Energy 48 (2012) 492–499

Contents lists available at SciVerse ScienceDirect

Energy

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

A study on the cell structure and the performances of wall-flow diesel particulate filter

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ARTICLE INFO

Article history:
Received 2 May 2012
Received in revised form
20 July 2012
Accepted 5 October 2012
Available online 2 November 2012

Keywords:
Diesel particulate filter
Diesel engines
Emission control
Filtration efficiency
Pressure drop
Regeneration

ABSTRACT

As for the recent PM regulations, a diesel particulate filter (DPF) has been one of the important after-treatment technologies. Although the square cell structure of DPF is a generally worldwide standard, several cell designs have been proposed to reduce the pressure loss due to the soot loading as well as the ash deposition in DPF. In this study, we focused on the cell geometry using a hexagonal cell DPF and a conventional square cell DPF. In the engine test bench under nearly real conditions, these DPF performances were evaluated. Results show that, in comparison with square cell DPF, the particle number concentration of the hexagonal cell DPF decreases more rapidly, and the filtration efficiency is higher. In addition, in DPF regeneration test, independent of the inlet temperature, the regeneration rate of the hexagonal cell DPF is higher. Between two DPFs, the aperture ratio of inlet/outlet cells is different. Thus, the superior DPF performance of the hexagonal cell DPF could be explained by the difference of exhaust gas flow and soot deposition region.

1. Introduction

Diesel engines have low fuel consumption and enough torque compared with equivalent gasoline engines. Diesel engines emitted less CO_2 which is known well as the greenhouse gas, and a percentage of new diesel passenger car registrations is increasing in EU year by year [1]. However, NO_x and the soot (particulate matter, PM) emitted by the diesel engines cause problems such as air pollution and asthma sickness [2]. Since the automobile regulations have been stricter for considering environments and human health [3], new technologies for the diesel emission have been proposed. For example, improvements on the fuel injection for the combustion process [4,5], exhaust gas recirculation (EGR) [6,7], and the engine control [8,9] are effective for the NO_x and PM reduction. In addition, some kinds of fuel additive have been used for the diesel smoke reduction [10–12]. The PM can be reduced by using water containing ethanol-biodiesel [13]. Moreover, the inlet manifold water injection has been also investigated for the NO_x and PM reduction of an automotive direct injection diesel engine [14].

As for the current regulations, the European Union restricts PM emissions to 5 mg/km for passenger diesel cars in the EURO 5 and 6 regulations. Furthermore, the basis of PM emission regulations is being changed from mass to number concentration [15]. A diesel particulate filter (DPF) is one of the most important technologies for the above strict PM regulations [16]. Fig. 1 shows the image of a wall-flow DPF made of the structured porous ceramic. It has many flow path channels called “cells”, and the exhaust gas is flown into cells. PM in exhaust gas is trapped on the surface of the wall when the exhaust gas is passed through the porous wall.

The DPF needs low pressure loss for the lower fuel consumption. Since the pressure loss increases by the formation of a thick soot cake as the soot is accumulated, the DPF needs to be periodically regenerated by burning off the accumulated soot. Therefore, DPF is mainly demanded three performances – filtration, pressure drop, and regeneration. Torregrosa et al. have proposed the model about the relationship of these DPF performances [17]. In particular, Payri et al. have evaluated the pore structure properties – permeability, porosity, and pore size, on experimental – theoretical methodology, because the pressure drop and the filtration process are strongly depending on these properties [18]. Dilip et al. have developed a mesh-type particulate filter for the regeneration required lower input power [19]. However, the filtration efficiency of the mesh-type particulate filter has not reached to the level of the strict regulations.

On the other hand, a lot of regeneration cycles cause the ash, which is the remaining of soot burning [20]. The ash is formed all

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http://dx.doi.org/10.1016/j.energy.2012.10.007

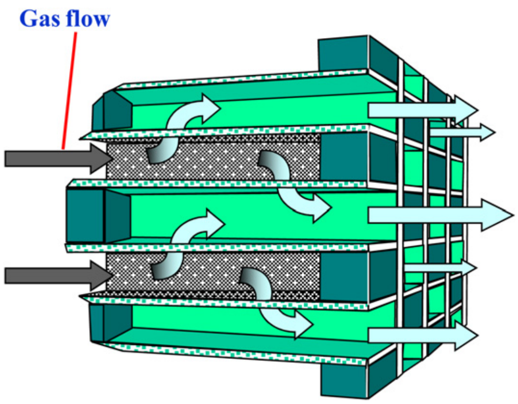

Fig. 1. Image of a wall-flow DPF.

along the filter walls of the inflow channels; and it induces the increase of the pressure loss [21]. The pressure loss also increases by the ash accumulation, and it is considered that the regeneration cycle is shortened by the ash accumulation [22].

Although the square cell DPF is a generally worldwide standard, several cell designs have been proposed to prevent the pressure loss from increasing by soot loading and to reduce the effect of the ash deposition. Ogyu et al. have reported that the increase of the pressure loss with the soot loading and the ash deposition can be controlled to be lower by changing the aperture ratio of inlet cells. In particular, the octagon-square cell DPF has superior performances on the pressure loss during the soot loading and the ash capacity, compared with the conventional square cell DPF [22,23]. At present, such DPFs that have specially shaped cells have been realized with advance of manufacturing technologies.

In our previous studies, we have examined an initial PM filtration efficiency, and have confirmed that the soot leakage is reduced due to the soot layer formation on the surface of the filter wall during the initial usage of the clean DPF. Additionally, the washcoat (W/C) samples for the catalyzed DPF, we have found that there is a proper range of the W/C amounts in terms of the W/C amounts and the pressure loss [24]. Amirnordin et al. have investigated a honeycomb monolith with hexagonal cell, and have reported that its pressure loss is relatively low [25]. However, they have focused on catalytic converters. It is not clear that the effect of the cell structure on the DPF performance. Therefore, in this study, we focused on the cell geometry by using a hexagonal cell DPF and a conventional square cell DPF to evaluate the DPF performances. The experimental study was carried out. As for the conditions of the engine test, we set the medium speed with high torque (1400 rpm 190 Nm) for the soot loading, and the high speed (3000 rpm) for the DPF regeneration [26].

2. Experimental methods

2.1. DPF

Two silicon-carbide (SiC) DPFs were prepared in this study. The specifications of two DPF samples are shown in Table 1, and their appearances and cell designs are shown in Fig. 2. Sample A has hexagonal cells, and sample B has conventional square cells. Two samples are non-catalytic filters. For each sample, size is Φ144 mm × L153 mm, cell density is 300 cpsi, and wall thickness is 0.25 mm. The pore structure characteristics were measured by mercury porosimetry (MICROMERITICS Co. AutoPore 9500), and showed that porosity and average pore diameter were almost the same.

Table 1
DPF specifications.

Samples	A	B
Substrate	SiC (silicon-carbide)	
Size (mm)	D144, L153	
Cell geometry	Hexagon	Square
Cell density (cpsi)	300	300
Wall thickness (mm)	0.25	0.25
Open frontal area (%)	46.2	34.2
Open rear area (%)	22.6	34.2
Porosity (%)	46.3	46.5
Average pore diameter (μm)	16.0	16.8
Washcoat	None	None
Pt loading	None	None

2.2. Measurement of PM filtration efficiency

The filtration efficiency of the DPF was evaluated with a QD32 diesel engine (NISSAN). Table 2 shows the engine specifications. The engine was connected to an eddy current dynamometer (Tokyo Plant Co. ED-150) on the test bench for the test condition at 1400 rpm and 190 Nm load. A schematic of the experimental setup is shown in Fig. 3. A diesel oxidation catalyst (DOC; ACR Co. EXCAT C15) was set upstream of the DPF. To measure the particle number concentration and the particle size distribution in the exhaust gas, an engine exhaust particle sizer (TSI Co. EEPS 3090) was used in conjunction with a flow path selection system to obtain the data downstream of the DPF [27,28]. Generally, the EEPS can measure the particle number concentration in the range from 10^3 to 10^7 particles/cm^3. The sampling particles are electrical charged, and are distributed in the range from 5.6 to 560 nm based on differential electrical mobility classification [29]. The data from EEPS or pressure sensor was recorded by 10 data per second. The sampling gas was diluted by 120 times using 350 °C air in a dilution machine (TSI Co. ASET). For reference, a flange with orifices was used without DPF downstream of the EEPS conjunction point for the equivalent backpressure of the DPF.

2.3. Measurement of backpressure and amounts of soot loading

The pressure loss during soot loading was measured as the backpressure by a pressure sensor (KEYENCE Co. AP-32A) in front of the DPF. The measurement range of the pressure sensor is from 0 to 100 kPa, with the resolution of 0.1 kPa. We also measured the initial

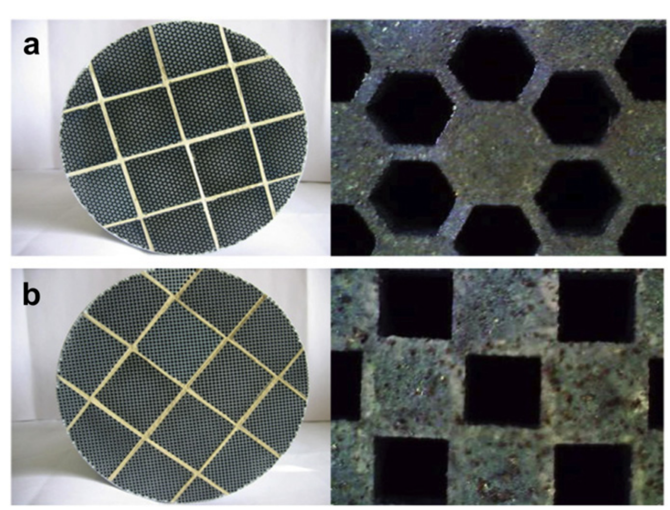

Fig. 2. Appearance and cell designs of (a) a hexagonal cell DPF, (b) a square cell DPF.