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New Filtration Systems for the Control of Exhaust Emissions from Light-Duty Diesel Engines

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ABSTRACT

The paper includes the design, installation and testing of two different diesel particulate filter systems for light-duty diesel engines. The systems were installed on mining vehicles at Kidd Creek Mine in Timmins, Ontario, Canada.

The first system utilizes a newly developed pleated-media filtration element. The filter must be cleaned off-board or replaced with a new unit after a duty cycle.

The second system applies a ceramic wall-flow monolith. The filter is catalyzed and self-regenerates during high temperature operation periods.

Each system includes a diesel catalytic converter which diminishes both the gaseous emissions and the odour of diesel exhaust.

Advantages and limitations of the applied technologies are compared in the paper. The results of the performance tests, both bench and harsh underground operations, are discussed.

INTRODUCTION

As environmental awareness plays an increasingly important role in our everyday life, so grows the demand for cleaner power-generating technologies.

In the field of diesel technology the emphasis is on the reduction of diesel particulate matter (DPM) emissions. These emissions are even more important as the new air quality regulations in respect of DPM level are expected to be implemented.

Several diesel exhaust filtration technologies have been developed, so far none of them being perfect. The purpose of this paper is to analyze diesel filter systems available for engines of smaller size, in particular, those addressed for underground mining auxiliary vehicles. The first system with a newly developed pleated-media filter is suitable for vehicles with an exhaust temperature of about 200 deg.C. It has been installed on a Toyota Land Cruiser serving as a mine supervisor's underground transportation. As such, the vehicle does not have a repeatable duty cycle. The exhaust temperature was recorded for several hours of operation. The results of the recordings indicated that the engine was running cool. There were, however, moments with temperature peaks reaching 300 deg.C.

To prevent any detrimental effect on the filter during these periods, the system was equipped with a temperature activated bypass valve.

The second filtration system has been installed on a Kubota tractor. The tractor is used as an underground service vehicle and has a more uniform duty cycle than the Toyota Land Cruiser. The vehicle regularly climbs a ramp causing the exhaust temperature to surpass 400 deg.C. It was decided to equip the tractor with a catalyzed ceramic wall-flow diesel filter, since the temperature was high enough for the trap regeneration.

Both filtration systems were additionally equipped with a diesel exhaust catalytic converter. The task of the catalytic converter was to diminish carbon monoxide and hydrocarbon emissions as well as to reduce characteristic diesel odour.

DIESEL EXHAUST PURIFICATION SYSTEM WITH A PLEATED-MEDIA FILTER

The utilized pleated-media filtration element was developed by Donaldson Company and has been recently tested on diesel forklifts [1].

The filter utilizes a proprietary high temperature pleated-media element resembling a typical engine intake air filter. All filter materials endure a normal operation temperature of 200 deg.C. A short term operating temperature of 260 deg.C is not detrimental to the filter.

The filter holds 0.45 kg of DPM. The filter loads from the inside out to encapsul the soot for handling and cleaning. The backpressure increases from about 1 kPa clean to 14 kPa loaded (2.5 liter diesel engine). Laboratory tested filtration efficiency of the filter is more than 99%.

The system was installed at Kidd Creek Mine on a Toyota Land Cruiser Personal Carrier, equipped with a 4-cylinder engine of 3431 cc, 84 HP (62.6 kW) @ 3500 rpm, Kidd Creek Mine ID # 805.

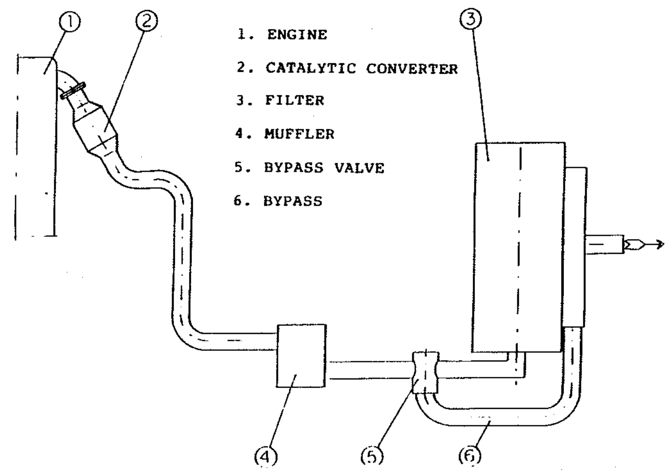

Fig.1 Exhaust purification system with the pleated media filter

A schematic of the system is shown in Fig.1. The first element is a catalytic converter (2) installed close to the engine. This position is favourable because of the increase of catalyst conversion efficiency with increased temperature. The filter (3) consists of the actual pleated-media filtration element enclosed in a steel housing. It is placed at the very end of the exhaust system to avoid exposure to high temperatures. In order to further protect the filter against high temperature damage, a bypass (6) and a temperature activated valve (5) are installed in the system. The valve is of a mechanical type and was set up to start opening at 200 deg.C. Its construction also enables a pressure-relief function in one design. The valve opens at pressures above 14 kPa, protecting the engine and the filter against excessive backpressure. The system is also equipped with a signal lamp on the operator's control panel (not shown in Fig.1). The lamp lights up when pressure at the filter inlet approaches 14 kPa, thus indicating the need for the cleaning or the replacement of the filter element.

The filter installation on the Toyota Land Cruiser is shown in Fig.2.

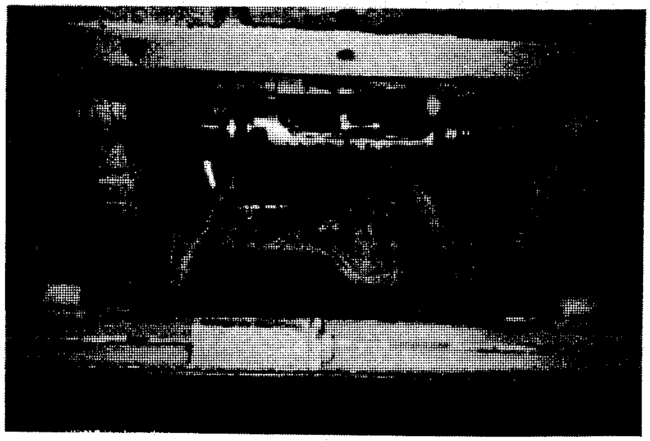

Fig.2 Filter installation on Toyota Land Cruiser

The exhaust gas temperature at the filter inlet is shown in Fig.3 (time units [days : hours : minutes]). The recording covers 2½ shifts of regular operation of the vehicle and can be considered as representative.

The analysis of the temperature recording shows that periods with temperatures over 200 deg.C occupy approximately 8% of the total operating time.

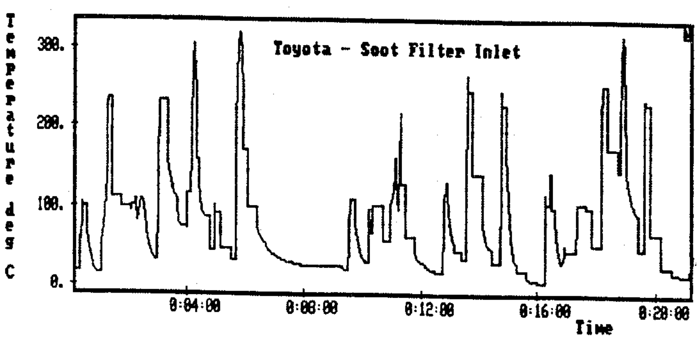

Fig.3 Toyota Land Cruiser exhaust gas temperature recording

During these periods of high temperature, a bypassing of the exhaust gas is necessary to prevent damage to the filter. The effective time-averaged efficiency of the filtration system will be decreased since the unfiltered exhaust is being bypassed and discharged to the environment during these periods of high temperature.

The operation of the bypass valve was investigated by means of simultaneous temperature recordings at the filter inlet and in the bypass. The pertinent graphs are shown in Fig.4.

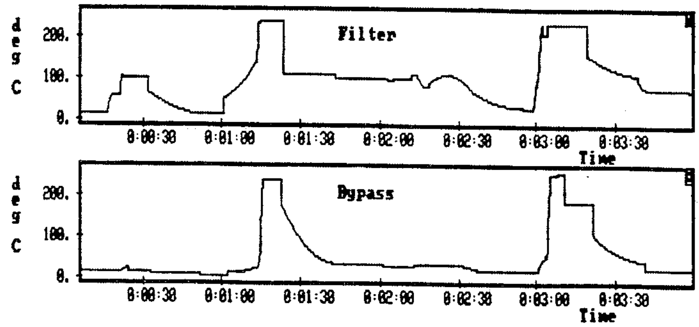

Fig.4 Filter and bypass temperature recordings

It can be seen that during periods with an exhaust gas temperature of the filter below 200 deg.C the bypass is closed. These are sections up to approximately 1:15, from 1:30 to 3:00 and over 3:20 on the time axis.

The corresponding bypass temperature amounts to about 30-40 deg.C due to heat conductivity of the piping and, possibly, small leakage of the valve. At the time coordinate points of 1:15 and 3:00 the exhaust gas temperature increases to over 200 deg.C and then the bypass opens. The bypass temperature rises due to the flow of exhaust gas. It can be seen that at the time of approximately 3:05 the bypass temperature is distinctly higher than that of the filter. At that moment, practically the entire exhaust gas stream is bypassed.

DIESEL EXHAUST PURIFICATION SYSTEM WITH A CERAMIC FILTER

A Corning ceramic diesel filter substrate was used. The size was 7.5" dia. x 12". The filtration efficiency of this material amounts to 65% (manufacturer's specifications).

The filter was catalyzed to lower the soot ignition temperature. A base metal catalyst was used with copper and vanadium as the main active components. The catalyst lowers the filter balance (regeneration) temperature to 380-420 deg.C, depending on the operating conditions.

While lowering the soot ignition temperature, the catalyst does not show oxidation activity in respect to gaseous components of the exhaust gas. Sulphur dioxide (SO_2) present in the exhaust gas is not oxidized to SO_3. The accumulation of sulphate deposits in the filter is thus avoided and the filter life span extended.

A system with the ceramic catalyzed filter was installed at Kidd Creek Mine on Kubota tractor M5030 equipped with a Kubota S2802-01 6-cylinder engine of 2791 cc and 49.7 HP (37.1 kW) @ 2600 rpm (Kidd Creek Mine ID # 831).

Main elements of the system are shown in Fig.5.

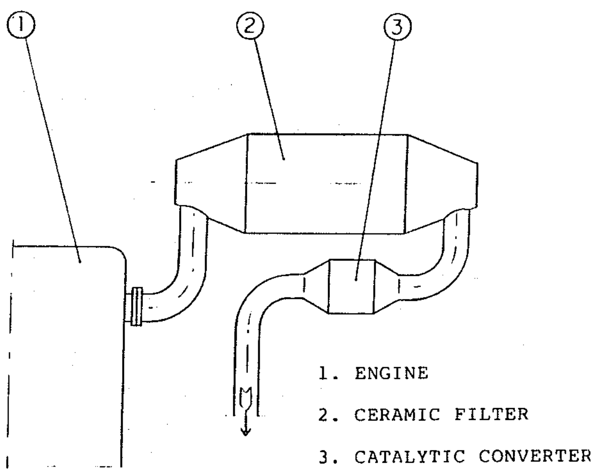

Fig.5 Exhaust purification system with the ceramic filter

The filter (2) is installed as the first element, close to the engine (1). This setting allows the filter to be exposed to the exhaust gas at the highest possible temperature. The catalytic converter (3) is installed down-stream of the filter. Some additional aspects of this arrangement will be discussed further.

The installation of the system on the Kubota tractor is shown in Fig.6. To maintain more heat in the filter the unit was insulated. The insulation is not shown in the picture.

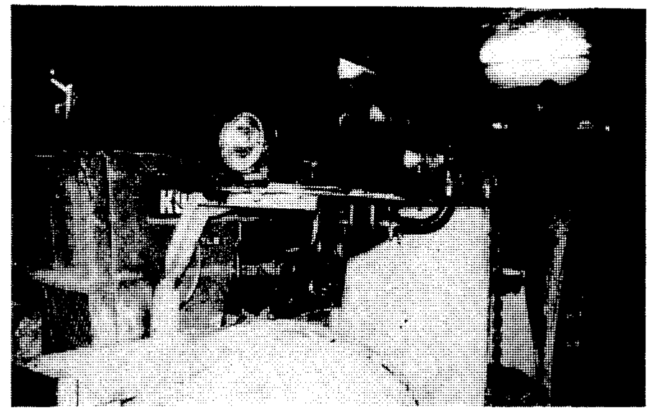

Fig.6 Filter installation on Kubota tractor.

The exhaust gas temperature at the filter inlet and the pressure drop on the ceramic filter are shown in Fig.7.

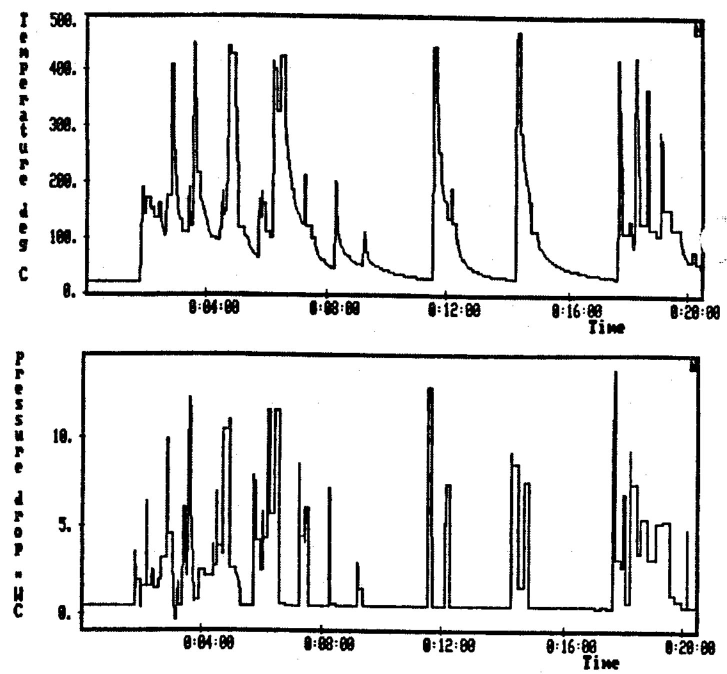

Fig.7 Kubota tractor exhaust gas temperature and filter pressure drop recordings

The Kubota tractor is used as a service vehicle. Its service areas are situated on many levels of the mine and the tractor climbs a ramp repeatedly. While climbing the ramp, the temperature of the exhaust gas exceeds 450 deg.C. These are the peaks in the temperature graph in Fig.7.

The frequent periods of high exhaust gas temperature allow the filter to self-regenerate. The lower graph in

Fig.7 shows the exhaust gas pressure drop on the ceramic filter. The pressure drop does not exceed 15" H_2O. There is no pressure build-up due to any excessive accumulation of soot on the filter.

A CATALYTIC CONVERTER IN DIESEL EXHAUST FILTRATION SYSTEMS

The task of a catalytic converter in diesel exhaust filtration systems is to reduce the gaseous pollutants, carbon monoxide (CO) and unburnt hydrocarbons (HC) as well as further reduce the diesel odour. The characteristic odour of diesel exhaust is partially reduced by the filter. A further significant decrease in the odour level, sometimes close to the olfactory threshold, can be attained by means of a catalytic converter.

The conversion efficiency of the catalyst used in both filtration systems is shown in Fig.8.

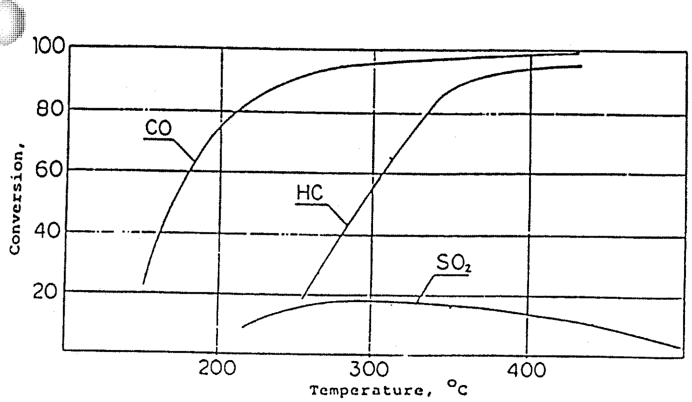

Fig.8 MINE-X diesel catalyst conversion efficiency

The curves were obtained in laboratory steady state tests at a space velocity of 50,000/h. Two important conclusions may be drawn from the graph:

- To gain a high conversion efficiency of CO and HC, the converter should be exposed to high temperatures, possibly over 300 deg.C.

- The diesel catalyst special formulation shows good selectivity. The maximum conversion of CO and HC exceeds 90% at high temperatures while the oxidation rate of SO_2 is suppressed to the maximum of 18%. Despite the high selectivity, some sulphate formation in the catalyst is unavoidable and must be taken into consideration.

In the system with the pleated-media filter, the catalyst was placed close to the engine. It was exposed to hot exhaust while the filter at the end of the system was exposed to cool exhaust. The performance of the catalyst did not affect the performance of the filter in this case. The exhaust system of the Toyota Land Cruiser was relatively long. The heat produced in the catalytic converter during an exothermic reaction was dissipated and had a marginal effect on the exhaust gas temperature at the filter inlet.

The relation between the catalytic converter and the ceramic catalyzed filter is much more complex and will require further investigation. According to some authors, an oxidizing catalyst placed in front of the filter causes a significant decrease of the filter balance temperature [2]. This is due to the fact that the oxidizing catalyst produces nitrogen dioxide (NO_2) which is a better oxidizing agent in respect to the soot than oxygen.

Prior to the installation of the system and the field test, an investigation took place to determine the correct system configuration. Balance temperature measurements were carried out for both arrangements - catalyst upstream and downstream the filter. The filter regeneration model according to Widdershoven J. et al. was assumed [3]. The filter was exposed to a climbing temperature ramp of the exhaust gas from a test engine. The pressure drop on the filter was monitored. The temperature at which the pressure drop stopped rising and assumed a constant value was considered as the filter balance temperature.

In the configuration with no catalyst upstream the filter, the balance temperature of 400-405 deg.C was found. With the catalyst placed upstream the filter, the balance temperature was over 450 deg.C.

The possible explanation of these results is that a selective diesel catalyst was used and the rate of NO_2 formation was marginal. The increase of the balance temperature might have been caused by the decreased oxygen concentration down-stream of the catalyst.

The soot ignition temperature might have also been increased as a result of a change in the DPM composition (less carbon, more inflammable sulphates).

On the basis of the experiment, it was decided to install the catalytic converter down-stream of the filter to obtain a lower balance temperature.

Such an arrangement should extend the ceramic filter life span as well since sulphate deposits do not accumulate in the filter. Otherwise, the sulphates, the main component of the inflammable ash, cause a decrease in the filter pore size and an increase in the pressure drop.

FILTRATION EFFICIENCY

Filtration efficiency of both filters was evaluated in laboratory conditions. The filters were installed on test engines specified in Table 1.

TABLE 1 Test engines specifications

	Pleated-media filter	Ceramic filter
Engine type	Perkins 1004-4	Caterpillar 3306 NA
Displacement (cm3)	4000	10500
Power (kW)	63	112
Max. speed, rpm	2600	2200

Each installation included a by-pass valve upstream of the filter and a filter pressure drop gauge. The maximum exhaust gas flow from both engines was larger than the capacity of both tested filters. The excessive exhaust gas flow at a high rpm was bypassed at the pressure drop on the filter over 20" H_2O.

The emissions of soot from both filters were measured by means of a Bosh RTT 100 smoke meter. The meter working principle is the absorbtion of light by diesel particulate matter. The exhaust gas is conducted through a measuring cell irradiated with light. The degree of the weakening of the light beam by the smoke is a gauge for the turbidity. Results are given in opacity percentage and soot mass concentration. The conversion from opacity into mass concentration is based on the conversion table of the British Motor Industry Research Association (MIRA).

The soot emissions measurements of both filters were taken at the four following modes:

1. High idle rpm;
2. Acceleration with no engine load;
3. High rpm with 80% of the maximum engine load;
4. Acceleration with the engine load.

The acceleration test readings represent the maximum soot concentrations during fast acceleration from low to high engine speed. The results of the pleated-media filter measurements are shown in Table 2 and of the ceramic filter in Table 3. The smoke level readings upstream and downstream of the filters are listed as well as the filtration efficiency calculated from mass concentration readings.

The filtration efficiency measurements were performed on clean filters. It can be expected that the filtration efficiency of both filters will increase with time.

TABLE 2 Pleated-media filter efficiency

TEST MODE	UPSTREAM		DOWNSTREAM		EFFICIENCY
	%	mg/m3	%	mg/m3	%
1	1.0	11	0.0	0	-
2	12.1	210	0.4	5	98
3	4.0	60	0.0	0	-
4	14.8	262	0.7	8	97
MEAN	8.0	136	0.3	3	98

TABLE 3 Ceramic filter efficiency

TEST MODE	UPSTREAM		DOWNSTREAM		EFFICIENCY
	%	mg/m3	%	mg/m3	%
1	4.9	75	1.5	18	76
2	69.1	1687	20.4	376	78
3	78.6	2169	15.5	275	87
4	81.8	2393	30.3	592	75
MEAN	58.6	1581	16.9	315	80

Each test result in Table 2 and 3 is an average from 4 measurements in the acceleration mode and from 10 to 15 measurements in the continuous mode.

The mean filtration efficiency of the pleated media filter amounts to 98%. This number is in agreement with the data from the manufacturer of the filter (99%). Assuming that the bypass valve of the Toyota system opens for 8% of the total operating time, the time-averaged filtration efficiency would be 90%.

The average filtration efficiency of the catalyzed ceramic substrate was 80%. This number is significantly higher than the specifications of the substrate's manufacturer equal to 65%. The discrepancy is caused by the catalyst coating. The manufacturer's data refers to the bare trap. The catalyst coating decreases the mean pore size of the ceramic substrate thus increasing the filtration efficiency.

CONCLUSIONS

1. A universal diesel exhaust filtration technology has not been developed yet. Two filtration systems were designed and tested in the harsh mining environment. The first system, with the pleated-media replaceable filtration element, is suitable for filtration of cool exhaust. The second system, with the catalyzed ceramic filter, requires repeating periods of high temperature operation for regeneration. In field tests, both systems proved to be successful on vehicles for which they were designed.

2. The filtration efficiency of the pleated-media element equals 98% and is higher than the filtration efficiency of the ceramic filter equal to 80%. The introduction of the bypass valve decreases the time-averaged efficiency of the system to about 90%, but even this number still exceeds the efficiency of the ceramic filter.

3. The main advantage of the ceramic filter is its maintenance-free operation. The pleated-media filter has to be inspected and serviced at least every 3 weeks.

4. The described technologies could cover a significant segment of the light-duty vehicle market. At this point, however, each vehicle should be analyzed separately. The exhaust temperature recording during the duty cycle is the basic factor to be taken into consideration.

5. The installation of diesel exhaust filtration systems was well received by the mine's crew. The miners noticed the clean tail-pipes and considered the introduction of the systems as a sign of care for their health. DPM forms a significant portion of the total respirable dust underground. The introduction of the diesel exhaust filtration systems could greatly contribute to the improvement of the work environment in mines.

ACKNOWLEDGEMENTS

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