JOSIP ZAVADA, D. Sc.
IVAN MAVRIN, D. Sc.
Faculty of Transport and Traffic Engineering
Fakultet prometnih znanosti
Zagreb, Vukelićeva 4

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REGENERATION OF DIESEL EXHAUST PARTICLE FILTERS

SAŽETAK

REGENERACIJA PROČISTAČA ČESTICA ISPUŠNIH PLINOVA DIESELOVA MOTORA

U radu se obrađuju mogućnosti regeneracije pročistača čestica ispušnih plinova Dieselova motora, kao i problemi koji pritom nastaju.

Primjena pročistača za čestice ispušnih plinova sve se više nameće zbog znatnog pooštravanja dopuštenih granica njihove emisije vozila s Dieselovim motorom. Aktualnost se pokazuje na teretnim motornim vozilima i autobusima. Nakupljene čestice u pročistačima povećavaju protutlak ispušnih plinova i pogoršavaju rad motora. Regeneraciju je najpogodnije provesti izgaranjem nakupljenih gorivih čestica.

Temperatura ispušnih plinova Dieselovih motora na spomenutim vozilima nije dovoljna da zapali čestice. Da bi se postigla temperatura iznad 550°C potrebna za zapaljenje čestica poduzimaju se odgovarajuće mjere. Efikasne su mjere izvan motora ili njihova kombinacija s mjerama unutar motora.

U radu se posebno obrađuju mjere izvan motora, kao što su zagrijavanje pročistača plamenikom, električnim grijačem ili mikrovalnom energijom, primjena aditiva u gorivu i primjena katalizatora.

1. INTRODUCTION

The emission of harmful components in motor vehicles presents a significant problem in all countries because of environmental pollution. Diesel engine exhaust emissions contain harmful components NO_x, CO, HC and particles. The emphasized problem is the reduction of nitrogen oxides and particles, because legislation is increasingly severe in their limitation. Emission of exhaust particles is efficiently reduced by the use of filters. Filters vary according to the material and design. The most common materials are ceramics and steel, and designs include porous wall, foam wall, fibres, plaited, synthetized and electrostatic ones. During service, particles start to deposit in the filters which causes a greater resistance to the flow of exhaust gases, i.e. it increases the counterpressure. This having an adverse effect on the engine performance, the filter needs to be regenerated in a controlled manner, i.e. cleaned as often as necessary. Regular filter replacement is not acceptable because of high costs and increased requirements in maintaining the vehicle.

2 - FILTER REGENERATION POSSIBILITIES

For the filter regeneration by burning the combustible particles, i.e. soot, a temperature higher than 550°C has to be provided. It is difficult to reach such a high temperature by Diesel engine exhaust gases, since the exhaust gases temperatures tend to be lower during the greater part of the working regime. An example showing the dependence of exhaust gases temperature on the working regime of a Diesel engine with a swirl chamber and pressure charging is given in Figure 1 [1]. It is obvious that only with full load and at higher engine speeds, the exhaust gases temperature reaches the degree necessary for soot combustion.

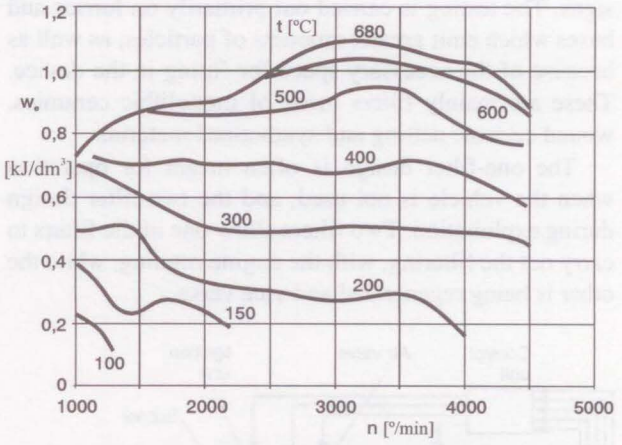

Figure 1 **- Dependence of exhaust gases temperature on load and Diesel engine speed.**

Since regeneration has to be carried out after a certain amount of particles had been deposited and Diesel engines in vehicles seldom work fully loaded, it is necessary to provide regeneration through additional measures.

The filter regeneration measures can be divided into:
– measures undertaken in the engine, and
– measures undertaken outside the engine.

2.1. Filter Regeneration Measures within the Engine

Measures undertaken within the engine that can cause an increase in exhaust gases temperature involve the following:

- return of exhaust gases back into the intake system,
- damping in the intake system, and
- pre-heating of intake air.

Each of these measures and their combinations increase the temperature of exhaust gases but none of them increases the temperature to the necessary degree (above 550°C) that would ignite the trapped combustible particles. Therefore, these measures alone do not suffice for the filter regeneration.

2.2. Filter Regeneration Measures outside the Engine

Measures undertaken outside the engine that allow the filter regeneration include:

- supply of heat by a burner,
- supply of heat by an electric heater,
- use of additives,
- use of catalyser, and
- application of microwave energy.

2.2.1. Supply of Heat by a Burner

The temperature increase in the particle filter up to the degree needed to ignite the trapped soot using a special burner is a promising solution, tested in various designs. The testing is carried out primarily on lorries and buses which emit greater amounts of particles, as well as because of the necessary space for fitting in the device. These are mainly filters made of monolithic ceramics, wound ceramic netting and synthetized material.

The one-filter design is often meant for operation when the vehicle is not used, and the two-filter design during exploitation. Two filters allow one of the filters to carry out the filtering, with the engine running, while the other is being regenerated and vice versa.

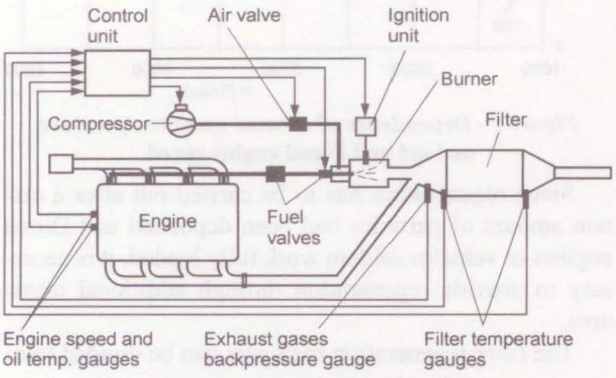

Figure 2 - **Scheme of a filter regeneration device with a burner**

An example of a one filter regeneration device designed by KHD is shown in Figure 2. The regeneration of a single part filter made of fine porous monolithic ceramics is carried out while the engine is running when the filter temperature reaches 600°C due to a burner. The burner uses 0.5 l of diesel fuel every ten engine operating hours and is insensitive to exhaust gases counterpressure during regeneration. The burner operates with air supplied by a special compressor. The device is controlled by an electronic control unit using the data on filter temperature, exhaust gases counterpressure, and engine operating regime. The device regenerates the filter efficiently regardless of the engine operating regime.

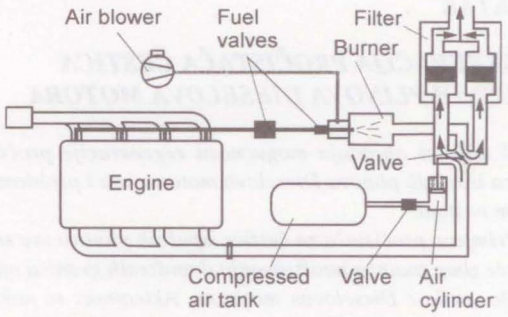

Figure 3 - **Scheme of the Duplex-filter for the regeneration with a burner**

The principle scheme of the so-called Duplex-filter, developed by MAN is shown in Figure 3. The filter is made of monolithic ceramics. The device is fully automated and operates while the engine is running. The pneumatic device is controlled by a valve directing the exhaust gases from the engine to the part of the filter for filtering, and the hot gases from the burner to the part of the filter for regeneration. The burner is switched on only during the filter regeneration. When the other part of the filter gets clogged, the valve redirects the gases to the regenerated part of the filter, and the clogged part is regenerated. In a 13-phase test according to ECE 49, the application of this filter has managed to reduce the particle emission to less than 7 g/kWh [2].

2.2.2. Supply of Heat by Electric Heater

Heating up to the temperature at which soot gets ignited by an electric heater is usually applied to monolithic ceramic filters. A more complex solution includes two parallel monolithic filters. While one filter is being regenerated, a special valve directs exhaust gases to the other. The regeneration is performed every 4 to 5 engine working hours, i.e. when the amount of trapped particles on the filter is about 40 g, and it lasts for about 15 minutes. The fuel consumption increases for about 1 to 2 %.

A principle scheme of a device for filtering exhaust gases particles with a built-in electric heater, designed by Volvo is shown in Figure 4. The filter is made of monolithic ceramics. After about every 300 clocked-up kilometers the filter needs to be regenerated. In order to

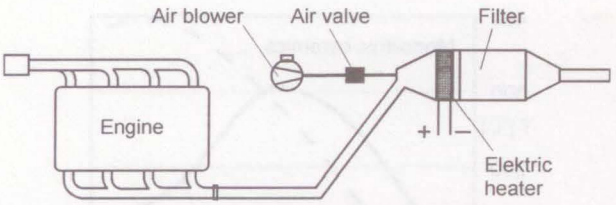

Figure 4 - **A scheme of a regeneration filter with an electric heater**

do this, an electric heater fitted before the filter is switched on with the necessary supply of air for combustion of the trapped combustible particles. The resulting emission of harmful components during the regeneration is comparable to the emission of the engine idling for only a couple of seconds. The filter reduces the emission of particles for at least 80%, the emission of HC for about 60% and CO for about 50% [2].

2.2.3. Use of Additives

The use of additives reduces the ignition temperature of particles by about 150÷200°C [3]. Additives are most often on the basis of copper, iron, manganese and more recently cerium, and they are added to the fuel or supplied directly before the filter. The deficiency of this solution is in polluting the environment by the metals from the additives. Since there are no results yet regarding effects that these elements have on the environment, this device is still in its experimental phase.

Fuel additives do not only reduce the ignition temperature of soot, they also affect the primary emission of harmful components from the engine. The influence of certain additives in the fuel on the primary emission of some harmful components is shown comparatively in Figure 5 [4]. The Figure clearly shows that the emission of total and organic particles is best reduced by cerium. At the same time cerium is only a little toxic and highly inert.

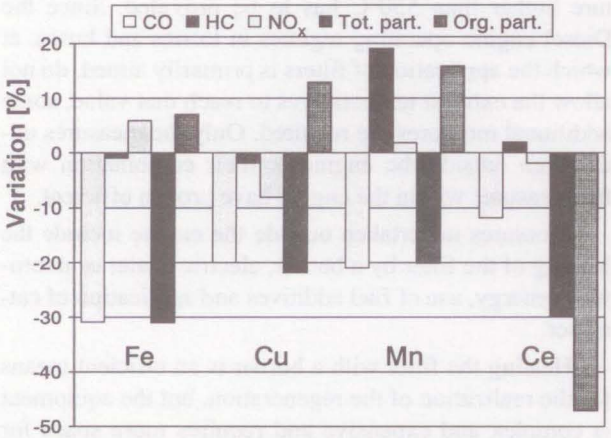

Figure 5 - **The influence of fuel additives on the primary emission of harmful components.**

The use of cerium as a fuel additive the ignition temperature of soot in the filter is reduced to about 400°C. For the regeneration to be carried out automatically without any special measures, i.e. so that the system is completely passive, the exhaust gases temperature should from time to time reach 400°C or more. Therefore, in order to apply this regeneration method it is necessary to know the engine operating regimes for a particular vehicle.

Some vehicles, as e.g. city buses, operate mostly under such small loads that they almost never reach the exhaust gases temperature of 400°C. The necessary temperature increase could be achieved by application of some active system, such as a burner or an electric heater. This, however, causes the design to be more complex, more expensive and less reliable. A more simple approach to obtaining the necessary exhaust gases temperature involves measures undertaken outside the engine, already previously mentioned.

The measures within the engine to increase the exhaust gases temperature also reduce the engine efficiency, i.e. increase the fuel consumption. However, the filter regeneration is a very short operation and the fuel consumption is only slightly increased. The influence is even less when one takes into consideration that cerium affects the reduction in fuel consumption as an active factor in the combustion process, as well as the reduction of soot and all particles emission.

2.2.4. The Use of a Catalyser

The use of a catalyser means coating the filter with catalytic material, e.g. copper oxide or vanadium. By adding a catalytic-activating medium directly before the filter, the regeneration process is activated already at temperatures of about 250°C [5]. Because of this, the regeneration is feasible in a very wide range of working regimes. The device requires a complex equipment for regulation which makes it more expensive. Its application is still in the experimental phase on certain industry vehicles.

The application of a catalytic medium alone, for coating the filter is a very attractive way of regeneration. However, this solution requires the use of diesel fuel with a very low content of sulfur, since a part of burnt carbon is substituted by sulfates when SO_2 comes into contact with the catalytic medium in the presence of oxygen. Since diesel fuel with such a low content of sulfur is not yet being used, this solution is not widely used.

2.2.5. Application of Microwave Energy

The application of microwave energy is a new regeneration method of particle filters, which is very efficient, saves energy, the equipment is not very expensive and it is suitable for use. This method offers possibilities to eliminate the deficiencies resulting from the other methods.

Heating by microwave energy differs from the common heating by conducting the heat or heat radiation. Microwave energy converts into heat in the body itself and therefore the energy conversion efficiency is much

greater. The absorbed microwave energy of the heated body in the microwave field is computed using the following formula:

$$P = \frac{10^{-10}}{1.8} \cdot f \cdot E^2 \cdot \varepsilon \cdot \tan\delta \quad [W/m^3] \qquad (1)$$

with:

f [Hz] - microwave frequency
E [V/m] - electric field power
ε - dielectric constant of the material
tan δ - material loss coefficient

The heating of the body expressed by the change in temperature per time unit can be computed by the following equation:

$$\frac{\Delta T}{\Delta t} = \frac{10^{-10} \cdot f \cdot E^2 \cdot \varepsilon \cdot \tan\delta}{1.8 \cdot \rho \cdot c_p} \quad [°C/s] \qquad (2)$$

with:

ρ [kg/m^3] - material density
c_p [J/kg°C] - specific warmth of the material

The given equations show that the absorbed energy and the temperature increase do not only depend on the power of the electric field and the frequency, but also on electric and physical properties of the materials. This is precisely what enables selective heating of certain materials by microwave energy, and what can be practically used for regenerating the filters.

Table 1 **- Microwave properties of filters and particles**

Filter	Condition	ε	tan δ
Ceramic foam	without particles	1.4661	1.9797
	with particles	1.5923	5.2815
Monolith ceramics	without particles	1.5053	0.8856
	with particles	1.5187	5.2890
	only particles	1.5186	161.2193

Microwave properties of ceramic filters in a foam and monolithic design, and of particles are shown in table 1 [6]. Measuring was done with a frequency at 9.37 GHz. The values of dielectric constant and loss coefficient are much greater for particles than for the ceramic filter. Therefore, particles absorb more microwave energy than ceramics. Using this property, the particles are selectively heated by the microwave energy to a higher temperature than the ceramic filter, thus causing the combustion of particles and the regeneration of the filter using up less energy.

The filter regeneration performed by using the device for creating microwave field of 2.45 GHz frequency and of 1 kW power with exhaust gas counterpressure of 20 kPa causes a change in temperature on the surface of the filter as shown in Figure 6 [6].

The experiments show that regeneration by microwave energy can be fully performed. However, attention

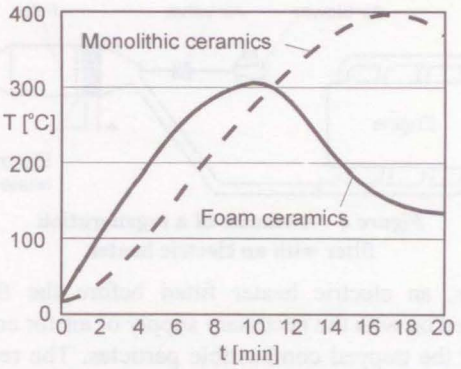

Figure 6 **- The change of temperature on the surface of the filter during regeneration**

should be paid to the amount of absorbed energy since central parts of the filter might begin to melt due to the exceeding temperature.

As a temperature of more than 550°C should be provided for the combustion of particles, and the ceramics begins to melt at temperatures higher than 1500°C, the filter temperature during regeneration should be maintained between 600 and 1200°C. An approximately likely range of temperatures is obtained by the calculation in parts from the periphery towards the center of the filter. For this temperature range microwave power of 580 to 600 W lasting from 5 to 10 minutes per regeneration is required [6]. Power should not exceed 1000 W.

A relatively small microwave device can be fitted into the vehicles. It should be switched on automatically, when the exhaust counterpressure reaches an appropriate value.

3. CONCLUSION

Filter regeneration is performed by combustion of the trapped particles. To ignite the particles a temperature higher than 550°C has to be provided. Since the Diesel engine operating regimes in lorries and buses, at which the application of filters is primarily aimed, do not allow the exhaust temperatures to reach that value, some additional measures are required. Only the measures undertaken outside the engine or their combination with the measures within the engine have proven efficient.

Measures undertaken outside the engine include the heating of the filter by a burner, electric heater or microwave energy, use of fuel additives and application of catalyser.

Heating the filter with a burner is an efficient means for the realization of the regeneration, but the equipment is complex and expensive and requires more space for fitting-in. It slightly increases the fuel consumption (about 0.5 l of diesel fuel to every ten engine running hours).

Heating by an electric heater is a simple solution, but a great burden on the vehicle battery. Because of the

greater battery charging, the fuel consumption rises by about 1 to 2%

The use of fuel additives reduces the ignition temperature of the particles by about 150÷200°C. Additives are mostly based on copper, iron, manganese and cerium. The deficiency of this solution lies in the pollution of the environment by metals from the additives. Most of the additives also reduce the primary emission of harmful components in exhaust gases. The primary particle emission is best reduced by cerium. To achieve the ignition temperature of gases of about 400°C, this measure should be combined with measures within the engine. Also an electronic device for controlling the engine is needed. Measures undertaken within the engine to increase the temperature of exhaust gases, increase the fuel consumption. However, this increase is only slight due to the short time needed for regeneration. If cerium, which reduces the fuel consumption, is used as an additive because it improves the combustion process in the engine cylinder, then the total fuel consumption is only slightly increased.

The use of a catalytic medium for coating the filter is a very attractive passive way of regeneration. However, such a solution requires the use of very low sulfur content diesel fuel. Since diesel fuels with such low level of sulfur are not yet widely used, this solution hasn't got a wider application.

Application of microwave energy is an efficient and relatively simple solution for the filter regeneration. The particles absorb more microwave energy than does ceramic filter. This property allows the trapped particles to be selectively heated to a higher temperature than the filter itself which requires less energy to ignite the particles. A small built-in microwave device on a vehicle is switched on automatically by an electronic device, when certain counterpressure values are reached in the exhaust gases. To activate the regeneration the device should give a power of 580 to 600°C.

Each of the mentioned ways for regenerating the filters has certain advantages and disadvantages, and experience from exploitation and development will point to the most suitable solution.

SUMMARY

The paper studies the regeneration possibilities of Diesel exhaust particle filters, as well as the resulting problems.

The application of exhaust particle filters is more and more required, because of the increasingly severe limitations imposed on the exhaust emissions of the Diesel engine vehicles. They are particularly necessary on lorries and buses. The particles trapped in filters increase the counterpressure in the exhaust gases and reduce the engine performance. The most suitable method for performing regeneration is to burn the combustible particles trapped in the filter.

The temperature of the Diesel engine exhaust gases in the mentioned vehicles is not high enough to ignite the particles. To reach the temperatures higher than 550°C, certain measures have to be undertaken. There are efficient measures outside the engine or their combination with measures within the engine.

The paper deals especially with measures undertaken outside the engine, such as heating the filter using a burner, electric heater or microwave energy, use of fuel additives or application of a catalyser.

LITERATURE

[1] **F. SCHÄFER, R. VAN BASSHUYSEN**: Schadstoffreduzierung und Kraftstoffverbrauch von Pkw-Verbrennungsmotoren, Springer-Verlag, Wien, New York, 1993.

[2] **E. HOEPKE**: Partikelfilter fûr Omnibusse und Kommunalfahrzeuge, ATZ 91(1989) 12, 680-683.

[3] **E. MÜLLER, B. WIEDEMANN, A. PREUSS, H. SCHÄDLICH**: Diesel Partikelfiltersystem mit additivgestûtzter Regeneration, ATZ 91(1989) 12, 674-678.

[4] **J. LEMAIRE, W. MUSTEL, P. ZELENKA**: Fuel Additive Supported Particulate Trap Regeneration Possibilities by Engine Management System Measures, SAE Paper 942069 (1994).

[5] **H. J. FÖRSTER**: Entwicklungsreserven des Verbrennungsmotors zur Schonung von Energie und Umwelt - Teil 1, ATZ 93(1991) 5, 258-272.

[6] **Z. CHUNRUN, C. JIAHUA**: Studies on Regeneration of Diesel Exhaust Particulate Filters by Microwave Energy, SAE Paper 941774 (1994).