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Numerical and experimental study on the gaseous emission and back pressure during regeneration of diesel particulate filters

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ABSTRACT

In this study, the back pressure of Diesel Particulate Filter (DPF) during loading and regeneration phase is measured. Then, one dimensional approach has been implemented to model the exhaust emissions and back pressure of a DPF, focusing on the regeneration phenomenon. The simulation has been divided in three parts. In the first part, the model is validated with two types of experimental data. The first test has been done by the authors on a light duty diesel engine and the second one was conducted by Rothe et al. on a heavy duty diesel engine. In the next part, some parameters, which were costly to measure, are numerically obtained. In the last part, the effect of these parameters on exhaust emissions and back pressure during regeneration has been investigated. The results showed that the substrate/cake soot mass ratio has a strong effect on exhaust emissions, back pressure and improvement of the DPF regeneration efficiency. When this value increases from 0 to 1, the exhaust emissions (CO, CO_2) increase by 94% and 95%, regeneration efficiency improves by 25% and back pressure dips to 22% respectively. It is found that the cake layer is a more efficient bed for soot burning in low substrate temperature and conversely the substrate wall is a most appropriate bed for soot burning at high temperature. Also, with an increasing in soot porosity from 0.56 to 0.96, the CO, CO_2 emissions and regeneration efficiency, increase about 61%, 62% and 60% and the back pressure dips to 56% respectively.

1. Introduction

Nowadays, one of the most important problems in mankind's life is air and environmental pollutants. Environment conservation and pollutant reduction are the two most prominent issues that researchers have investigated in recent years. One of the air pollution resources is internal combustion engines with fossil fuels. Various aftertreatment systems have been employed to reduce these emitted emissions. Diesel particulate filters (DPFs) are a type of aftertreatment devices specially designed to remove the particulate matter. Modern DPFs have been developed to meet the desirable thermal and mechanical resistance and their efficiency has been improved to more than 90% (Knecht, 2008). The main concern about such filters is reduction of emitted pollutant of heavy duty vehicles. Among all the exhaust emissions of gasoline vehicles under urban driving like carbon monoxide (CO), unburned hydrocarbons (HC), Nitrogen oxides (NO and NO_2) (Silva, 2006), which are toxic to human life and the environment, the main concern is assigned to particulate matter. To prevent such emissions, since 2000 many standards have been legislated to prevent the particulate matter and other toxic gas emissions to the environment (Knecht, 2008).

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Nomenclature

Ac	flow cross sectional area [m^2]
As	surface area of control volume [m^2]
D	equivalent diameter [m]
C_f	fraction losses
C_p	pressure losses
V	volume of control volume [cm^3]
$\dot{r}_{g,n}$	rate production [mol cm^3 sec^{-1}]
$W_{g,i}$	molecular weight [g/mole]
$\nu_{i,n}$	stoichiometric dimensionless coefficient
$\xi_{contraction}$	contraction back pressure coefficient
$\xi_{expansion}$	expansion back pressure coefficient
ρ	gas density [kg/m^3]
U	gas velocity [m/s]
μ	gas viscosity [Pa s]
Q	inlet gas volume flow rate [m^3/s]
w_{soot}	thickness of soot cake layer [m]
w_{wall}	thickness of filter substrate walls [m]
w_{ash}	thickness of ash layer [m]
L	the length of channel [m]
k_{soot}	permeability of soot cake layer [m^2]
k_{ash}	permeability of soot ash layer [m^2]
β	forchheimer constant
T	filter substrate temperature [K]
f_{CO}	dimensionless CO selectivity of the thermal reaction
M_C	molecular weight of soot [kg/mol]
M_{O2}	molecular weight of oxygen [kg/mol]
Y_{O2}	dimensional mass fraction of oxygen
A_T	pre-exponential factor (thermal frequency factor) [m/K-sec]
E_a	thermal activation energy [J/mole]
ϕ	partition coefficient
$d_{c,1}$	diameter of unite collector in the first slab [m]
$d_{c,0}$	diameter of unite collector of clean filter [m]
ψ	percolation constant
M_{sub}	collected soot mass inside the substrate wall
M_{cake}	collected soot mass inside the soot cake layer
M_{cs}	ratio
CO_2	carbon dioxide
CO	carbon monoxide
DPF	diesel particulate filter
DOC	diesel oxidation catalyst
NO	nitrogen monoxide
O_2	oxygen
PM	particulate matter
HC	unburned hydrocarbon

Equations: Governing equations for plug

Wall velocity equation $\frac{du_w}{dx} = \frac{2u_w}{D-2w+2x}$

Density differential equation $\frac{d\rho_w}{dx} = \sum_{k=1}^{k_s} \frac{\dot{s}_k W_k}{u_w}$

Mass fraction equation $\frac{dY_k}{dx} = \frac{[W_k \dot{s}_k - Y_k \sum_{k=1}^{k_s} \dot{s}_{k,m} W_k]}{\rho_w u_w}$

Soot oxidation rate equation $\dot{r}_{soot} = \rho_{w1} u_{w1}(D{-}2w){-}\rho_{w2} u_{w2} D$

Heat release in reaction $\dot{h}_{rxn} = \rho_{w1} u_{w1}(D{-}2w) h_{w1}{-}\rho_{w2} u_{w2} D h_{w2}$

Lupše et al. (2016) have studied the material and geometries of DPF's channel to find the optimized conditions (Lupše et al., 2016). Many researchers have studied the number and size distribution of the Diesel engine emissions (Myung and Park, 2012; Mohr et al., 2003; Zervas et al., 2004). Other pollutants with lower concentrations are also emitted from these engines which are called non-regulated emissions (Mohr et al., 2006; Yang et al., 2009). Some other researchers have studied the emissions of individual hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and carbonyl compounds (Nam et al., 2004; Miguel et al., 1998; Bikas and Zervas, 2007).

Also, some researchers examined the effect of pollutant transport in urban areas. Tong et al. (2012) have investigated the concentration of black carbon on the highway building environment for two different cities: South Bronx and New York by applying a Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model. They found that with the absence of roadside buildings, the concentration of black carbon decreased. Also, Zhang et al. (2004) have studied the particle transport and transform near the freeways. They suggested that high particle number concentrations have an adverse effect on the health of people living there.

Overall, the particulate matter (PM) generally known as a soot is one of the important emissions of diesel engines. Although these particles cannot be completely removed from the exhaust gases, they can be reduced by optimizing the combustion chamber geometry (Kaminaga and Kusaka, 2006). Another way to remove these particulates more efficiently is applying the diesel particulate filter (DPF) as a trap to remove the soot emissions (Setiabudi et al., 2004). Diesel particulate filter technology is applied to both light (Pattas et al., 1998) and heavy duty vehicles (Khair et al., 2000; Chandler et al., 2000). The main problem of these after treatment systems is the soot accumulation in the filter substrate wall which leads to increase in the back pressure through the filter. There are some techniques to revive the filter such as: burning soot by oxygen, NO and hydrocarbon injection (active regeneration). Filters equipped with continuous regeneration use the nitrogen oxides NO_2 at a lower temperature (300 °C) in comparison with oxygen reaction in the temperature range of 500–600 °C to oxidize the soot mass inside the trap (Kaminaga and Kusaka, 2006; Jiao et al., 2017; Konstandopoulos and Kostoglou, 1999).

The reactions happening during regeneration could not be completely measured due to some limitations and high costs. For this purpose, the simulation has been applied to estimate the unknown parameters like soot cake layer porosity. Tang et al. (2007) studied both zero dimensional and 1-D model, both of which are able to simulate the deep bed filtration, PM storage and regeneration. They found that, if zero dimensional model is calibrated well, some parameters such as collected soot mass inside the filter and pressure drop will be achieved and lead to savings in cost and time. They also found that by applying the 1-D model, the regeneration phenomena could be investigated in more detail (Peters et al., 2004; Wurzenberger et al., 2004).

Apart from the types of regeneration, the contents of fuels have a prominent effect on the DPF exhaust emissions during