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Regeneration modes and peak temperatures in a diesel particulate filter

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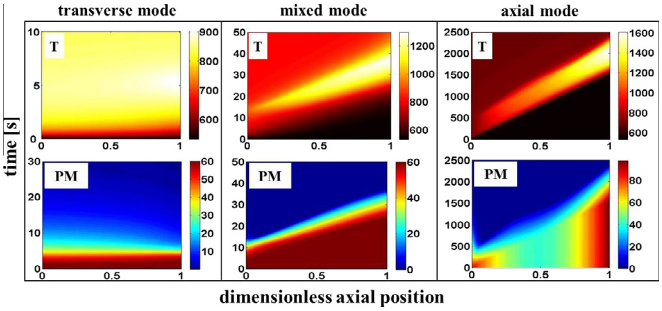
HIGHLIGHTS

- Two limiting modes of PM regeneration, transverse and axial, are analyzed.
- Criteria are developed for predicting the peak temperature of limiting modes.
- DPF selections to decrease the peak temperature of the mixed mode are discussed.
- The peak temperature can be decreased by widening the width of temperature front.
- Suggestions are provided to decrease the peak temperature under Drop to Idle (DTI).

GRAPHICAL ABSTRACT

DPF regeneration modes and their spatio-temporal regeneration temperature (in K) and PM (in μm) profiles: *Transverse mode* leads to the lowest peak temperature with close to uniform axial temperature and PM distribution during regeneration. *Axial mode* leads to the highest peak temperature with sharp moving temperature front and non-uniform PM profiles. Behaviors in the wide range between above limiting cases are in the *mixed mode*. DPF designs that lead the mixed mode towards the transverse mode decrease the peak temperature.



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ABSTRACT

Diesel particulate filters (DPF) are regenerated by combustion of the accumulated particulate matter (PM). This can lead to high peak temperature which can damage the DPF. We present guidance about how this peak temperature depends on the DPF design and operating conditions. Simple criteria are developed for predicting the peak temperature of two limiting regeneration modes. One is the *transverse regeneration mode* during which the PM is consumed uniformly along the DPF and the axial temperature is close to uniform. The second is the *axial regeneration mode* under which a negligible temperature difference exists between the solid phase and the gas, the filtration velocity is highly non-uniform and a sharp temperature front forms during the PM combustion. Most DPFs operate in the *mixed regeneration mode*, and their peak temperature is bounded between those predicted by the two limiting modes. The predictions of the behavior of the two limiting models provide useful guidance and bounds on any DPF design and operating conditions which will lower the peak regeneration temperature. For example, choices that widen the width of the moving temperature front decrease the maximum regeneration temperature under stationary feed conditions. A major technological challenge in the regeneration of the ceramic cordierite filter is that a sudden decrease of the engine load, referred to as Drop to Idle (DTI), may create a transient temperature peak much higher than under either the initial or final stationary feed conditions. The results for the stationary feed conditions suggest selections that decrease the peak temperature under stationary operation will also decrease the peak DTI temperature rise.

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Notations

Roman letters

A_o	adjusted pre-exponential factor, m/s
B	dimensionless adiabatic temperature rise, defined by Eq. (14)
$C_{\rho g}$	gas specific heat capacity, J/(kg K)
$C_{\rho s}$	solid wall specific heat capacity, J/(kg K)
$C_{\rho p}$	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. (14)
E	adjusted activation energy, J/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, g/mol
M_p	particulate molecular weight, g/mol
M_{o_2}	oxygen molecular weight, g/mol
Nu_{Ω}	Nusselt number, defined by Eq. (14)
p	pressure, Pa
$\hat{P}$	dimensionless pressure, defined by Eq. (14)
p_{amb}	atmosphere pressure, Pa
Δp	backpressure, Pa
$\Delta\hat{p}$	dimensionless backpressure
P	transverse Peclet number, defined by Eq. (14)
Pe_h	axial heat Peclet number, defined by Eq. (14)
r_{o_2}	oxygen reaction rate, $mole/(m^3\ s)$
R_g	gas constant, J/(mol K)
R_{Ω}	quarter of the hydraulic diameter 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. (14)
V	velocity, m/s
V_w	filtration velocity, m/s
w	particulate layer thickness, μm
$\overline{w_o}$	average PM thickness of initial PM deposit, μm
$\hat{w}$	dimensionless particulate layer thickness, defined by Eq. (14)
w_s	substrate layer thickness, μm
x	dimensionless axial position, defined by Eq. (14)
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. (14)
γ	dimensionless activation energy ,defined by Eq. (14)
ΔH	heat of reaction, J/mol
λ	conductivity, W/(m K)
θ	dimensionless temperature ,defined by Eq. (14)
μ	exhaust gas viscosity, kg/(m s)
υ	kinematic exhaust gas viscosity, m^2/s
ρ	density, kg/m^3
τ	dimensionless time ,defined by Eq. (14)
Λ_1	flow resistance ratio, defined by Eq. (14)
Λ_2	flow resistance ratio ,defined by Eq. (14)
Λ_3	dimensionless pressure drop ratio, defined by Eq. (14)
σ	Dimensionless heat capacity ratio, defined by Eq. (14)
ϵ	Dimensionless heat conductivity, defined by Eq. (14)
ΔT_{ad}	adiabatic temperature increase, K, defined by Eq. (14)

Subscripts and superscripts

b	downstream
e	effective
f	upstream
g	exhaust gas
ig	ignition
in	DPF inlet
p	particulate layer
s	substrate layer
w	filtration through the filter wall

1. Introduction

Diesel particulate filters (DPFs) are widely used in automotive exhaust after-treatment systems to reduce the emission of particulate matter (PM), which adversely affects human respiratory systems and is a carcinogen. The DPF alternatively blocked channels force the exhaust gas to flow through the porous filter walls capturing more than 95% of the PM inside the inlet channels (Fig. 1). The accumulated PM is periodically combusted to avoid pressure drop build-up, which decreases the engine fuel efficiency. An active PM combustion is usually initiated by feeding a hot exhaust gas containing oxygen to the DPF, whose initial temperature is lower than the ignition temperature. Temperature excursions that lead to melting or cracking of the DPF may occur during the PM combustion. Therefore, the two main objectives in the design and operation of a DPF undergoing regeneration are (i) limiting the maximum local temperatures during regeneration to values that are well below the melting point of the substrate and (ii) avoiding large temperature gradients that can crack the support. It has been shown that the maximum temperature gradient inside the DPF increases monotonically with the peak temperature [1,2]. Therefore, the peak temperature can predict both the melting and cracking of the DPF. In this work, we analyze the DPF regeneration and its peak temperature in two modes: transverse and axial regeneration modes based on the knowledge of flow distribution, heat transfer and light-off [3,4]. The analysis enables an efficient optimization of the DPF design and operating conditions that leads to lower peak temperatures during these two and mixed mode regeneration.

This paper is organized as follows: the dimensionless DPF model is presented in Section 2 along with identification of the dimensionless groups. Section 3 reviews the main results from our previous studies on the DPF hydraulic, heat transfer and light-off characteristics [3,4]. Based on this knowledge, DPF regeneration under the two limiting cases of transverse and axial PM reduction modes are studied in Section 4. Under the *transverse mode*, the axial PM and temperature profiles are rather uniform during the regeneration while under the *axial mode*, the flow and PM deposit are non-uniform and a sharp temperature front forms. Analytical expressions were derived to predict an upper bound on the peak regeneration temperature for each mode. We define the *mixed mode* PM regeneration to be those that differ from either one of the two limiting modes. The temperature and PM profiles under