CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
 ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125167

Influence of Operative Parameters on Microwave Regeneration of Catalytic Soot WFF for Diesel Engines

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Wall-Flow Diesel Particulate Filters (DPFs) are considered the most effective devices for the control of diesel particulate emissions; however they need a periodic continuous regeneration. Recently, there has been a lot of interest in using MW energy for DPF regeneration due to its instantaneous and selective heating process. So the objectives of this study were to conduct experiments to:

1. prepare a specifically catalysed SiC DPF with MW absorption properties;
2. demonstrate the efficiency of the microwave regeneration.

1. Introduction

Diesel engine is the most efficient internal combustion engine with regard to fuel consumption, which reduces CO_2 emissions and global warming (Ohara et al., 2007; Schejbal et al., 2009, Martyrosian et al., 2010). Environmental benefits of diesels are balanced by emissions of NOx and diesel particulates (DPM or soot). Actually the Wall-Flow Diesel Particulate Filters (DPFs) are considered the most effective devices for the control of diesel particulate emissions, consisting of ceramic monoliths with alternatively plugged channels: so the exhaust gas is forced through the wall and the soot is collected on the surface of the inlet channels (Sang-Jin Lee et al., 2009; Pallavkar et al., 2009). The technological requirement of these filters is the periodic oxidation of the accumulated soot at its ignition temperature - above 600 °C (Zhang-Steenwinkel et al, 2004). On-board filter management can use a variety of strategies (Ohno et al, 2000; Koltsakis et al, 2006; Opris et al., 1998; Konstandopoulos et al., 2001), all requiring an extra energy consumption to realise the filter regeneration: increase the exhaust temperature by engine management or by a catalytic oxidizer with a post-injection (HC-Doser) or by resistive heating coils; use of a fuel borne catalyst to reduce soot burn-out temperature. Typically an on-board CPU, based on pre-programmed set points makes decisions on when to activate the regeneration (Gautam et al, 1999). Recently, there has been a lot of interest in using MW energy for DPF regeneration due to the instantaneous penetration of microwaves into the filter body (Ma et al, 1997), without heating the exhaust gases; so a filter material with high dielectric constant and loss factor can easily absorb the microwave energy and convert it into heat (Ma et al, 1997; Zhang-Steenwinkel et al, 2005; Ning, 1999). Among the others, due to its dielectric properties SiC seems to be the most adequate filter material and also the soot is a good MW absorber (Meredith, 1998). Furthermore, if the oxidation catalyst is formulated to absorb microwaves, one may combine microwave heating with catalytic combustion for the effective oxidation of diesel soot at lower temperature and higher

Please cite this article as: Palma V., Ciambelli P. and Meloni E., 2011, Influence of operative parameters on microwave regeneration of catalytic soot wff for diesel engines, Chemical Engineering Transactions, 25, 1001-1006
DOI: 10.3303/CET1125167

reaction rate, lowering the time and the energy required for the filter regeneration step (Palma et al., 2004; Palma et al., 2007). So the objectives of this study were to conduct experiments to:

1. prepare a specifically catalysed SiC DPF with MW absorption properties;
2. demonstrate the efficiency of the microwave regeneration.

2. Experimental details

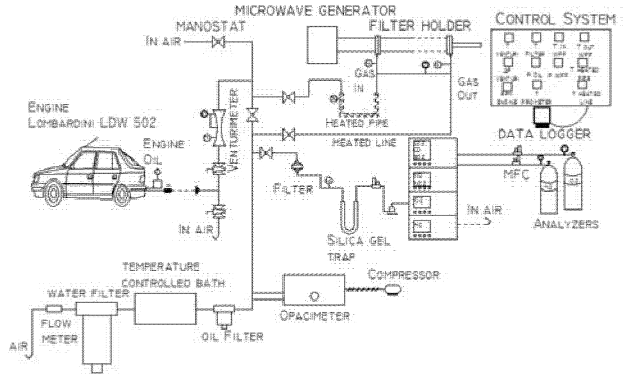

Figure 1: Sketch of the experimental plant

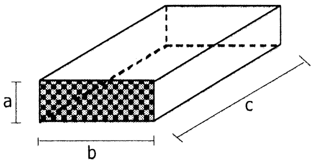

Figure 2: WFF geometrical characteristics

To perform the experiments a well-equipped diesel emission control laboratory (Palma et al., 2010) was established (Fig. 1); it includes a 505 cm^3 city car diesel engine, a DPF system, two annular shaped geometry SiC electrical resistances designed to heat the engine exhaust stream up to 900°C, an Hall effect clamp meter to monitor the electrical power supplied by the resistances, a MW energy supply system (Fricke and Mallah Microwave Technology GmbH), an AVL 439 opacimeter, a differential pressure sensor, a temperature measurement system, an on-line gas analysis system for the continuous monitoring of CO, CO_2, NO, NO_2, SO_2 and O_2, a data acquisition system in Lab-View Ambient to log all the analogical signals. The DPF is a 200 cpsi Pirelli Ecotechnology SiC wall-flow monolith (Fig. 2), whose characteristics are reported in table 1. Its porosimetric characteristics have been measured by the Hg penetration technique using the “PASCAL 140” and “PASCAL 240” Thermo Finnigan instruments obtaining a pore medium radius of 15 micron and of 10 micron for uncatalytic and catalytic filter, respectively.

Table 1: physical and geometrical characteristics of the filters

Total channels	*Open channels*	*Channel lenght (L) [mm]*	*Wall thickness [mm]*	*a [mm]*	*b [mm]*	*c [mm]*
585	277	1.5	0.6	36	80	124

The Specific Surface Area of the filters has been obtained by the mean of the Sorptometer Kelvin 1040 Costech instrument, and the values are 3.90 m^2/g and 0.52 m^2/g for uncatalytic and catalytic filter, respectively.

Catalytic filters

As said, formulating a MW sensible catalyst simultaneously active towards the soot oxidation one may combine MW heating with catalytic soot combustion. It has to be noted that due the microwave frequency values, a catalytic material can be considered a good MW receptor especially when the support is a metal oxide containing a number of polar hydroxyl groups (Palma et al., 2004). In the literature, the activity of catalysts based on Cu and Fe oxides towards soot oxidation in the presence of microwaves was studied: in particular Ma et al. (1997) performed experiments of soot oxidation with and without catalyst using external heating to elucidate the influence of MW irradiation on catalysis. They found that Fe and Cu were the most active in lowering the soot ignition temperature, while Pd was a necessary component to achieve complete combustion. In addition, the Fe based catalyst was very effective and energy-efficient at low MW input. In previous works, the regeneration of a ceramic foam soot filter at the exhaust of a gas–oil burner had been performed in a single mode MW cavity (Ciambelli et al., 2003; Palma et al., 2002; Palma et al., 2007). So, in this work we wanted to study the performances of $CuFe_2O_4$ catalysed WFF specifically prepared by repeated impregnation phases in aqueous solution of Cu and Fe nitrates, drying at 120°C and calcination at 1000 °C, in order to obtain a 15%wt of active species on the WFF (Palma et al., 2004); in particular, we want to evaluate the MW energy required to heat the soot up to its ignition temperature at different operative conditions, in order to optimise the regeneration stage in terms of time and energy required for the complete combustion of the accumulated soot.

3. Results and discussion

Filtration efficiency

Known the soot concentration in the exhaust stream before and after the filter, is possible to obtain the filtration efficiency (FE) using the following equation:

$$\eta_f = \frac{C_{before} - C_{after}}{C_{before}} \times 100 \qquad (1)$$

where C_{before} and C_{after} are the soot concentration in the exhaust stream before and after the filter. Experimental results showed that the FE is always higher than 99%.

Typical soot loading on Pirelli SiC WFF filters

The typical ΔP profile of a WFF during the deposition phase at the operating engine conditions of 600 rpm and P_{oil} = 50 bar is reported in Fig. 3, in which is also reported the opacity of the exhaust gas before and after the WFF. The data show the three stages involved in the soot loading in the DPF. During the early minutes of the test the soot starts to fill the voids inside the DPF filtration walls, resulting in a rapid increase of DP across the filter. With the test running, soot disperse deep inside the filter-wall pores and form

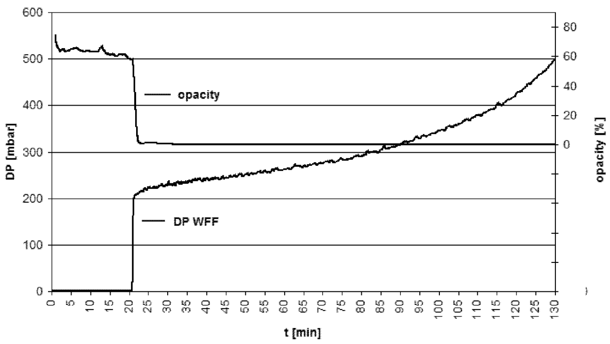

Figure 3: Typical DP and opacity profiles during a soot deposition test on a Pirelli SiC WFF

pore bridges thus causing a significant decrease in filter wall porosity and a further increase in the pressure drop values. By increasing the test time, the filtration process starts to develop to the second phase where the soot layer is forming also on the filter-wall surfaces. Once a critical mass of soot has accumulated on the filter surfaces, the soot layer reach an appreciable thickness, and start to act itself as a filter (third phase). From this point, an additional increase in the pressure drop curve slope is observed. It is important to note that the opacity data show a transient time lower than 3 min.

Deposition and microwave assisted regeneration tests

The uncatalytic soot deposition tests were performed at 600 rpm and P_{oil} = 50 bar at fixed flow rate into the filter of about 100 l/min, while the regeneration has been performed at 600 rpm and P_{oil} = 1 bar; the catalytic deposition tests were performed at 1500 rpm and P_{oil} = 30 bar with a fixed flow rate into the filter of about 100 L/min, and at 1500 rpm and P_{oil} = 1 bar during the regeneration phase, with the same fixed flow rate into the DPF of about 100 L/min. In all the cases the valued soot load was about 5 g/L. In Fig. 4 are reported the ΔP and the outlet gas temperature as function of time during the DPF regeneration at different MW power values. In both the tests, simultaneously to the MW application, the outlet gas temperature and the slope of ΔP-time curve increase; but while in the uncatalytic tests (Fig. 4a) we need a MW power of 1800W to obtain the filter regeneration, in the catalytic tests (Fig. 4b) the presence of the catalyst generate an higher combustion rate with a sensible lowered time required for the complete filter regeneration (about 45 min and about 20 min for the uncatalysed

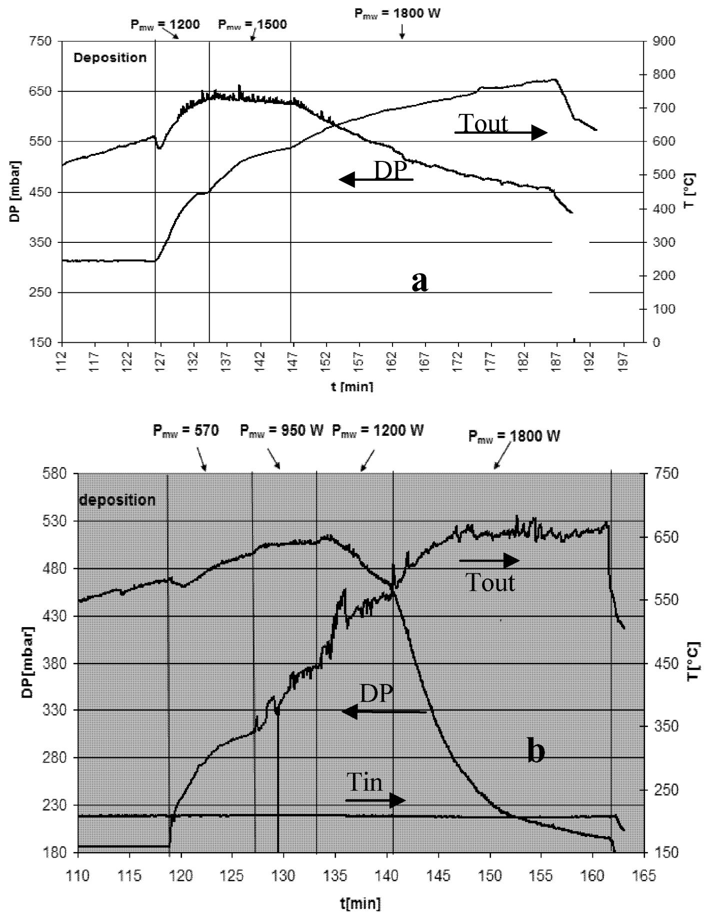

Figure 4: DP and temperature profiles during regeneration test of an uncatalysed (4a) and a catalysed (4b) WFF.

and catalytic filter). By looking more deeply, it is possible to emphasize that in the catalytic case, at the temperature of about 420 °C, corresponding to a MW power of about 950 W, the DP curve shows a plateau indicating that the catalysed soot combustion rate is comparable to the soot deposition rate, while in the uncatalytic test at the same temperatures the DP curve shows an increasing behaviour. In both the tests the average FE is about 99.5%. The tests can be considered completed when the DP value reached is corresponding to the initial value corrected for the temperature change. The comparison of the MW energy supplied during the two regeneration phases (about 5700 kJ and 3400 kJ for the uncatalytic and catalytic filter, respectively), indicates that for the catalytic filter is required only about a 60 % of the energy supplied for the uncatalytic filter regeneration. One of the main differences between the MW and the classical WFF heating procedures is that in the first case, the filter, together with the soot and the catalyst, acting as MW absorbers, are heated, while the colder exhaust gas by a simple thermal transfer generate a quenching effect on the filter temperature. As a consequence one can choose to heat the WFF with a lower gas flow rate, minimizing this negative effect and obtaining the filter regeneration with further lower energy consumption. So some regeneration tests on the catalytic WFF were performed with the flow rate of 30 L/min, with the MW generator set at 50% of its maximum power (Fig. 5). At the temperature of about 400 °C, DP starts to decrease, due to the catalytic combustion of soot: so the regeneration performed at lower exhaust gas flow rate, results in a lower energy supplied (about 1955 kJ) and a very fast regeneration (it lasts about 20 minutes).

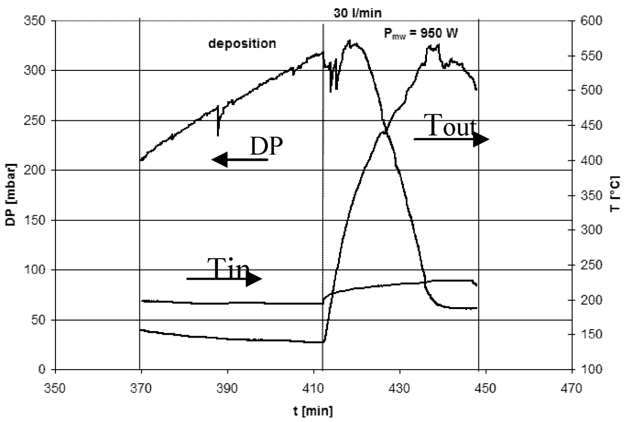

Figure 5: DP and temperature profiles during the regeneration phase of the catalytic WFF

4. Conclusions

Experimental results of deposition and on-line regeneration tests on uncatalysed and catalysed WFF, showed that:
- the designed system employing MW assisted regeneration has been able to achieve the complete filter regeneration;
- the FE of the uncatalytic and catalytic filter is always higher than 99 %;
- the energy supplied for the regeneration employing simultaneously the MW generator and the catalysed filter is about 67 % less than the energy supplied for the uncatalytic filter regeneration;
- the time required for the MW regeneration stage for the catalytic WFF is about 70 % lower than that required by the uncatalysed filter.

The two last observations suggest that the MW energy is required to heat up the soot to its ignition temperature, and after that, the released heat from the soot combustion will support the continuous burning of the remaining soot without any additional MW energy. The application of MW may be further optimized if the regeneration stage is performed at lower gas flow rate through the WFF.

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