat transfer characteristics of the DPF are described in Section 4. The main operation and design recommendations are summarized in the last section. All analytical predictions are validated by numerical simulations.

2. Mathematical model

The one-dimensional two-phase model of the DPF analyzed here has been described in the literatures [14–16] and is based on the following simplifying assumptions: (i) heat conduction and diffusion in the gas phase is negligible, (ii) the flow in the channels is laminar and entrance effects can be neglected, (iii) the pressure drop in the channel is small so that its effect on the concentration and velocity may be neglected, (iv) the cross-section of the inlet channel is constant due to the small thickness of the soot layer compared with the channel hydraulic diameter, (v) the gas flow can be described by a quasi-steady state model since its dynamic response is faster than that of the solid temperature. The corresponding continuity, momentum and energy balances of the exhaust gas in the inlet ($i = 1$) and outlet ($i = 2$) channels are:

$$\frac{\partial}{\partial z}\left(R_\Omega^2 \rho_i V_i\right) = (-1)^i R_\Omega \rho_w V_w \tag{1}$$

$$\frac{\partial p_i}{\partial z} + \frac{\partial}{\partial z}\left(\rho_i V_i^2\right) = -\hat{f}\mu V_i/(4R_\Omega)^2 \tag{2}$$

$$C_{pg}\rho_1 V_1 \frac{\partial T_1}{\partial z} = h_1 \frac{1}{R_\Omega}(T_s - T_1) \tag{3}$$

$$C_{pg}\rho_2 V_2 \frac{\partial T_2}{\partial z} = (h_2 + C_{pg}\rho_w V_w)\frac{1}{R_\Omega}(T_s - T_2) \tag{4}$$