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Repeatable regeneration testing with a controlled Diesel Particulate Generator

The paper describes a new technique for the operation of a Diesel Particulate Generator (DPG) which produces a Diesel combustion aerosol at conditions representative of a Diesel engine exhaust. The DPG has been used to rapidly and repeatably load a Light Duty Diesel Particulate Filter (DPF) to a loading level close to the Maximum Soot Load. Highly repeatable DPF loading is demonstrated. The DPF is loaded at a soot generation rate of ~10 g/hr and then regenerated by changing the DPG setpoints to produce hot, lean, particle-free exhaust at a controlled flow rate, with a repeatable inlet temperature profile. The regeneration program heats the DPF to a controlled temperature below regeneration (e.g. 330°C) and then the controlled flow through the system is reduced to suddenly raise the inlet temperature (above that required to initiate regeneration) in a repeatable way. Thermocouples monitoring the temperatures in and out of the DPF, together with internal temperatures are logged by the DPG to establish the extent of any exotherm. The pressure drop across the DPF is also recorded continuously. The regeneration of the DPF continues with inlet temperature rising slowly to around 700°C. After around 30 minutes of the regeneration program, the DPF is found to weigh the same as the clean DPF. The DPF is loaded with soot using a light duty Diesel engine and regenerated on the DPG in the same way. Data is presented showing that the maximum temperatures during the exotherm from the Diesel Particulate Generator soot are similar to those from soot generated on an engine. Repeatability of the test technique is demonstrated. Changing the soot distribution on the DPF is found to have a significant effect on the pressure drop at a given soot load as well as the maximum regeneration temperature.

Badania okresowej regeneracji z zastosowaniem regulowanego Generatora Cząstek Stałych Diesla

Artykuł opisuje nową technikę pracy Generatora Cząstek Stałych Diesla (DPG), który wytwarza aerozol (gazy spalinowe) w warunkach reprezentatywnych względem gazów w układzie wydechowym silnika Diesla. DPG zastosowano do szybkiego i powtarzalnego ładowania filtra cząstek stałych (DPF) lekkiego silnika Diesla do poziomu bliskiego maksymalnego stopnia załadowania sadzą. Pokazano wysoką powtarzalność stopnia załadowania DPF. DPF jest ładowany przy stopniu generacji sadzy ok. 10 g/h, a następnie regenerowany przez zmianę ustawień DPG, umożliwiających wytwarzanie gorących, ubogich, nie zawierających cząstek stałych gazów spalinowych o regulowanym stopniu przepływu, z powtarzalnym profilem zmian temperatur na wlocie. Program regeneracji umożliwia w sposób powtarzalny podgrzewanie DPF do regulowanej temperatury poniżej procesu regeneracji (np. 330ºC), a następnie zmniejszanie regulowanego przez układ przepływu, w celu uzyskania gwałtownego wzrostu temperatury na wlocie (powyżej wymaganej temperatury zainicjowania procesu regeneracji). Termopary monitorują temperatury na wejściu i wyjściu z DPF, które razem z temperaturami wewnętrznymi są rejestrowane przez DPG dla ustalenia zakresu egzotermiczności. W sposób ciągły rejestrowany jest również spadek ciśnienia na filtrze. Regeneracja DPF przebiega przy rosnącej powoli temperaturze gazów na wlocie do ok. 700ºC. Po około 30 minutach regeneracji, DPF wraca do wagi takiej samej jak miał czysty DPF. Następnie w ten sam sposób DPF ładowany jest sadzą przy zastosowaniu lekkiego silnika Diesla i regenerowany przy zastosowaniu DPG. Prezentowane dane pokazują, że maksymalne temperatury podczas egzotermicznej regeneracji sadzy wytwarzanej przez DPG są takie same jak dla sadzy generowanej przez silnik. Przedstawiono powtarzalność techniki pomiarowej. Zmieniając rozkład sadzy w DPF stwierdzono, że ma on znaczący wpływ zarówno na spadek ciśnienia dla danego stopnia załadowania, jak również na maksymalną temperaturę regeneracji.

Introduction

Regeneration in DPFs

The scheduling of regeneration in Light Duty Diesel DPFs is often based on a pressure drop measurement made across the DPF. The regeneration process causes the DPF temperature to be raised sufficiently to ensure oxidation of the soot which is trapped. Manufacturers of DPFs and calibrators of vehicle strategies need to consider regeneration carefully. The frequency of regeneration affects fuel economy. The soot capacity of the DPF is limited by thermal damage which may occur due to localized exotherms during regeneration. This limit is sometimes called the Maximum Soot Load (MSL) and for Si C DPFs is around 5-10 g of soot per litre.

To date, development of DPFs and strategies for regeneration have involved intensive testing of Diesel engines and vehicles – which leads to problems of expense, throughput and repeatability. A Diesel Particulate Generator (DPG) based on a continuous burner has been developed to address the above problems.

DPG description

Figure 1 describes the operation of the DPG. A fuller description may be found in reference 1.

A filtered, heated and controlled primary flow of atmospheric air is admitted to a Diesel burner. For soot generation, the air to fuel ratio of this flow is significantly richer than stoichiometry. The combustion is stabilised with a rotating flow and surrounded by co-rotating secondary air flow (which is also filtered, heated and controlled). This secondary flow serves to „quench" the combustion adjacent to the flame and also to prevent the soot impinging on the walls of the combustion chamber. A tertiary air flow (filtered, heated and controlled) is added when combustion is complete and is used to allow control of the overall aerosol flow-rate and temperature entering the DPF.

The flow-rate of combustion aerosol through the DPF test DPF is controlled with a downstream exhaust blower. An air to air heat exchanger is used to cool the outlet from the DPF.

The Diesel combustion occurs at a pressure fixed slightly below atmospheric. As the DPF becomes loaded, this pressure does not change, and the exhaust blower power is increased to maintain the flow-rate through the test DPF.

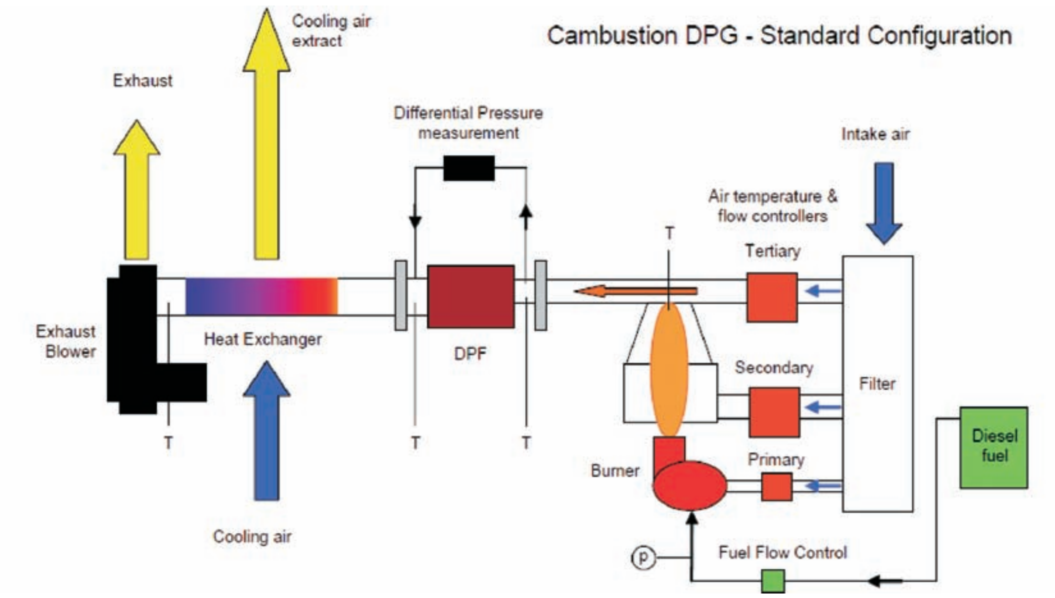

Fig. 1. DPG schematic description

Rys. 1. Schemat generatora cząstek stałych

Test description

A 5.66" diameter ×10" (144 × 254 mm), Silicon Carbide DPF was taken from a MY2006 Light Duty Diesel vehicle. The oxidation catalyst was removed and the canning modified with a new inlet cone and couplings to allow rapid fitting and removal. Before testing, the canned DPF was comprehensively de-greened by multiple loading and regeneration cycles on the DPG in addition to several oven-based regenerations (at>650°C for >1 hr).

The DPF was instrumented with 8 thermocouples as indicated in Figure 2.

DPG soot load and repeat

The DPG was operated at standard conditions to load the same DPF (after cleaning and verification of zero

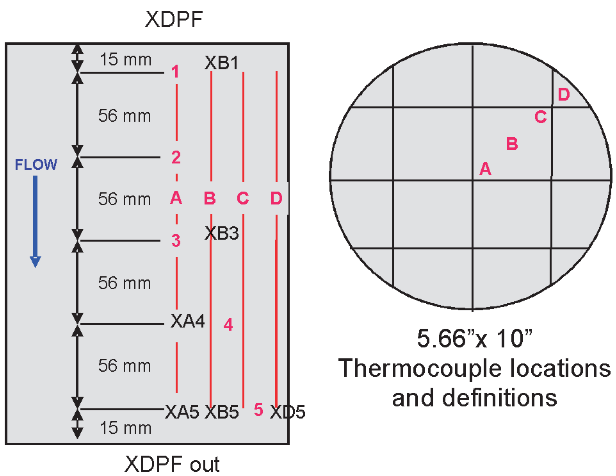

Fig. 2. Thermocouples locations in DPF

Rys. 2. Lokalizacja termopar w DPF

Table 1. DPG soot loading schedule
Tablica 1. Program załadowania DPF sadzą

Mode name	Description	Soot rate [g/hr]	Air Flow [kg/hr]	Fuel Flow [kg/hr]	Inlet Temp. [°C]	Duration [min]
Warm up #1	Warm up DPF	0	250	1.07	240	15
Zero Weigh #1	Stop rig to allow weighing of DPF at >220°C	–	–	–	–	~5
Warm up #2	Warm up DPF	0	250	1.07	240	5
10g/hr load	Drops primary air flow to produce soot	10	250	1.07	240	150
Loaded Weigh #2	Stop rig and weigh DPF at >220°C	–	–	–	–	~5

weight). The schedule for the loading is listed below in Table 1.

The loading for these tests was done in a single stage, however, loading to an exact target weight can be done in 2 stages for increased precision. The DPG loaded weights are shown in Table 3.

Figure 3 shows the pressure drop across the DPF vs time during the DPG soot loading schedule.

The actual soot load is determined from gravimetric measurements and the data from Figure 3 can be plotted as pressure drop vs sootload. This is a standard technique for characterizing the performance of DPFs and the DPG can repeatably determine this characteristic. Figure 4 shows this plot for a standard DPF loaded several times on different DPG rigs. Diagrams of the pore filling and cake formation phases are also shown.

Engine soot load and repeat

A common rail Diesel engine on a dynamometer was run at steady state conditions chosen to produce a relatively high soot rate (~10g/hr). The engine-out soot rate was controlled by progressively closing the EGR valve as the back pressure on the DPF increased. The conditions are listed in Table 2.

Table 2. Engine soot loading conditions
Tablica 2. Warunki pracy silnika podczas załadowywania sadzą

Engine Speed	2500 rpm
Engine Load	40 nm
Exhaust flow	71 kg/hr
DPF inlet temperature	330°C
Exhaust Lambda	1.4
Injection timing offset from base cal	+5°
Injection pressure	65 MPa (base 100 MPa)

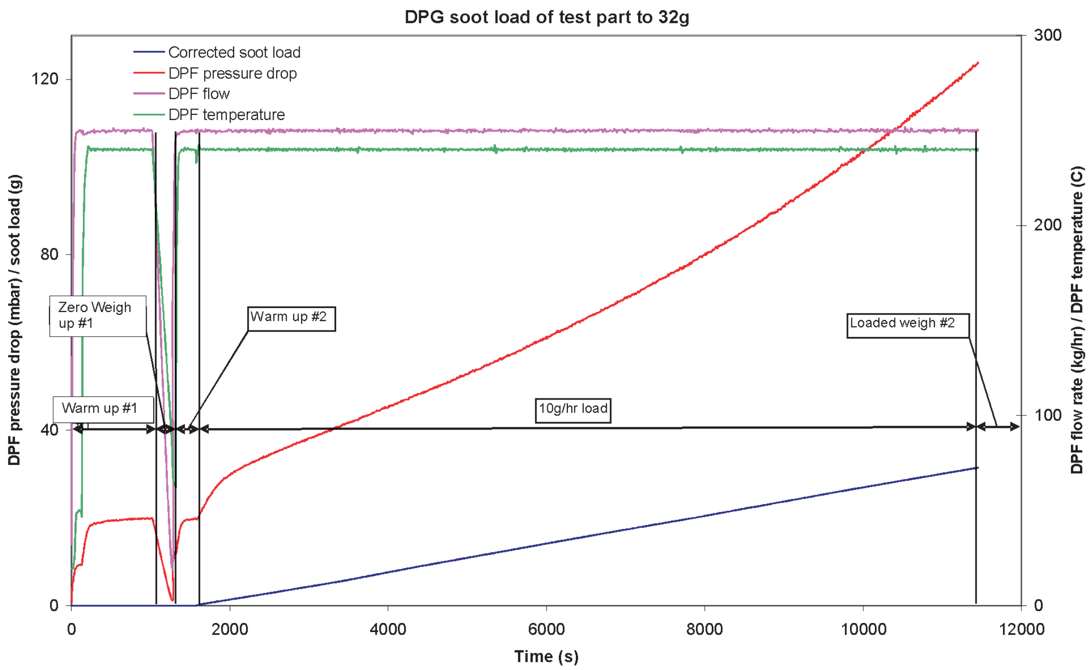

Fig. 3. Pressure drop across DPF, gas flow rate and inlet temperature during loading schedule

Rys. 3. Spadek ciśnienia wzdłuż DPF, prędkość przepływu gazu i temperatura wejściowa podczas programu załadowywania

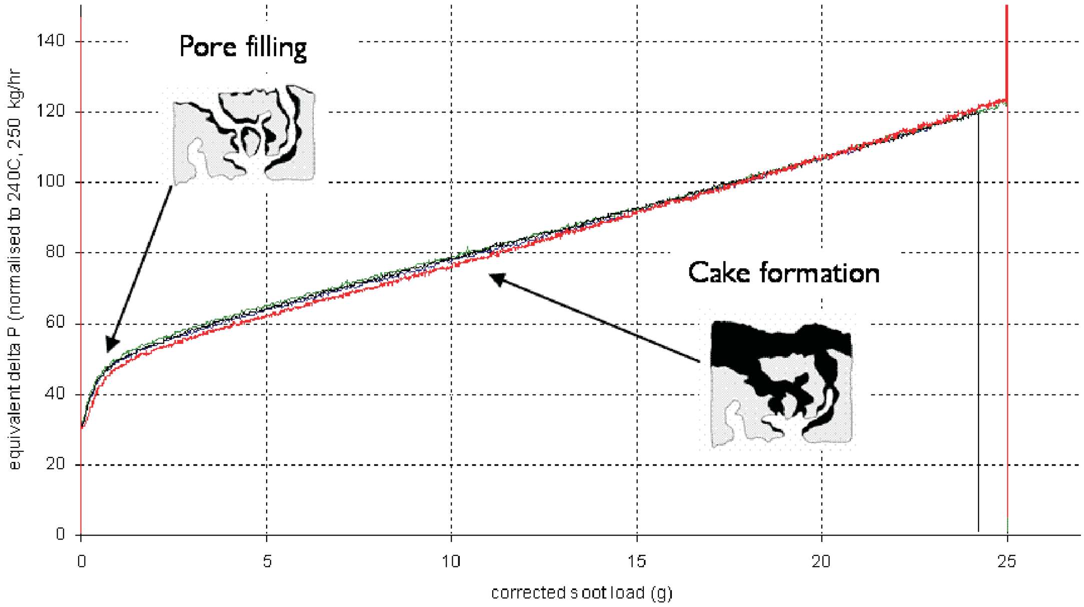

Fig. 4. Repeatability of soot load vs pressure drop for a standard DPF on uncoupled DPGs

Rys. 4. Powtarzalność załadowywania sadzą w odniesieniu do spadku ciśnienia na typowym DPF, na odłączonym DPG

The engine-based loaded weights are shown in Table 3. When loaded, the pressure drop measured by the engine at the final soot mass was 61 mbar (at ~71 kg/hr, 330°C).

Regeneration using the DPG

The test DPF was regenerated four times, twice with engine loaded soot and twice with DPG loaded soot. The sootloads on the DPF for the each regeneration is shown in Table 3. In each case, the sootload corresponds to about 7.5 g/l – which is near to the maximum soot load.

A schedule was developed for the Diesel Particulate Generator system to regenerate the DPF (listed in Table 4).

Table 3. Gravimetric measurements

Tablica 3. Pomiary grawimetryczne

	Test 1	Test 2
Deposited soot mass (engine)	31.9 g	32.2 g
Deposited soot mass (DPG)	31.4 g	30.8 g

The schedule ensures that the system is in a repeatable thermal 'state' before regeneration. Figure 5 is a graph showing the pressure drop across the DPF, the DPF inlet temperature and DPF flow during the above schedule. The Air to Fuel ratio for the DPF during the regeneration is 47.3 ($\lambda = 3.24$).

Table 4. Regeneration schedule

Tablica 4. Plan regeneracji

Mode	Description	Air flow [kg/hr]	Fuel flow [kg/hr]	Inlet Temp [°C]	Duration [min]
Warm up #1	Warm up DPF	192	1.55	330	10
Loaded Weigh #1	Stop rig to allow weighing of loaded DPF at >300°C	–	–	–	~5
Warm up #2	Warms up DPF	192	1.55	330	5
Regeneration	Cause inlet temperature to rise >650°C and regenerate DPF.	73.4	1.55	330 > 650	30
Warm down #3	Inlet temperature cooled back down to 330°C for weighing	172	1.55	650 > 330	10
Post Regen. Weigh #2	Stop rig and weigh DPF at >300°C	–	–	–	~5

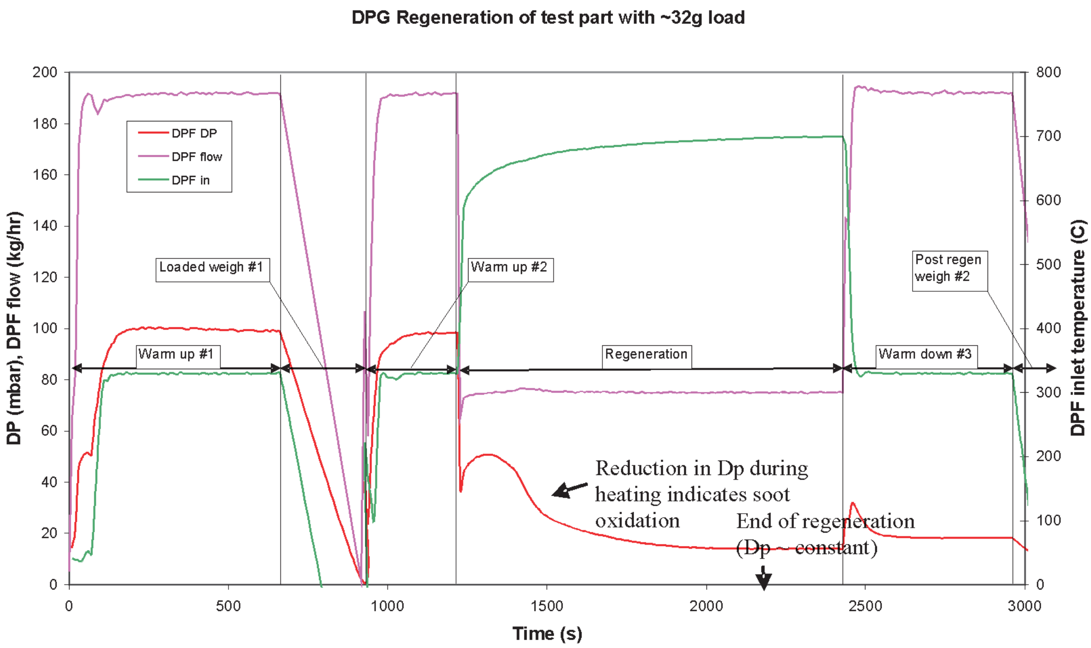

Fig. 5. Pressure drop, inlet temperature and flow during Regeneration schedule

Rys. 5. Spadek ciśnienia, temperature wejściowa i przepływ podczas realizacji planu regeneracji

Results and discussion

Below is presented thermocouple and pressure drop data for the four regeneration tests.

Figure 6 shows all of the temperatures (6 internal and 2 external) as well as the pressure drops for all four regeneration tests. Subsets of the data are plotted in subsequent figures for discussion.

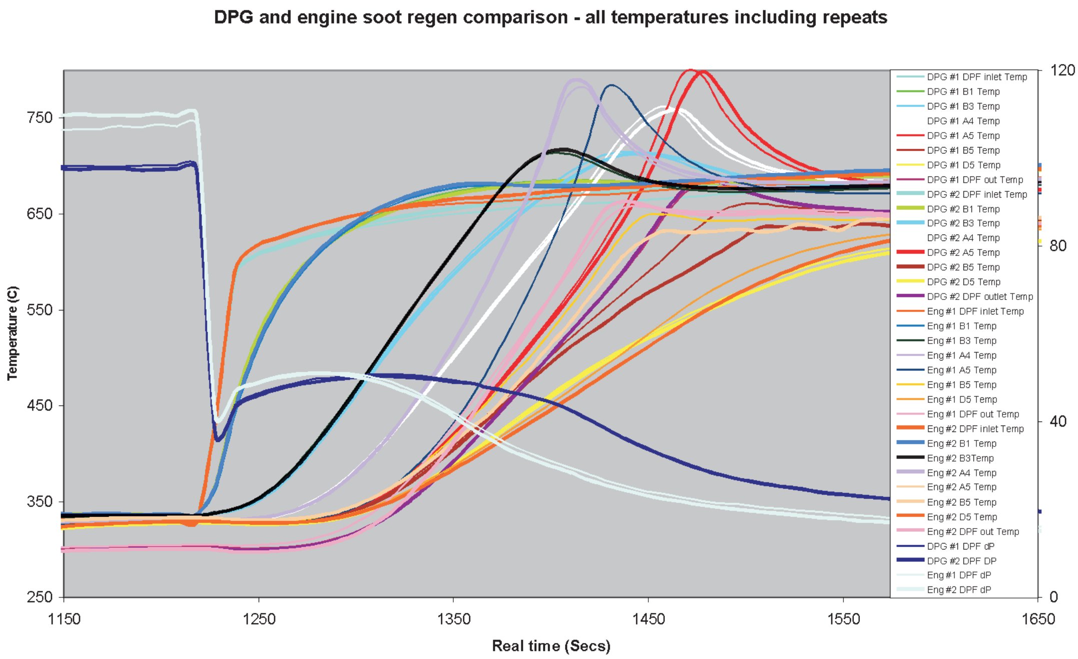

Fig. 6. Temperatures and pressure for all 4 regeneration tests

Rys. 6. Temperatury i ciśnienia podczas czterech testów regeneracji

Repeatability

The repeatability of the regeneration tests is shown in Figure 7 for DPG loaded soot and Figure 8 for engine loaded soot. The data indicate that the tests are generally repeatable in terms of both pressure drop, internal and external DPF temperatures for both engine and DPG soot.

Engine and DPG soot regeneration comparison

Figure 9 shows the pressure drop and the temperature measured near to the centerline of the DPF from inlet to outlet with 2 internal temperatures measured at 183 mm from the front face (A4) and 240 mm from the front face (A5).

It is expected that the highest temperatures in the loaded

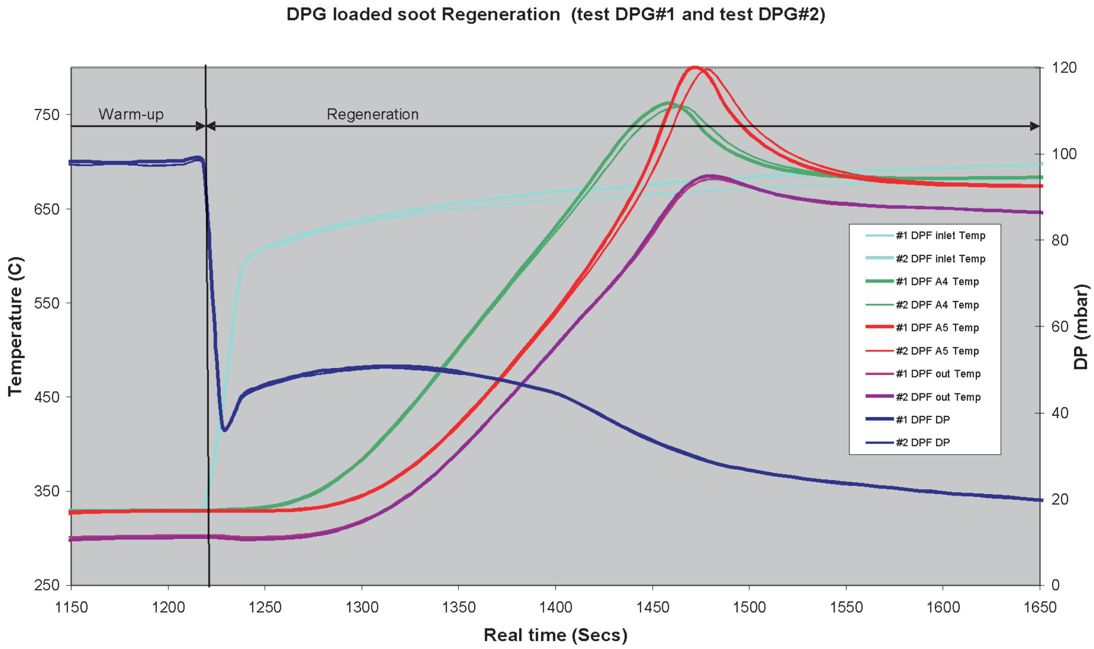

Fig. 7. Repeat of regeneration of ~32 g DPG soot

Rys. 7. Powtórzenie regeneracji dla ~32 g sadzy z DPG

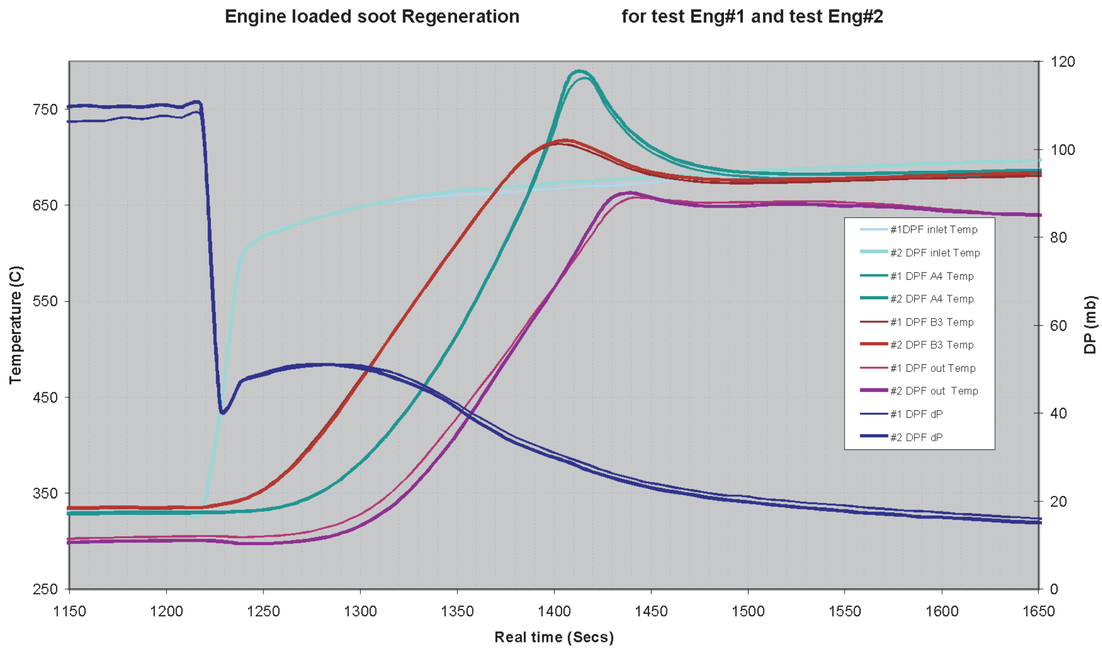

Fig. 8. Repeat of regeneration of ~32 g of Engine loaded soot

Rys. 8. Powtórzenie regeneracji dla ~32 g sadzy z silnika

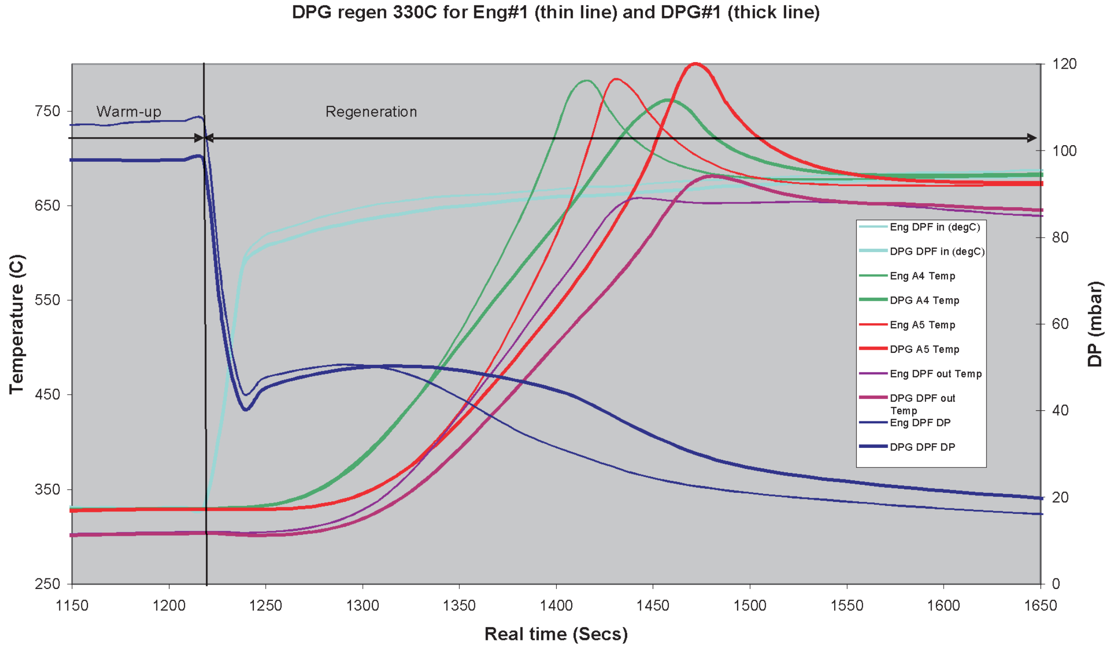

Fig. 9. Comparison of DPG and Engine loaded ~32 g soot regeneration

Rys. 9. Porównanie regeneracji załadowania ~32 g sadzy z DPG i silnika

brick during regeneration will be near the centerline and towards the rear. The results are summarized in Table 5.

Table 5. Regeneration results summary

Tablica 5. Zestawienie wyników regeneracji

	DPG#1	DPG#2	Engine#1	Engine#2
DPF Pressure drop at 32 g sootload [mbar]	98	97	107	109.5
Maximum internal temperature [°C]	800	797	780	787

The data indicates: For a similar sootload, the engine soot has a slightly higher pressure drop (~108 mb vs ~98 mbar at the warmup condition before regeneration). Note that the pressure drop vs sootload characteristic for an engine depends on the operating conditions.

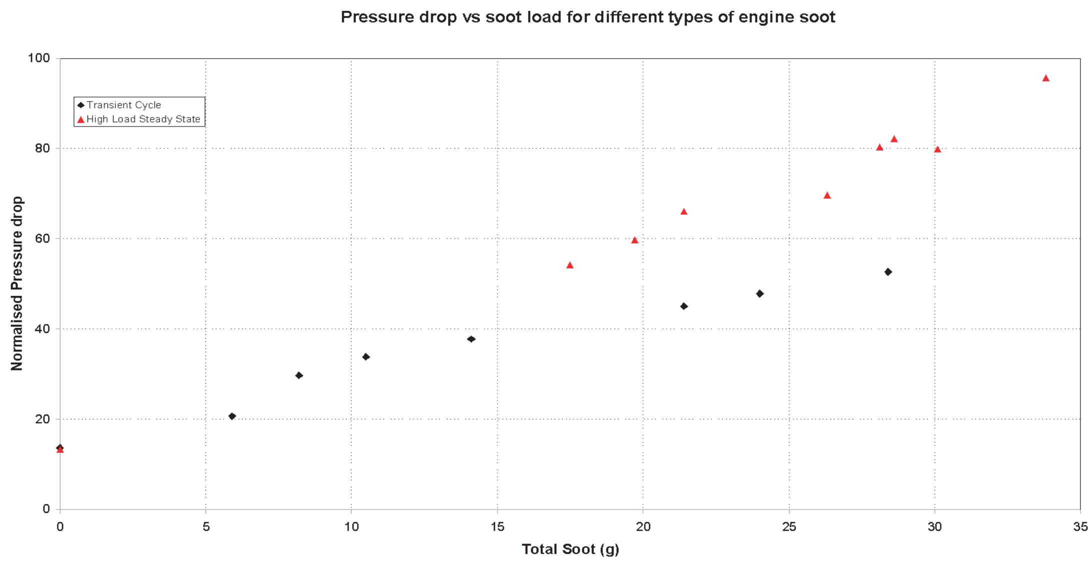

Fig. 10. DP vs sootlad for 2 types of Diesel engine soot

Rys. 10. Zależność spadku ciśnienia od załadowania sadzą dla dwóch typów silników Diesla

Figure 10 shows the normalized backpressure vs soot load for a common rail 2.0l DI Diesel engine running the NEDC drive cycle and running at a high load steady state. Differences in this parameter may be due to passive regeneration of the DPF at load points where the engine produces significant amounts of NO_2. The DPG produces <1 ppm NO_2 and the soot vs DP characteristics is constant over a wide range of soot rates (from 2-20 g/hr).

The maximum temperatures measured in the DPF are similar for DPG and engine soot (~800°C for DPG compared with ~780°C for the engine). The temperature measured at the rear of the DPF is affected by the exotherm throughout the brick. This similarity indicates that the 'energy content' of the 2 forms of soot are very similar. This is supported by Thermogravimetric results (which indicate a similar Elemental Carbon to Organic Carbon ratio of ~85% – see reference 1) and electron microscope pictures which indicate a similar morphology (see Figure 11).

may be exposed to a range of flows and temperatures over a long period of time before regeneration. In the general case, the soot may not be uniformly distributed throughout the DPF (axially or radially). Passive regeneration (where high NO_2 concentrations can remove soot at relatively low temperature) tends to remove soot from the front of the DPF. Partial regeneration tends to remove soot from along the axis of the DPF and leave more soot nearer to the edges of the DPF.

In order to try to simulate with the DPG soot which is more representative of that from an actual vehicle, the DPF used for the above tests was regenerated and re-loaded to a higher soot mass than that reported above (40.1 g compared with ~32 g). The DPF was then exposed to clean gas at an elevated inlet temperature of 540°C and flowrate of 115 kg/hr. This temperature was chosen as giving very slow oxidation of solid Carbon (and fast oxidation of hydrocarbon [HC]). At this temperature, the soot mass on

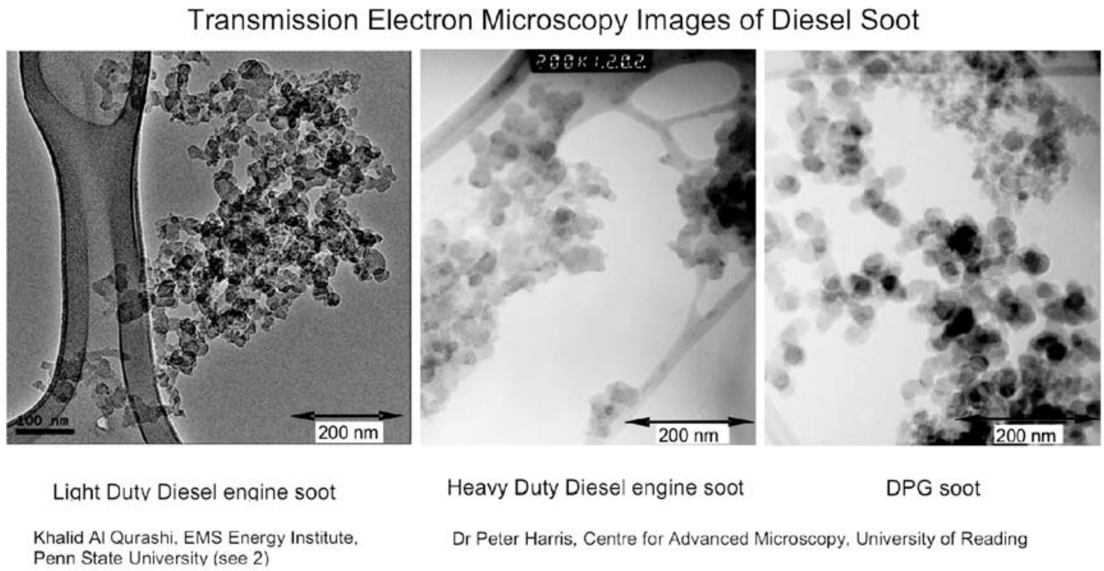

Fig. 11. TEM images of DPG soot and engine soot

Rys. 11. Obrazy z transmisyjnego mikroskopu elektronowego cząstek sadzy z DPG i silnika

The temperature rise rate was repeatably faster for the engine soot than for the DPG soot. The pressure drop indicates that the exothermic energy release is slightly delayed for the DPG soot.

'Part-oxidised' soot tests – non uniform sootload

In a DPF fitted to a vehicle, the soot load occurs over a range of engine conditions and regeneration occurs when a threshold in pressure drop across the DPF is exceeded. Therefore, soot deposited on the DPF in the general case

the DPF is found to decrease slowly over time. The rate of removal of soot is expected to be higher at the front and close to the axis of the brick and lower nearer to the wall (where the temperatures will be generally lower). For the purpose of description on the figures, I have called this process 'part- oxidisation'.

The sootload on the DPF was reduced from 40.1 g to 31.4 g (measured at 240°C) in 4 stages over a total period of 850 s. Following this, the DPF was regenerated with the same schedule (shown in Figure 5).

The results are shown in Figure 12.

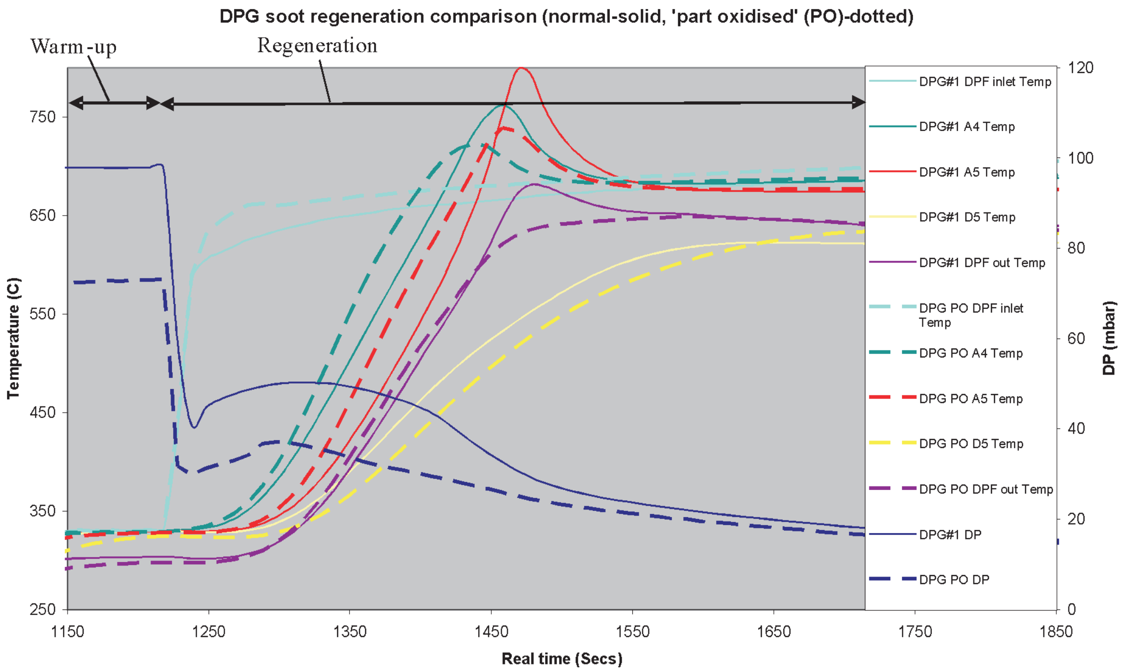

Fig. 12. Regeneration of normal DPG soot and part-oxidized (PO) DPG soot

Rys. 12. Regeneracja normalnej i częściowo utlenionej (PO) sadzy z DPG

These results indicate: The pressure drop for a similar soot load is reduced for the part-oxidised soot from 97 mbar to ~70 mbar (see the warm-up condition before regeneration at 1220 s in Figure 12).

There is generally higher flow along the central axis of the DPF for the part-oxidised soot (possibly because this area is preferentially cleaned). This leads to gene-rally faster temperature rises in these areas (e.g. inlet, A4 and A5). Note that the reverse is true near to the edge of the DPF – the temperature rise at location D5 (near to the rear at the edge of the DPF) is significantly slower for the 'part-oxidised' soot (indicating lower flow rate here).

The maximum temperatures in the DPF are generally reduced by 'part-oxidisation' (e.g. for A5, the max temperature for the standard soot load is 800°C and this is reduced to 740°C for the part-oxidised soot). This is probably due to the combined effects of the reduced exotherm from less deposited soot in these areas together with a higher flow rate (see above). Note that the reverse is true near the edge of the brick (D5) where the part-oxidised soot temperature eventually rises higher than the standard DPG soot (after 1650 s, standard soot ~ 625°C compared with 645°C for the part-oxidised soot).

The regeneration rate (indicated by the time reach a stable, clean pressure drop) is generally similar for the standard and 'part-oxidised' soot (~870 s from the start of regeneration).

Concerning the soot composition/reactivity, the regeneration schedule preheats the DPF to 330°C and therefore the VOC (HC) content of the soot is expected to be low (only the heaviest fractions will be present in the soot). Thermogravimetric analysis of DPG soot collected at 240°C indicates a typical Elemental Carbon to Organic Carbon ratio of 80:20 (see reference 1). Further heating to 540°C will generally reduce the organic carbon content and it is expected that the material which is regenerated in the 'part-oxidised' soot case may have a relatively higher elemental carbon content than the standard soot.

Conclusions

A DPG has been used to investigate DPF regeneration of soot deposited from an engine and from a burner based Diesel particulate generator. The following has been demonstrated:

- Repeatable soot loading of a test DPF to a target weight on both and engine dynamometer and a Diesel Particulate Generator.
- Repeatable regeneration of loaded DPFs for both engine soot and DPG soot.
- The maximum temperatures during regeneration oc-

curred near to the brick axis towards the rear face and were similar for both the engine soot and the DPG soot (800°C and 780°C respectively).

The pressure drop for the DPG loaded soot was ~10% lower than this type of engine soot.

The maximum temperatures for regeneration of the engine soot occurred sooner than the DPG soot. This effect is not fully understood and requires further investigation.

Tests on DPG soot which was part-oxidised by heating demonstrated:

- The pressure drop for a given soot load can be significantly affected by part-oxidisation.
- The exotherm in the DPF for a similar soot mass, but different soot distribution can be significantly different.
- It is hard to separate possible effects of soot reactivity from local flow rate.
- Maximum DPF temperatures are significantly lower when the soot in the DPF is distributed towards the edges of the DPF.
- The Diesel Particulate Generator is demonstrated to be a useful tool in the investigation of Regeneration of DPFs.

Recenzent: doc. dr Michał Krasodomski

References

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[2] Al-Qurashi K., Boehman A.L.: Combustion and Flame 155, 675-695, 2008.