Applied Energy 181 (2016) 14–28

Contents lists available at ScienceDirect

Applied Energy

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

# Multidisciplinary design optimization of the diesel particulate filter in the composite regeneration process

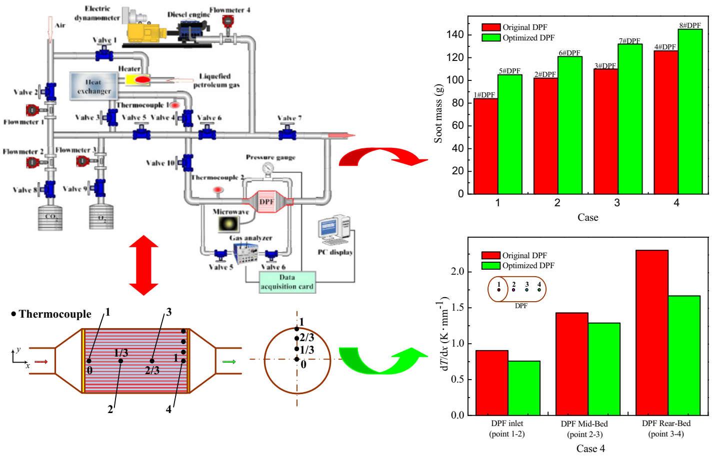
Bin Zhang [a,b,c], Jiaqiang E [a,b,*], Jinke Gong [a,b,*], Wenhua Yuan [c], Wei Zuo [a,b], Yu Li [a,b,c], Jun Fu [c]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China
[c] Department of Mechanical and Energy Engineering, Shaoyang University, Shaoyang 422004, China

## HIGHLIGHTS

- The multidisciplinary design optimization (MDO) for the DPF is presented.
- MDO model and multi-objective functions of the DPF are established.
- The optimal design parameters are obtained and DPF's performances are improved.
- The optimized results are verified by experiments.
- The composite regeneration process of the optimized DPF allows a higher energy saving.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 19 June 2016
Received in revised form 4 August 2016
Accepted 8 August 2016

*Keywords:*
Diesel particulate filter
Multidisciplinary design optimization
Adaptive mutative scale chaos optimization algorithm
Composite regeneration
Microwave energy

## ABSTRACT

In our previous works, the diesel particulate filter (DPF) using a new composite regeneration mode by coupling microwave and ceria-manganese base catalysts is verified as an effective way to reduce the particulate matter emission of the diesel engine. In order to improve the overall performance of this DPF, its multidisciplinary design optimization (MDO) model is established based on objective functions such as pressure drop, regeneration performance, microwave energy consumption, and thermal shock resistance. Then, the DPF is optimized by using MDO method based on adaptive mutative scale chaos optimization algorithm. The optimization results show that with the help of MDO, DPF's pressure drop is decreased by 14.5%, regeneration efficiency is increased by 17.3%, microwave energy consumption is decreased by 17.6%, and thermal deformation is decreased by 25.3%. The optimization results are also verified by experiments, and the experimental results indicate that the optimized DPF has larger filtration efficiency, better emission performance and regeneration performance, smaller pressure drop, lower wall temperature and temperature gradient, and lower microwave energy consumption.

---

* Corresponding authors at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
*E-mail addresses:* ejiaqiang@126.com (J. E), gongjinke@126.com (J. Gong).

http://dx.doi.org/10.1016/j.apenergy.2016.08.051
0306-2619/© 2016 Elsevier Ltd. All rights reserved.

## Nomenclature

| | |
|---|---|
| $L$ | filter length (mm) |
| $D$ | filter diameter (mm) |
| $F$ | friction coefficient of the filter wall |
| $Q$ | exhaust flow rate ($g{\cdot}s^{-1}$) |
| $V$ | filter volume ($m^3$) |
| $T_g$ | exhaust gas temperature (K) |
| $T_f$ | internal temperature of the filter (K) |
| $\Delta p$ | total pressure drop of the DPF (Pa) |
| $\Delta p_{cont}$ | local pressure drop of the inlet with variable cross-section in filter channels (Pa) |
| $\Delta p_{exp}$ | 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) |
| $\Delta p_{wall}$ | pressure drop of the filter wall (Pa) |
| $\Delta p_{ash\_layer}$ | pressure drop of the ash layer (Pa) |
| $\Delta p_{soot\_layer}$ | pressure drop of the soot layer (Pa) |
| $\Delta p_1$ | pressure drop of the DPF with PM (Pa) |
| $\Delta p_c$ | pressure drop of the clean DPF (Pa) |
| $\Delta p_r$ | pressure drop of the DPF after regeneration (Pa) |
| $C_{before}$ | soot concentration in the exhaust stream before the filter (%) |
| $C_{after}$ | soot concentration in the exhaust stream after the filter (%) |
| $M$ | mass (kg) |
| $P_{mw}$ | microwave power (kW) |
| $Q_{mw}$ | microwave energy consumption (kJ) |
| $\alpha$ | channel width (mm) |
| $d$ | mean pore size (μm) |
| $k_{wall}$ | permeability of the filter wall ($m^2$) |
| $k_{ash}$ | permeability of the ash layer ($m^2$) |
| $k_{soot}$ | permeability of the soot layer ($m^2$) |
| $w$ | wall thickness (mm) |
| $w_{ash}$ | thickness of the ash layer (mm) |
| $w_{soot}$ | thickness of the soot layer (mm) |
| $c_o$ | oxygen content in the exhaust gas (%) |
| $m_{soot}$ | amount of PM deposition ($kg{\cdot}m^{-3}$) |
| $c_a$ | catalytic additive mass concentration ($mg{\cdot}L^{-1}$) |
| $\lambda$ | porosity (%) |
| $\theta$ | cone angle of inlet and outlet cones (deg) |
| $\mu$ | dynamic viscosity of exhaust gas ($kg{\cdot}(m{\cdot}s)^{-1}$) |
| $\sigma$ | thermal stress in DPF (MPa) |
| $\Delta\varepsilon$ | maximum thermal deformation (mm) |
| $\eta_f$ | filtration efficiency (%) |
| $\eta_r$ | regeneration efficiency (%) |
| $\xi_{cont}$ | contraction coefficient of the inlet channel |
| $\xi_{exp}$ | expansion coefficient of the outlet channel |
| $\zeta$ | ratio of efficiency to energy ($\%{\cdot}(10^5\ J)^{-1}$) |
| $\rho_g$ | exhaust gas density ($kg{\cdot}m^{-3}$) |
| $\rho_{cell}$ | cell density of the filter ($cells{\cdot}in.^{-2}$) |

## 1. Introduction

Diesel engines have dominated the market of heavy-duty vehicles and have been growing in the market of light-duty vehicles due to their high fuel economy, high output power, reliable performance, etc. However, diesel powered vehicles produce a considerable amount of nitrogen oxide ($NO_x$) and particulate matter (PM), which is thought to be the main source of air pollution [1–3]. Nowadays, the design of vehicles in the world is being driven by technical, economic, and social forces such as reliability, durability, low cost, and environmental benefits [4–7] that meet the stringent emission regulations, so many effective solutions for reducing harmful emissions in exhaust gas have been investigated [8–12].

Currently, some new combustion modes (PPCI (partially premixed compression ignition) [12,13], RCCI (reactivity controlled compression ignition) [14,15], HCCI (homogeneous charge compression ignition) [16,17], etc.) have been proposed and studied to solve the particulate emissions. However, the diesel particulate filter (DPF) is considered to be one of the most effective and simplest methods for reducing particulate emissions in diesel powered vehicles [18–20] and its regeneration technology is the key process for actual application of the DPF. There are 3 kinds of regeneration techniques (catalyst mixed in fuel or deposited on filter substrate to reduce regeneration temperature from 823 K to 673 K (passive regeneration) [21,22], thermal regeneration with methods to raise the exhaust temperature by the supply of external energy from electricity, fuel and microwave (active regeneration) [23,24], and composite regeneration with combining above two methods [25]) to accelerate the DPF regeneration process. At present, there are some problems in the microwave regeneration process of the DPF, such as the shortage of battery energy storage, low energy utilization efficiency, higher thermal stress and poor durability of the filter. Although the composite regeneration technology of catalyst combustion-supporting combined with microwave heating [26–28] could make the particles burn under a condition of low temperature by reducing the particle ignition temperature with chemical catalyst, it requires around 0.5–2 kW of electrical power for achieving the light off temperature [29].

With the increasing requirement of automobile's performance, the PM emission of diesel engines can hardly satisfy the new emission regulation. So it is seriously necessary to design a high performance, long life, energy-saving and low cost DPF. Basic design requirements of a DPF include high filtration efficiency and regeneration efficiency, low pressure drop and energy consumption and better thermal durability, while it is difficult to meet these requirements simultaneously in its actual working process, so its design method and parameters requires further optimization for improving these performances [30]. Among these design targets, the microwave heating power determines the amount of energy consumption of the DPF, and thermal shock on the porous medium filter of the DPF caused by high temperature in the regeneration process is a key factor that leads to its thermal fatigue and failure [31].

These years, lots of numerical and experimental investigations have been conducted to improve the design of DPF [32–36]. For example, Sarli et al. [37] established a two-dimensional mathematical model of soot regeneration for a single-channel catalytic diesel particulate filter. Pontikakis et al. [38] developed a three-dimensional model for the regeneration of the diesel particulate filter, which is an engineering tool for the detailed design optimization of SiC diesel filters of modular structure. Konstandopoulos et al. [39] established optimal design and selection criteria of the DPF based on the established constraint equation of geometric parameters of the filter such as channel width, channel length, wall thickness and permeability for a given filter volume, regarding the sizing of the wall-flow DPF for application in continuously regenerating trap systems, employing a range of CFD analytical tools validated against experimental data and