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Original article

Effect analysis on regeneration speed of continuous regeneration-diesel particulate filter based on NO_2-assisted regeneration

Jiaqiang E [a, b, *], Longfu Xie [a, b], Qingsong Zuo [a, b], Guiju Zhang [a, c]

[a] College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China
[b] Institute of New Energy and Energy-saving & Emission-reduction Technology, Hunan University, Changsha 410082, China
[c] Department of Mechanical and Energy Engineering, Shaoyang University, Shaoyang, Hunan 422004, China

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ABSTRACT

In order to improve the regeneration speed of Continuous Regeneration-Diesel Particulate Filter (CR-DPF) based on NO_2-assisted regeneration, a mathematic model of the NO_2-assisted regeneration is developed and verified by experiments and numerical simulation. Furthermore, the influences on regeneration speed from exhaust airflow and filter structure are studied in NO_2-assisted regeneration process of CR-DPF. The results show that: the regeneration speed will be increased due to the increase of the volume of the exhaust gas, the temperature of the exhaust gas, the concentration of the NO_2 and the concentration of the O_2 in exhaust gas, but the regeneration speed will be decreased under other conditions such as $m(NO_2)/m(PM)$ being less than its threshold in exhaust gas, the increase of the filter length in CR-DPF or the increase of the channel density when initial amount of the carbon particles in filter being less than its threshold, moreover, thickness of channel wall has no effect on regeneration speed. And the suitable range of values for some key parameters being useful for enhancing regeneration speed and reducing pressure drop of CR-DPF has been provided.

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1. Introduction

It is well known that diesel engines have been the mainstream of the vehicle power in the world due to their good performances such as low fuel consumption, reliable performance and strong power performance etc. But the development of diesel engines is restricted seriously for their particulate emissions(Liu et al., 2009; Caserini et al., 2013; Onat and Stakeeva, 2013; Jaffe et al., 2014) and it also is regarded as a major PM2.5 source, which has been associated with a variety of adverse health effects, visibility reduction, as well as changes in the Earth's radiation balance (Dockery et al., 1993; Burnett et al., 1995; Hinds, 1999). The emissions from diesel engines are also the important contributor to the global anthropogenic aerosol burden (Kohler and Dameris, 2001). It is estimated that air pollution from motor vehicular emissions constitutes more than 50% of the total particulate air pollution in developed countries (Harrison et al., 1997; Cao et al., 2006). Nowadays the diesel particulate filter (DPF) is considered as one of the most effective and simplest method to reduce particulate emissions (Chen et al., 2011; Quiros et al., 2014; Zuo et al., 2014). Obviously, regeneration technology is a key factor for actual application of the DPF. At present, there are a large number of theoretical and experimental researches on regeneration technology of the DPF (Palma et al., 2007; Bogdanić et al., 2008; Torregrosa et al., 2011), and continuous regeneration technology (CRT) includes diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) is considered as the most valuable and promising method of regeneration technology for the DPF. In continuous regeneration process, the NO from exhaust gas will be cataleptically oxidized to the NO_2 with strong oxidizing property after the DOC, and NO_2 is useful for carbon particles to generate oxidizing reaction under the temperature 623 K of the exhaust gas, therefore, continuous regeneration of the DPF comes true will be ensured with no additional control system or heat sources. Obviously, diesel oxidation catalyst is key part of the CRT, therefore, some researches on the thermodynamic and kinetic mechanism(Liu et al., 2002; Piscaglia and Ferrari, 2009; Premchand et al., 2009; Zheng and Banerjee,

* Corresponding author. College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China.
E-mail address: ejiaqiang@126.com (J. E).
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2009; Schejbal et al., 2010; Azambre et al., 2011) of the NO oxidized to the NO_2 after the DOC based on influence factors such as space velocity, temperature, catalyst component and exhaust gas component. Furthermore, CRT is of good advantages such as low-cost, simple structure and wider regeneration window (Tighe et al., 2012; Serrano et al., 2013; Yu et al., 2013; Giménez-Mañogil et al., 2014). Therefore, CRT has become a predominant regeneration technique (Lee et al., 2008).

It is obvious that too small regeneration speed in Continuous Regeneration-Diesel Particulate Filter (CR-DPF) will lead to insufficient regeneration problems and high exhaust back pressure in CR-DPF, which will reduce the dynamic performance and fuel economy of a diesel engine and cause more fine particles emitted into the ambient air so that diesel exhaust particulate emission control has become the main task to prevent the automotive pollution due to increasingly stringent emission regulations. Therefore, it is necessary to study the influences of the physical parameters of exhaust gas and the structure parameters of the diesel particulate filter on the regeneration speed in NO_2 assisted regeneration process and reduce the fine particles emissions from the diesel engines. In the paper, a mathematic model in NO_2 assisted regeneration process of CR-DPF is established and tested by using of experimental data. The research results will provide theoretical basis how to optimize design of CR-DPF and reduce the fine particles emissions from the diesel engines into atmospheric environment.

2. Mathematic model of CR-DPF

2.1. Working principle of CR-DPF

As shown in Fig. 1, the CR-DPF is consisted of diesel oxidation converter (DOC) and DPF. The working principle of the CR-DPF can be expressed as follows: Firstly, the exhaust gas of diesel engine firstly flows through DOC, then NO will be cataleptically oxidized to the NO_2 with strong oxidizing property after carbon monoxide and HC are purified. Subsequently, carbon particles on the filter deposition in CR-DPF will be simultaneously burned up due to strong oxidizing function from the NO_2 under the temperature (usually 453–673 K) of the exhaust gas of the diesel engine, which will be necessary to ensure low back pressure of the exhaust pipeline of diesel engine.

The mechanisms of regeneration reaction of CR-DPF are expressed as follows (Liu et al., 2002; Azambre et al., 2011).

$$CO + NO + O_2 \rightarrow NO_2 + CO_2 \tag{1}$$

$$C + \left(1 - \frac{\alpha_1}{2}\right)O_2 \rightarrow \alpha_1 CO + (1 - \alpha_1)CO_2 \tag{2}$$

Where, α_1 is selectivity coefficient for completely reaction between O_2 and carbon particle, $\alpha_1 = 0.55 \sim 0.9$.

$$C + (2 - \alpha_2)NO_2 \rightarrow \alpha_2 CO + (1 - \alpha_2)CO_2 + (2 - \alpha_2)NO \tag{3}$$

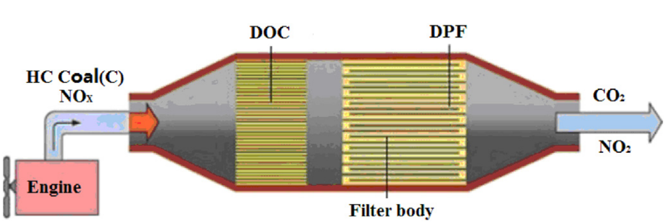


Fig. 1. Representative CR-DPF.

Where, α_2 is selectivity coefficient for completely reaction between NO_2 and carbon particle, $\alpha_2 = 1.2–1.8$.

The reaction Eq. (1) is the main reaction in the DOC which is coated with noble metal such as platinum (Pt) and palladium (Pd) etc. Thus NO will be converted into the NO_2 with strong oxidizing property at working temperature of exhaust gas in the diesel engine. The oxygen will play a dominant role in the chemical reaction shown in Eq. (2) when the temperature of the exhaust gas is higher than 673 K and the NO_2 will play a dominant role in the chemical reaction shown in Eq. (3) under the work temperature of the exhaust gas in the diesel engine.

2.2. Establishment of mathematical model of CR-DPF

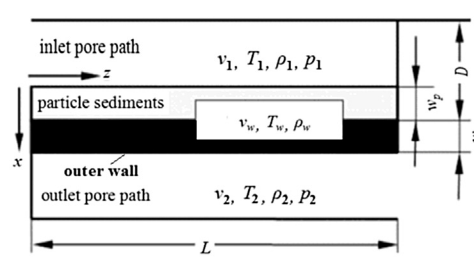
Fig. 2 presents the working principle and the flow model of inside channel in CR-DPF. As shown in Fig. 2, after exhaust gas in the diesel engine flows into a channel and flows out of an adjacent channel through the ceramic wall, the PM of exhaust gas is deposited on porous wall surface in CR-DPF.

According to the research results (Kandylas et al., 2002), some assumptions can be made as follows: (a) The thermal radiation loss in CR-DPF can be neglected; (b) The PM of exhaust gas is consisted of pure carbon particle; (c) The inlet size of channel in CR-DPF will be unaffected by particle's deposition and regeneration reaction on wall surface; (d) The effect of radial direction on the air temperature inside channel and concentration parameters in CR-DPF are both neglected; (e) No chemical reactions happen inside wall surface in the filter.

According to above assumptions, the one-dimensional mathematic model of single channel can be expressed as follows:

(1) Conservation of mass equation of the exhaust gas

Conservation of mass equation of the exhaust gas can be expressed by Formula (4).



(1) v_1 is inlet velocity of exhaust gas in the channels, m/s;
(2) v_2 is outlet velocity of exhaust gas in the channels, m/s;
(3) T_1 is temperature of the exhaust gas in inlet channels, K;
(4) T_2 is temperature of the exhaust gas in outlet channels, K;
(5) ρ_1 is the density of exhaust airflow in inlet channels, kg/m^3;
(6) ρ_2 is the density of exhaust airflow in outlet channels, kg/m^3;
(7) p_1 is the pressure of exhaust gas in inlet channels, Pa;
(8) p_2 is the pressure of exhaust gas in outlet channels, Pa;
(9) T_w is temperature of the exhaust gas inside the filter, K;
(10) v_w is the velocity of the airflow inside the filter, m/s;
(11) ρ_w is the density of airflow inside the filter, kg/m^3;
(12) w_p is thickness of soot particle deposition layer, m;
(13) w_s is thickness of the filter wall, m;
(14) D is side-length of square channel, m;
(15) L is the length of the filter, m

Fig. 2. Flow model of inside channel in CR-DPF.

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