IR Imaging of Soot Regeneration on a Planar Diesel Particulate Filter

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ABSTRACT

An extensive set of experiments was conducted using IR imaging to determine the impact of fixed operating conditions such as oxygen concentration, soot loading and flow rate on the spatiotemporal temperature during the catalytic soot combustion in a single channel planar diesel particulate filter. The experiments revealed that the behavior features of the soot regeneration were highly depended upon the oxygen concentration from 5 to 15 v. %. At high oxygen concentrations local ignition occurred at either one or several locations and then propagated on the surface. In general, increasing either the oxygen concentration or soot load increased the moving front temperature and velocity. As the flow rate per unit filter surface area was increased, the maximum temperature attained first a local maximum and later a local minimum.

Keywords: diesel particulate filter, soot regeneration, moving temperature front, IR imaging

1 INTRODUCTION

Diesel Particulate Filter (DPF) is the most efficient device for the removal of particulate matters (PM) from the diesel engine effluents [1]. The exhaust gas passes through the filter porous wall into the adjacent channels, while more than 95% of the PM accumulates on the filter [2-4]. The pressure drop across the filter increases with the mass of the accumulated PM. The accumulated PM has to be periodically regenerated. The exothermic combustion leads in some cases to excessive local temperature rise, which melts the ceramic filter and destructs the DPF [5]. To circumvent this potential DPF failure, it is essential to be able to predict the impact of the operating conditions and regeneration procedure on the formation of very high local temperatures. Most previous experiments were carried out using a diesel engine exhaust during the regeneration. Unfortunately, under the dynamic operation of a diesel engine some of the key operating conditions such as the exhaust temperature, oxygen concentration, soot loading and flow rate are not constant.

We report here the results of an extensive set of experiments aimed to determine the impact of fixed operating conditions such as oxygen concentration, soot loading and flow rate on the spatiotemporal temperature during the catalytic soot combustion in a single channel planar DPF. The experimental results revealed some rather surprising novel features about the evolution and dynamics of the moving temperature fronts.

2 EXPERIMENTAL SETUP

Infra-red (IR) imaging was used to measure the spatio-temporal temperature during the soot combustion in a mixture of air and nitrogen on a planar catalytic single layer DPF, cut from a commercial DPF. The planar DPF was held in a stainless steel insulated reactor with an IR transparent quartz window on its top. It enabled visual and infrared imaging of the temperature field on the planar DPF, located at about 3 mm from the window. The temperature around the DPF was measured by four K-type thermocouples installed in the reactor. The first one placed near the entrance measured the inlet gas temperature. The second was located 10 mm downstream from the inlet, the third in the reactor middle and the fourth 10 mm ahead of the outlet. The spatiotemporal temperature was measured by a high speed infrared camera (Merlin, MW18, Indigo Systems) held 50 cm above the quarts window. The magnitude, shape and motion of the thermal front on the DPF were determined by image analysis software. Typical soot combustion lasted a few minutes. The IR images of the soot combustion were recorded at the rate of 10 per second. A schematic of the experimental system is shown in Figure 1.

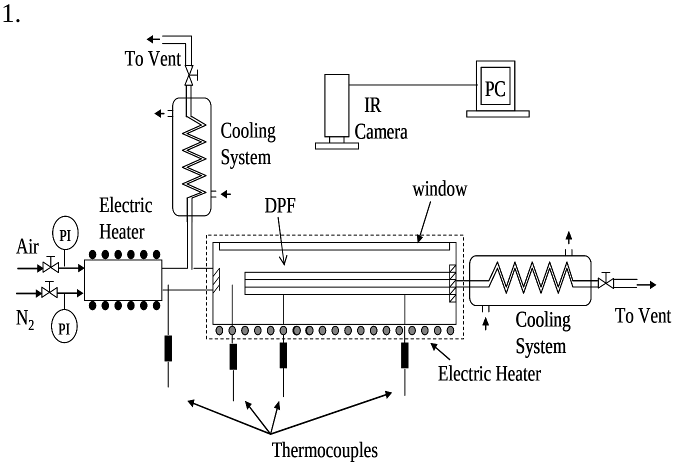

Fig.1. A schematic of the experimental system

The experiments were conducted using soot loadings of either 10 or 20 g/L and mixtures of pressurized nitrogen and air containing 5 - 15 v. % oxygen were fed to the reactor during soot regeneration. Before each experiment compressed nitrogen was used to purge the air from the reactor. After that the reactor walls temperature was increased from room temperature to the pre-set temperature. The planar DPF was preheated to the desired experimental temperature by an electric heater while the reactor was fed by pure nitrogen. After the desired temperature was reached the feed was switched to the air-nitrogen mixture. Each experiment was repeated at least five times to check its reproducibility.

3 RESULTS

The experiments revealed some very intricate and unexpected features of the moving temperature fronts during PM combustion and their sensitive dependence of the combustion mode and number and locations of the ignition points on the operating conditions.

Fig. 1 shows the impact of oxygen concentration (range of 5 to 15 v. %) on the soot regeneration behavior at soot loadings of 10 g/L and a fixed gas flow rate of $12cm^3/(s*cm^2$ through the filter). At low oxygen concentrations the soot combustion was uniform all over the surface (feed temperature of 635 ^oC). A typical case for a feed containing 5 v. % oxygen is shown in Figure 2, a. The variation of temperature among different surface points was very small (~5 ^oC). The deposited soot was uniformly consumed all over the DPF surface in ~15 minutes after the start of the experiment. The reproducibility of at least five repeated experiments indicates that the soot was deposited uniformly. At higher oxygen concentrations local ignition occurred at either one (Fig. 2, b) or several locations (Fig.2, c). The maximum temperature of the moving fronts was at least 60^{o}C higher than those attained during the uniform combustion. The temperature fronts bounding an ignited zone propagated on the surface and their peak temperature and velocity changed as they moved on the surface.

With a feed of 12.5 v. % of oxygen (Fig. 2, b) the combustion was initiated next to the end of the DPF. The hot zone was separated from the surrounding colder region by a sharp temperature front. It moved from the downstream to the upstream of the DPF, eventually conquering the whole surface. For a feed of 15 v. % of oxygen (Fig. 2, c) initially a single point ignited close to the end of the DPF and propagated upstream, i.e., in a direction opposite to the feed flow rate. After some time (43 seconds in the case shown here) ignition occurred at a location 20 mm downstream from the inlet. The downstream moving front eventually collided with the one originating from the end of the PDF. The coalescence of the two temperature fronts generated one moving upstream front with a velocity of 0.35 cm/s and a peak temperature of 770 °C.

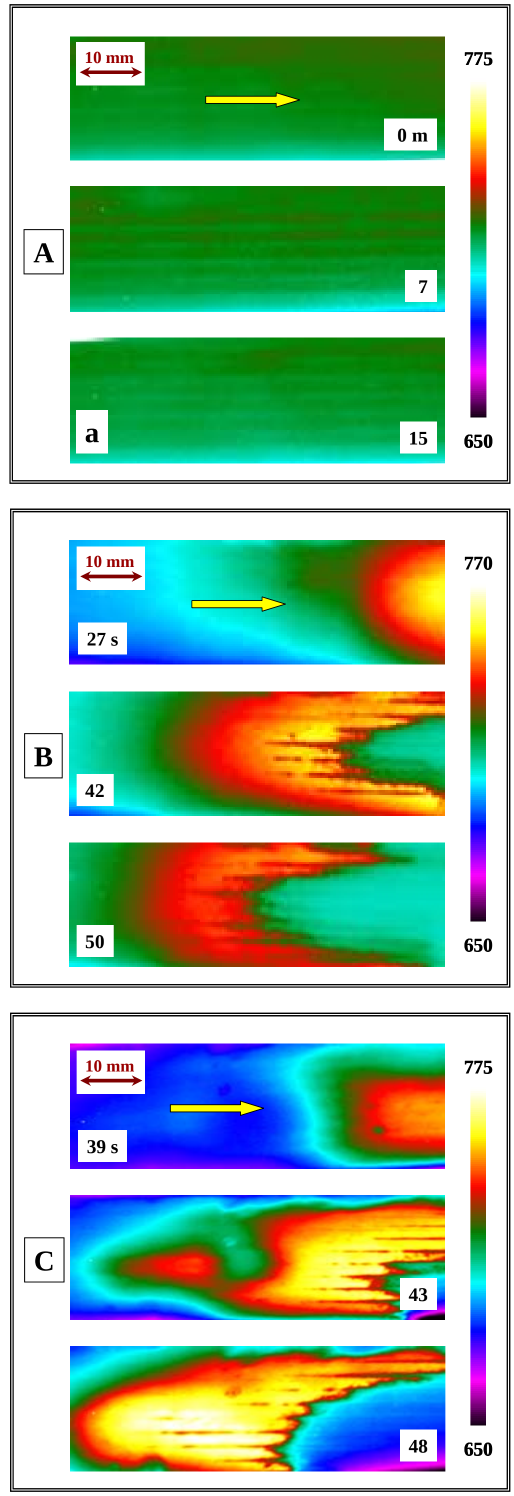

Figure 2: Thermal images of soot regeneration for soot loading of 10 g/L. Feed oxygen concentration (a) 5 v. %; (b) 12.5 v. %; (c) 15 v. %.

Detailed axial profiles of the moving temperature front on the DPF for the case of 12.5 v. % oxygen concentration

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are shown in Fig. 3. About 27 second after the O_2/N_2 mixture was fed to the reactor, ignition occurred close to the end of the DPF. The ignited zone was separated by a sharp temperature front from the colder part of the DPF. It moved in the upstream direction. For about 12 seconds the amplitude of the moving temperature front was rather constant. As the ignited zone moved upstream its amplitude decreased. For example the difference in the peak temperature between the profile observed at 39 and 50 seconds was ~15 ^oC. As the temperature front moved further upstream the amplitude of the peak temperature and front velocity decreased.

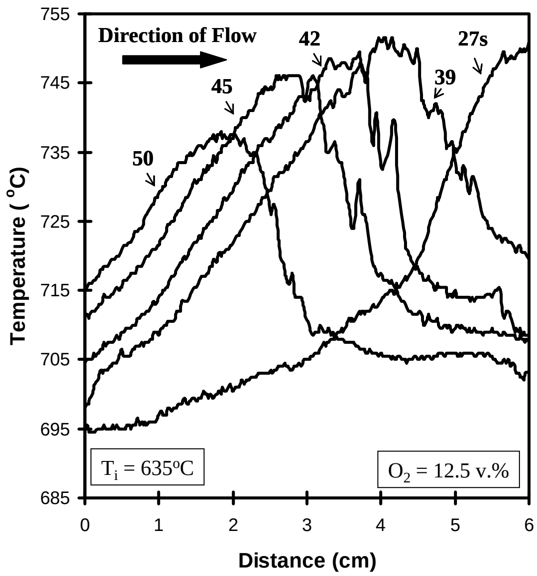

Figure 3: Moving temperature profiles originating from end of DPF. Soot loading of 10 g/L and O_2=12.5 v. % (same experiment as that in Fig. 2, a).

Figure 4a describes the relation between the peak front temperature and front velocity at several oxygen concentrations. The peak temperatures of the moving fronts and their velocity changed as they moved on the DPF. In general, when the ignition occurred next to the DPF end the peak temperature and velocity decreased as the front moved upstream. When a hot zone formed in the middle of the DPF, the front moving downstream had a higher peak temperature and velocity than one moving upstream. The increase or decrease of the peak front temperature led to corresponding change in the front velocity. The data in Figure 4a suggest a linear dependence between the peak front temperature and front velocity. The slope for feed mixtures containing 15 v. % oxygen is steeper than those containing a lower oxygen concentration.

To check the impact of the soot loading we conducted a series of experiments at a soot loading of 20 g/L. The experiment showed that the change in the soot loading affected the combustion modes and the dynamic of the temperature fronts. The dependence of the maximum front temperature rise on the oxygen concentration at a soot loading of 20 g/L is shown in Figure 4b. The letters (a-d) in the figure correspond to the different combustion modes with increasing oxygen concentration. As in the case of the 10 g/L the maximum temperature was a monotonic increasing function of the oxygen concentration. The moving combustion front mode (b, c, d) led to a at 80 ^oC higher peak temperature than the uniform combustion mode. The changes in the oxygen concentration affected the location of the ignition point and the direction in which the reaction fronts moved.

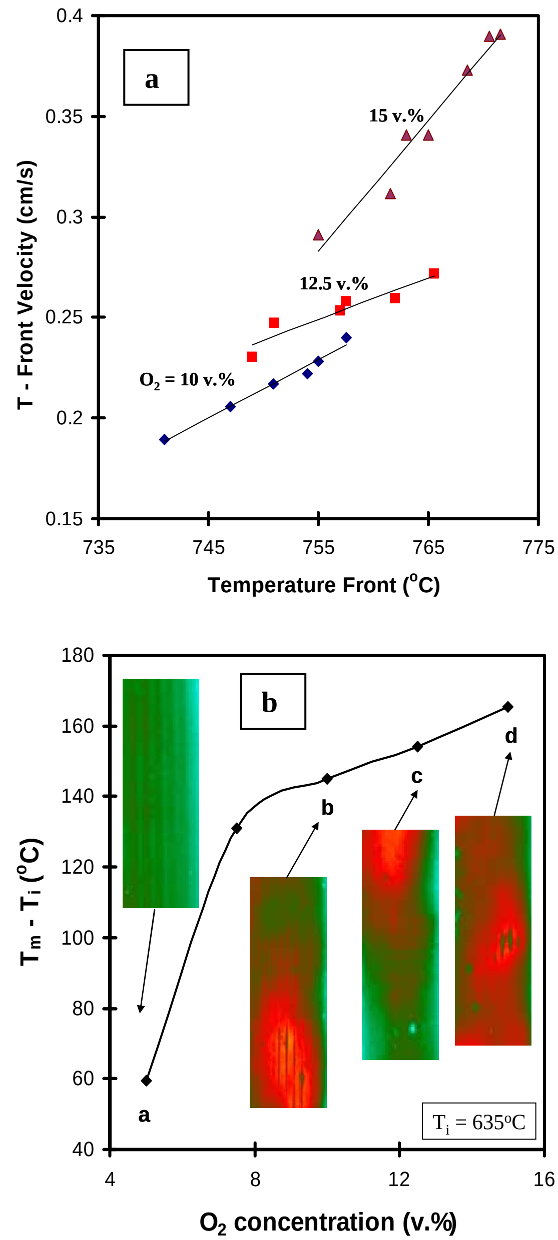

Figure 4: (a) Effect of oxygen concentration on the relation between maximum front temperature and its propagation velocity. Soot loading of 10 g/L; (b) Dependence of the maximum temperature rise on the oxygen concentration for soot loading of 20 g/L.

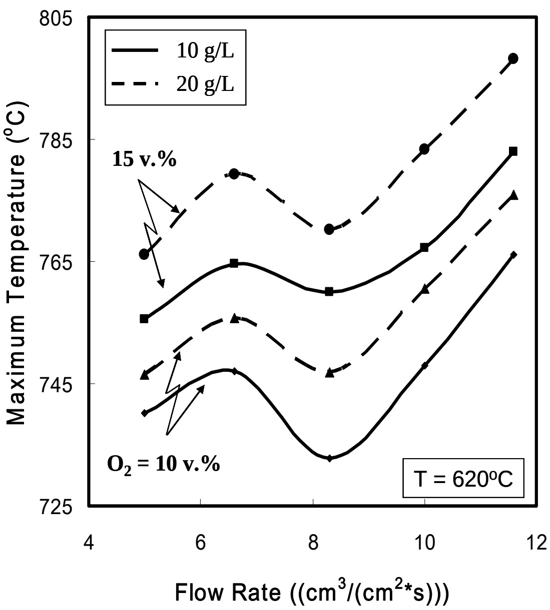

Figure 5: Impact of filter wall flow rate on maximum front temperature at several O_2 concentrations and soot loading of 10 and 20 g/L, feed temperature of 620 °C.

A shifting the vehicle speed changes the exhaust flow rate and hence the flow rate per unit surface area of the DPF. We conducted several experiments to determine the impact of the flow rate at several oxygen concentrations and soot loadings of either 10 or 20 g/L. The maximum temperature exhibited a moderate dependence on the flow rate (Fig. 5). At low flow rates the maximum temperature increased as the flow rate was increased. It eventually reached a local maximum (at a flow rate ~7 $cm^3/(s*cm^2)$ in these experiments). Further increase in the flow rate decreases the maximum temperature until a local minimum was reached (at about 8.5 $cm^3/(s*cm^2)$). Further increase in the flow rate led to a monotonic increase of the peak temperature. The flow rates at which the local maximum and minimum were obtained was rather insensitive to the values of either the oxygen concentration or the soot load. For a soot loading of 10 g/L the range of peak temperature over the flow rates range of (5 to 12 $cm^3/(s*cm^2)$) was (732, 766 ^oC) and (755, 782 ^oC) for oxygen concentrations of 10 and 15 v. %, respectively. For a soot loading of 20 g/L the range of maximum temperature over the same range of flow rates was (746, 775 ^oC) and (766, 798 ^oC) for oxygen concentrations of 10 and 15 v. %, respectively.

4 DISCUSSION

IR measurements of the spatiotemporal temperature on a planar DPF provide important information about the special dynamic features that can be encountered during soot combustion in DPF and their sensitivity on the operating conditions. The main advantage of these experiments is that they provide information about the temporal temperature all over the surface. This information cannot be attained by experiments in which a few thermocouples are inserted in the DPF. The disadvantage of our experiments is that they provide only qualitative but not quantitative information about the maximum temperature rise and the temperature front dynamic features in a commercial DPF. The heat loss from the planar DPF surface is much higher than that inside a DPF. Thus, the temperature rise in a DPF is expected to exceed that observed in our experiments. Moreover, experiments using a planar DPF cannot account for the impact of the radial heat conduction and wall heat loss on the temperature field in a DPF, which may lead to local hot regions.

This paper described the dependence of the temperature rise and velocity of the moving reaction fronts on one operating condition such as oxygen concentration, soot loading or flow rate.

Acknowledgments

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