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Research Paper

Investigations on the temperature distribution of the diesel particulate filter in the thermal regeneration process and its field synergy analysis

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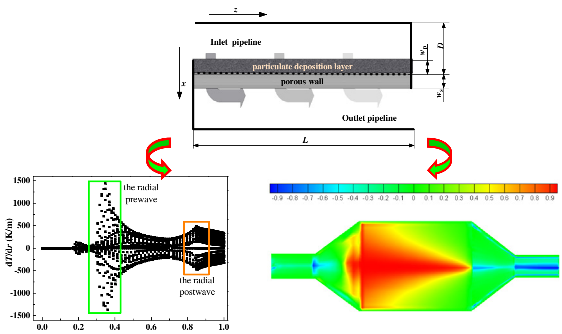
HIGHLIGHTS

- A thermal regeneration model of the DPF is developed in the thermal regeneration process.
- The internal temperature and temperature gradient in channels are investigated.
- The Temperature distribution of the DPF is optimized based on Field synergy theory.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to enhance the reasonableness of temperature distribution of the diesel particulate filter (DPF), a thermal regeneration model of the DPF is developed to investigate the temperature distribution of the diesel particulate filter in the thermal regeneration process, and the internal temperature and temperature gradient in channels are simulated. Moreover, field synergy theory is used to optimize temperature distribution of the DPF in the thermal regeneration process due to synergy degree between velocity vector and temperature gradient. The results reveal that increase of the exhaust mass flow in the thermal regeneration process will lead to the increase of temperature value from the filter section to the contraction section of along the axial direction, the peak of the radial temperature gradient will appear in the front of the filter section and contraction section, and the maximum value will first decrease and then increase, but the peak of axial temperature gradient will appear in the front of the filter section. When the exhaust mass flow is about 20–30 g/s, there is an optimum flow area for the peak of radial temperature gradient, and the peak of axial temperature gradient will decrease gradually. Moreover, particle load which is less than 5 g/L can avoid the melt failure and the thermal stress damage.

1. Introduction

In the automotive market, the diesel engines are attractive for their advantages of high thermal efficiency, reliability and good fuel economy [1,2]. But a big issue worldwide is that the major

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Nomenclature

c_g	specific heat capacity of exhaust gas ($J\cdot kg^{-1}\cdot K^{-1}$)
c_p	specific heat capacity of particulate deposition layer ($J\cdot kg^{-1}\cdot K^{-1}$)
c_s	specific heat capacity of ceramic wall ($J\cdot kg^{-1}\cdot K^{-1}$)
D	side length of square of wall (m)
$4/D$	specific surface area of wall (m^2)
E	activation energy (150 $kJ\cdot mol^{-1}$)
F	pressure drop of square tubes (28.45)
h_i	heat transfer coefficient between exhaust gas and filter wall ($W\cdot m^{-1}\cdot K^{-1}$)
k_p	permeability of particulate deposition layer
k_s	permeability of ceramic wall
M_c	molecular mass of carbon
M_{ox}	molecular mass of oxygen
M_i	molecular mass of exhaust gas in inlet channel ($kg\cdot mol^{-1}$)
M_w	molecular mass of exhaust gas on wall surface ($kg\cdot mol^{-1}$)
m_c	carbon deposition mass in unit volume (kg)
m^o_{cx}	carbon deposition mass in x-section (kg)
m_{cx}	carbon deposition mass in other point (kg)
p_i	pressure of exhaust gas in inlet channel (Pa)
p_w	pressure of exhaust gas on wall channel (Pa)
p_{mw}	distribution of flux density of thermal ($W\cdot m^{-2}$)
P_{mi}	the energy stream surface densities of the incident waves
P_{mo}	the energy stream surface densities of the reflective waves
q_m	the exhaust mass flow ($g\cdot s^{-1}$)
R_g	exhaust gas constant by mass ($J\cdot kg^{-1}\cdot K^{-1}$)
S_p	specific surface area of particulate deposition layer (m^2)
T_i	temperature of mixed exhaust gas in inlet channel (K)
T_w	temperature on wall surface ($m\cdot s^{-1}$)
v_i	velocity of exhaust gas in inlet channel ($m\cdot s^{-1}$)
v_w	seepage velocity of exhaust gas on wall surface ($m\cdot s^{-1}$)
w_p	thickness of carbon particulate layer (m)
w_s	thickness of ceramic wall (m)
Y_1	oxygen concentration of inlet channel (mol/m^3)
Y_w	oxygen concentration of on wall surface (mol/m^3)
α	complete coefficient of particulate oxidation reaction (0.55–0.90)
α_{eff}	the equivalent attenuation constant of wall-flow type filter body
ρ_c	apparent density of particulate (56 $kg\cdot m^{-3}$)
ρ_i	density of exhaust gas in inlet channels ($kg\cdot m^{-3}$)
ρ_p	density of particulate deposition layer ($kg\cdot m^{-3}$)
ρ_s	density of ceramic ($kg\cdot m^{-3}$)
ρ_w	density of exhaust gas on wall surface ($kg\cdot m^{-3}$)
μ	dynamic viscosity of exhaust gas ($N\cdot s\cdot m^{-2}$)
λ_p	thermal conductivity of particulate deposition layer ($W\cdot m^{-1}\cdot K^{-1}$)
λ_s	thermal conductivity of ceramic wall ($W\cdot m^{-1}\cdot K^{-1}$)
$\Delta H_{(i)}$	enthalpy reacting from CO_2 ($J\cdot mol^{-1}$)
$\Delta H_{(ii)}$	enthalpy reacting from CO ($J\cdot mol^{-1}$)
Γ	the reflection coefficient of the filter body wall

sources of particulate matter (PM) by diesel engine which causes damage to the environmental and human health [3]. The great efforts were taken to reduce the emissions of PM (Partially Premixed Compression Ignition (PPCI) [4,5], RCCI (Reactivity Controlled Compression Ignition) [6–9], HCCI (Homogeneous Charge Compression Ignition) [10,11], etc. [12–15]) are becoming of increasing stricter, so it is getting difficult to meet the stringent emissions regulations only using the technology for improving the combustion processes in diesel engine [16–19]. It is well known that a DPF will be an essential component for most diesel exhaust after-treatment system to trap PM [20–22], but the key technology is regeneration [9,10], including the thermal regeneration, fuel catalytic regeneration and continuous regeneration etc. While the catalyst could be damaged by the sulfur poisoning and the filter substrate may also be cracked, which leads to low generation efficiency [23,24], the thermal one will remain the main regeneration of particulate filter.

In the process of thermal regeneration, the use of this method is restrictive. The DPF carrier can be melted or cracked due to excessive temperature or excessive thermal stress. So it is necessary to study the temperature distribution characteristics of the DPF in the regeneration process [25–28]. In previous studies, the researchers focus on the operating mechanism, combustion rule and flowing law of the heating regeneration technology to reduce the ignition temperature [29–34]. Currently, more and more researchers begin to involve the other aspects to reduce temperature gradient. Bensaid et al. [35] developed a fully predictive three-dimensional mathematical model to describe the soot deposition process into the filter which simulated the gas and particulate flow fields in DPF to analysis of the filter body temperature gradient distribution. Shi et al. [36] designed Non-thermal plasma (NTP) injection system to study the regeneration of DPF which could regenerate at a lower temperature and both axial and radial temperature gradients were less than the limit of DPF temperature gradient at this temperature. Chen et al. [23] studied the variation characteristics of the temperature gradient in the regeneration of diesel particulate filter, and the experiments was used to analyze the relationship between the intake oxygen concentration and the particle deposition layer. Yu et al. [37] developed two limiting regeneration models, which predicted the peak temperature in the most mixed DPF regeneration modes and provided useful guidance and bounded on any DPF design and operating conditions. Wang et al. [38] proposed the control solutions for the idle thermal protection to validate DPF drop-to-idle uncontrolled regeneration, which verified the increase in oxygen concentration and the decrease in exhaust flow rate could result in a sharp exotherm in the filter and high temperature to damage the substrate. Liu et al. [39] investigated the low temperature with hydrogen and performed the DPF used in this experiments was coated with Pt/Al_2O_3 25 g/ft^3 which showed DPF regeneration could be realized at about 150 °C or even lower.

As noted above, several experimental and theoretical investigations [40–43] such as pressure drop, regeneration speed and temperature gradient distribution of the DPF regeneration have been conducted in recent years. Though the optimal ranges of structural parameters of the DPF have been investigated, further studies about field synergy optimization of velocity vector and temperature gradient in the DPF should be developed. It is noted that the design process of a DPF is so extremely complex that velocity vector and temperature gradient in the DPF could strongly conflict with each other. The field synergy principle (FSP) [44], as a more practical design methodology, has become increasingly popular in many research fields such as the fluid flow [45], the micro combustion [46], the water jet [47] and the heat dissipation [48], so it provides a new avenue for enhancing the reasonableness of temperature distribution of the diesel particulate filter (DPF) based on field synergy optimization.