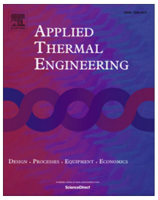
Applied Thermal Engineering 121 (2017) 838–852

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Research Paper

Influence of structural and operating factors on performance degradation of the diesel particulate filter based on composite regeneration

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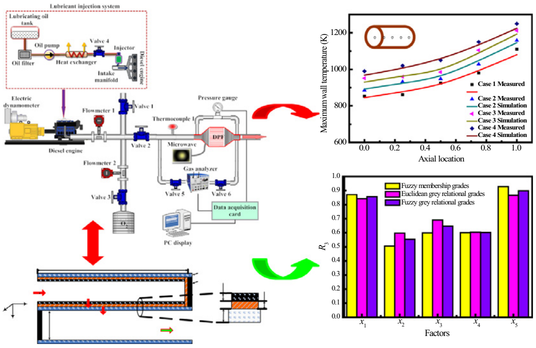
HIGHLIGHTS

- An efficient method combining OED and FGRA for evaluating impacts is presented.
- Pressure drop and maximum wall temperature under various conditions are obtained.
- Fuzzy grey relational grades are employed for comprehensive evaluation.
- The primary influence factors of the DPF's performance degradation are obtained.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 17 November 2016
Revised 29 March 2017
Accepted 30 April 2017
Available online 2 May 2017

Keywords:
Diesel particulate filter
Composite regeneration
Performance degradation
Influence factor
Fuzzy grey relational analysis

ABSTRACT

In order to effectively investigate the effects of various factors on the DPF's performance deterioration, and obtain the primary influence factor, an efficient evaluation method is proposed in this work. Firstly, the maximum wall temperature and the pressure drop are taken as the evaluation indexes of DPF's performance deterioration (thermal aging and filter clogging) respectively, and the orthogonal experimental design is used for obtaining the simulation conditions of test cases. Then, the impacts of four structural factors (wall thickness, mean pore size, porosity and channel width) and five operating factors (exhaust flow rate, exhaust oxygen concentration, microwave power, catalytic additive mass concentration and deposited ash mass) on DPF's performance deterioration are evaluated by fuzzy membership grades and Euclidean grey relational grades, respectively. Finally, fuzzy grey relational analysis is employed to make a comprehensive evaluation. The results show that the wall thickness and the channel width have the most noticeable effect on filter clogging and thermal aging among all structural factors, respectively. Moreover, the deposited ash mass and the microwave power are the most important operating factors for filter clogging and thermal aging, respectively. This work offers us great reference value for optimizing DPF performances and improving its degradation resistance.

1. Introduction

With the rapid increase of car ownership, the impact of automobile emission pollutants on the environment become more and more serious [1,2]. At present, various emission control methods

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http://dx.doi.org/10.1016/j.applthermaleng.2017.04.155

Nomenclature

A_1	cross-sectional area of the inlet channel [m^2]
A_2	cross-sectional area of the outlet channel [m^2]
A_{soot}	area of the soot layer [m^2]
A_{ash}	area of the ash layer [m^2]
A_w	area of the substrate wall [m^2]
L	filter length [mm]
D	filter diameter [mm]
E	activation energy [$J\ mol^{-1}$]
F	friction coefficient of the filter wall, $F = 28.45$
Q	exhaust flow rate [$g\ s^{-1}$]
R	universal gas constant, $R = 8.314\ J\ (mol\ K)^{-1}$
Rcat O_2	oxygen consumption rate by catalytic soot oxidation
Rth O_2	oxygen consumption rate by thermal soot oxidation
V	filter volume [m^3]
C_g	specific heat capacity of the exhaust gas [$J\ (kg\ K)^{-1}$]
C_{soot}	specific heat capacity of soot [$J\ (kg\ K)^{-1}$]
C_{ash}	specific heat capacity of ash [$J\ (kg\ K)^{-1}$]
C_w	specific heat capacity of the substrate wall [$J\ (kg\ K)^{-1}$]
M_C	molar mass of carbon particles [kg/mol]
M_{OX}	molar mass of oxygen [kg/mol]
Y_1	oxygen concentration in the inlet channel (%)
Y_0	oxygen concentration of the exhaust gas (%)
H_{acc}	the amount of energy for solid phase [J]
H_{con}	convection heat [J]
H_{tran}	transfer heat [J]
$\triangle H_{cat}$	heat of reaction for catalytic oxidation [J]
$\triangle H_{th}$	heat of reaction for thermal oxidation [J]
$Q_{reaction}$	reaction heat of soot oxidation [J]
S_p	specific surface area of carbon particle layer [m^{-1}]
T_1	exhaust temperature in inlet channels [K]
T_2	exhaust temperature in outlet channels [K]
T_w	exhaust temperature inside the substrate wall [K]
T_{w_max}	maximum wall temperature [K]
T_0	initial exhaust temperature [K]
Re_1	Reynolds number in the inlet channel
Re_2	Reynolds number in the outlet channel
Δp	total pressure drop of the DPF [Pa]
Δp_{cont}	local pressure drop of the inlet with variable cross-section in filter channels [Pa]
Δp_{exp}	local pressure drop of the outlet with variable cross-section in filter channels [Pa]
$\Delta p_{inlet\_channel}$	pressure drop along the inlet channel [Pa]
$\Delta p_{outlet\_channel}$	pressure drop along the outlet channel [Pa]
Δp_{wall}	pressure drop of the filter wall [Pa]
Δp_{ash_layer}	pressure drop of the ash layer [Pa]
Δp_{soot_layer}	pressure drop of the soot layer [Pa]
Δp_1	pressure drop of the DPF with PM [Pa]
Δp_c	pressure drop of the clean DPF [Pa]
Δp_r	pressure drop of the DPF after regeneration [Pa]
p_0	atmospheric pressure [Pa]

p_1	exhaust pressure in inlet channels [Pa]
p_2	exhaust pressure in outlet channels [Pa]
P_{mw}	microwave power [kW]
a	channel width of the filter [mm]
a_1	channel width for inlet channels considering soot and ash deposition
a_2	channel width for outlet channels
d	mean pore size [μm]
k_{wall}	permeability of the filter wall, $k_{wall} = 1.8 \times 10^{-13}\ m^2$
k_{ash}	permeability of the ash layer, $k_{ash} = 3.08 \times 10^{-14}\ m^2$
k_{soot}	permeability of the soot layer, $k_{soot} = 1.0 \times 10^{-14}\ m^2$
k_{O2_0}	pre-exponential factor of oxidation reaction rate, $k_{O2\_0} = 5.96 \times 10^2\ m\ s^{-1}$
w	wall thickness [mm]
w_{ash}	thickness of the ash layer [mm]
w_{soot}	thickness of the soot layer [mm]
w_{s_0}	the initial thickness of soot layer at initial time [mm]
m_{soot}	the mass of PM deposition [$g\ L^{-1}$]
m_{ash}	the mass of ash deposition [$g\ L^{-1}$]
Y_0	exhaust oxygen concentration [%]
c_a	catalytic additive mass concentration [$mg\ L^{-1}$]
ε	porosity [%]
β	complete coefficient of the soot oxidation reaction, $\beta = 0.8$
μ_1	dynamic viscosity of the exhaust gas in the inlet channels [Pa s]
μ_2	dynamic viscosity of the exhaust gas in the outlet channels [Pa s]
ξ_{cont}	contraction coefficient of the inlet channel, $\xi_{cont} = 0.4$
ξ_{exp}	expansion coefficient of the outlet channel, $\xi_{exp} = 0.4$
ρ_1	exhaust gas density in inlet channels [$kg\ m^{-3}$]
ρ_2	exhaust gas density in outlet channels [$kg\ m^{-3}$]
ρ_w	exhaust gas density inside the substrate wall [$kg\ m^{-3}$]
ρ_{soot}	packing density of the soot layer, $\rho_{soot} = 1500\ kg\ m^{-3}$
ρ_{ash}	packing density of the ash layer, $\rho_{ash} = 450\ kg\ m^{-3}$
ρ_{wall}	density of the filter wall [$kg\ m^{-3}$]
ρ_{cell}	cell density of the filter [cells in^{-2}]
v_1	inlet velocity of the exhaust gas in the channels [$m\ s^{-1}$]
v_2	outlet velocity of the exhaust gas in the channels [$m\ s^{-1}$]
h_1	heat transfer coefficient between exhaust flow and filter wall in inlet channels [$W\ (m^2\ K)^{-1}$]
h_2	heat transfer coefficient between exhaust flow and filter wall in outlet channels [$W \cdot (m^2\ K)^{-1}$]
λ_{soot}	thermal conductivity of the soot layer [$W\ (m\ K)^{-1}$]
λ_{ash}	thermal conductivity of the ash layer [$W\ (m\ K)^{-1}$]
λ_w	thermal conductivity of the filter wall [$W \cdot (m\ K)^{-1}$]
α_1	thermal carbon monoxide selectivity
α_2	catalytic carbon monoxide selectivity

and electric vehicle technologies are used to solve environmental pollution and to comply with the increasingly stringent emission standards [3–5]. It is well known that diesel engines have been widely used as the vehicle power in the world due to their low fuel consumption, strong power performance and better reliability [6–9]. Unfortunately, diesel powered vehicles produce a considerable amount of particulate matter (PM) [10], which is thought to be the main source of air pollution. Currently, the wall-flow diesel particulate filter (DPF) is considered to be one of the most effective aftertreatment device for PM abatement in diesel powered vehicles [11,12], and the regeneration technology [13,14] is the key process for its actual application. However, widely application of the DPF in automobiles is restricted due to its deterioration after multiple regenerations in the porous media filter [15,16], and DPF degradation can inevitably result in the increase of pressure drop as well as the decrease of filtration efficiency and regeneration efficiency, limiting the DPF's in use service life, so that the DPF requires removal for periodic cleaning or replacement. Therefore, it is quite necessary to investigate the performance degradation or durability of the DPF to improve its service life.

Over the years, the material of the filter, the regeneration strategy, the filter structural parameters, and the operating condition have been investigated to guarantee best performances, such as high filtration efficiency and regeneration efficiency as well as low pressure drop during standard operations, but also reliability and durability in the long run.