Title: REGENERATION OF DIESEL PARTICULATE FILTERS USING LAMBDA VARIATION

Abstract: This invention provides a method of regenerating a diesel particulate filter in an exhaust-gas purification system of a diesel engine using lambda variation. During regeneration on demand, the ratio of air to fuel for the corresponding operating point of the diesel engine is adjusted so as to achieve the substantially highest possible exhaust-gas temperature. For this purpose, the ratio of air to fuel (lambda value) is preferably kept at a minimum and substantially constant over the major part of the load range so that the engine is operated at full load during the regeneration phases.
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Regeneration of diesel particulate filters using lambda variation

The present invention relates to the use of engine modifications to support or create regeneration conditions of diesel particulate filters, and more particularly, the regeneration of preferably catalytically coated diesel particulate filters using lambda variation.

Today's world of internal combustion engines is dominated by two engine versions, gasoline engines and diesel engines. The ongoing development of the two combustion concepts concentrates on reducing emissions for which legal regulations to protect people and the environment are being increasingly tightened.

Compared to combustion in gasoline engines, diesel engines produce low emissions of carbon monoxide, hydrocarbons and nitrogen oxides, but also greatly increased particulate emissions which are typical of diesel engines. Examining these emissions is of particular significance so that generation, prevention and disposal of particulate emissions can be controlled. Generation and prevention of particulates in conventional diesel engines is still very difficult to influence so that the main focus is on disposal. This trend is strongly supported and required by applicable law.

One way to collect most particulates from the exhaust gas of diesel engines is to use so-called diesel particulate filters. These filters are placed in the exhaust-gas line in order to achieve a highest possible filtering rate for the particulates contained in the exhaust gas.

However, this very effective and efficient filtering process leads to a follow-on problem. That is, the filter becomes increasingly loaded with particulate matter. As a result, it is difficult for exhaust gas to flow through the filter, and a pressure increase is generated upstream of the filter which can be considered to be equivalent to increased exhaust work of the engine. This increased exhaust work is
reflected in power loss and increased fuel consumption of the engine, respectively. In order to prevent an unnecessarily high increase in pressure upstream of the filter, the filter must be burned free from time to time. This is done by various regeneration measures and strategies, respectively.

It is strongly expected that the structure of the honeycomb filter, also referred to as a ceramic monolithic cell filter, will determine the technology of diesel particulate filters, hereinafter referred to as DPFs. The DPF is a filter having alternately open and closed channels. As a result of this construction, the exhaust gas is forced to flow through the porous channel walls where particulate matter can deposit on the walls. Therefore, such a filter is also called a wall-flow filter.

In addition to these honeycomb filters, there exist also filters which may have a wound construction, for example. In such a filter, the exhaust gas passes through without meeting a direct obstacle. Its construction is similar to a catalyst, i.e., without any closed channels. Compared to the honeycomb filter, which may achieve a filtering effect of more than 99%, the filtration efficiency for particulate matter is in an unacceptably low range, however.

Moreover, there are sintered metal filters, wound fiber filters, knitted fiber filters, braided fiber filters and filter papers as well as non-woven filters. Taking all parameters such as production expenditure and manufacturing cost, physical properties, filtering effect, durability etc. into account, honeycomb filters have advantages over any other filter development.

Regeneration of DPFs (without any additional modifications) is a chemical reaction which may be considered a pure oxygen regeneration (oxidation of soot). It starts at temperatures around 360 °C but only above 550 °C reaction and oxidation rates are achieved that are interesting from a practical point of view. This means that only at those temperatures sufficiently fast regeneration rates can be obtained which constitute an economically acceptable solution with respect to using the DPFs in vehicles.
The following regeneration strategies when employing diesel particulate filters are known:
- diesel particulate filters with additive support,
- CRT systems,
- catalytically coated diesel particulate filters,
- electrically supported diesel particulate filters,
- diesel particulate filters with burner systems, and
- compressed-air purged diesel particulate filters.

In catalytically coated diesel particulate filters, for example, metals are introduced into the surface of the filter. These metals serve as a catalyst lowering the soot ignition temperature below 400 °C. Using various noble metals, it is possible to reduce this initial temperature even further to a range below 350 °C. In addition, an oxidation catalyst may be provided upstream of the DPF to oxidize NO contained in the exhaust gas to NO₂ using the residual oxygen, thus supporting regeneration. Provided that the exhaust-gas temperatures exceed the initial temperature for a sufficiently long period of time, catalytically coated DPFs may be regenerated sufficiently well.

In intensive test series using catalytically coated diesel particulate filters on engine test benches, dynamic test cycles are being developed to simulate a real driving mode of a motor vehicle. The engine speed and load spectra during these tests are based on standardized exhaust-gas tests. These test cycles include both urban and extra-urban operation. The engine speed and load spectra occurring differ in that the percentage utilization of the engine in urban operation is very low (refer to Figure 1). By comparison, the engine load in extra-urban operation is relatively high. Directly related to this percentage utilization of the engine is its exhaust-gas temperature. Accordingly, high temperatures in the exhaust gas are reached at high utilization in extra-urban operation, while relatively low temperatures are reached in urban operation (refer to Figure 2).

The reason for simulating the real driving mode on the engine test bench is that the pressure loss behavior of a DPF may be predicted for later employment on a vehicle.
The engine's exhaust-gas temperatures are directly related to its percentage load (refer to Figures 1 and 2). As described above, this leads to very low temperatures in urban operation and very high temperatures in extra-urban operation. Fig. 3 depicts the temperature curve for urban operation. This curve may be plotted at any position in the exhaust-gas line and is thus regarded as a temperature spectrum in the exhaust-gas line. Fig. 4 shows the same situation for extra-urban operation.

Various engine speed levels are used for extra-urban operation during the test series. Thus, various temperature characteristics are obtained. As a result, temperature levels at which practically acceptable regeneration occurs may be determined for different filters.

The main conclusion from the results of the dynamic test cycles may be divided into two parts. One conclusion to be drawn is that the temperature spectra in extra-urban operation may be sufficient in order to force regeneration of the filter. This is achieved in an acceptable range as regards time. The second conclusion is that urban operation, due to its low temperature spectrum, fails to generate practically usable regeneration conditions.

These conclusions may be understood from Figures 5 and 6. These figures indicate the pressure loss described above. In persistent urban operation, this pressure loss increases with the duration of the test due to the rising filter loading (Figure 5).

The regeneration conditions in extra-urban operation may be generated in such a satisfactory manner that a decrease in pressure loss is possible after only a short period of time. As an example, Figure 6 shows a dynamic test involving a combination of both modes of operation. During extra-urban operation, which is very brief compared to urban operation, a rapid decrease in pressure loss is generated so that a falling pressure loss may be achieved over the entire duration of the test.
In summary, satisfactory regeneration of the filter may be achieved in extra-urban operation, but not in urban operation.

For the technology of diesel particulate filters to be interesting for all vehicle applications, the regenerative capacity must be provided in every operating mode of the corresponding vehicle. Development and application of the urban test cycle, which can simulate the driving mode for buses, garbage trucks or taxicabs, for example, has already shown that this "condition" cannot be met without any further modifications.

Accordingly, it is an object of the present invention to provide a method enabling regeneration of the filter at any point of time irrespective of the load profile (operating mode) of the vehicle. This type of regeneration will be referred to as regeneration on demand.

This object is solved with the features according to the claims.

In conventional diesel engines, quality-controlled combustion takes place. This means that the quality of the supplied mixture of air and fuel is controlled. This principle is implemented by controlling the fuel flow rate depending on the operating point of the engine (load/torque increase is achieved by raising the fuel flow rate). The air supply remains unaffected at all times. This results in different ratios of air and fuel which can be expressed using the dimensionless quantity lambda:

\[ \lambda = \frac{\text{air flow rate}[\text{kg/h}]}{14.6 \times \text{fuel flow rate}[\text{kg/h}]} \]

In a conventional diesel engine, the air flow rate is constant when the engine speed is fixed. Thus, lambda may only be influenced by the fuel flow rate. Combustion in diesel engines operates with excess air, i.e., more air is present than would be necessary for combustion. Therefore, lambda does not fall below 1. Further, if combustion in diesel engines falls below a lambda value of 1, it meets its functional and misfire limit, respectively. Looking at characteristic maps of diesel engines, the lowest lambda values
are found at full load, as the fuel flow rate is largest in this case.

In diesel engines provided with supercharging systems for the air supplied, the air flow rate varies at constant engine speed. More air is supplied to the engine with increasing load/torque. This is called supercharging. However, in addition to supercharging, more fuel may also be supplied so that lambda varies in the characteristic map of a supercharged diesel engine as well.

Therefore, the lowest lambda values in a diesel engine always occur at full load. Thus, the lowest air/fuel ratios lie in this range. This results in the highest exhaust-gas temperatures. The percentage contribution of air to combustion is maximum here. This contribution/utilization decreases with increasing lambda values so that the exhaust-gas temperature falls again. The relationship between lambda values and exhaust-gas temperatures is depicted in the characteristic maps (Figures 7 and 8).

The present invention relies on the following basic idea with respect to the necessary regeneration of the diesel particulate filter and the existing problem that the conditions for sufficient regeneration exist only at full load.

During regeneration on demand, the diesel engine is not operated as a quality-controlled engine but as a quantity-controlled engine similar to the gasoline engine principle. Power requirements of the engine are satisfied not only by adding fuel, but the flow rate of the combustion mixture is controlled. In a diesel engine that is not supercharged, this must be done using a throttle valve for the supply/intake air. The ratio of air to fuel is maintained constant and low similar to a gasoline engine. When the engine is running at partial load, the throttle valve restricts the air flow rate. Thus, there is no quality control by means of the fuel flow rate, but quantity control of the mixture. As a result, the engine may be operated at a desired lambda (or lambda value). Using different throttle states for an operating point of the engine, different mixture states may be adjusted. This may be called lambda variation.
In addition to the above-mentioned throttle valve, supercharged diesel engines require a system for varying the boost pressure. Influencing the boost pressure directly varies the air flow rate. At the corresponding operating point of the engine, the boost pressure is adjusted such that the required air flow rate for the desired lambda value is supplied to the engine. This combination of a throttle valve and a system for varying the boost pressure constitutes the overall solution for supercharged diesel engines enabling a constant lambda value, or desired lambda value, to be used for the corresponding operating point of the engine in the entire characteristic map. Also, designs may be employed fulfilling both functions together, such as a regulating valve downstream of the supercharger, which closes or restricts the air passage to the engine and, at the same time, opens a passage to the environment. The idea or functional principle may also be implemented using other systems. For example, the entire air flow rate may also be throttled upstream of the supercharger so that the resulting boost pressure is varied by means of the air flow entering the supercharger.

Influencing the air flow rate using boost pressure variation and/or throttling also creates a "variable engine". Variability refers to its power capacity. An engine that is uninfluenced reaches its maximum temperature at full load at the lowest lambda value. For regeneration on demand, this lambda value constitutes the target value for the entire load range. The boost pressure is varied (minimized) in such a way that the target lambda is run at partial load. At the same time, this is the current full load of the engine, as more load cannot be generated with the now-reduced air flow supply and the thus minimally operated target lambda value. During operation with regeneration on demand, the engine is always operated close to its currently possible full load. This inevitably produces the highest possible exhaust-gas temperature because, as has been known, when lambda is lowest, the least excess of air is present and the supplied air flow participates best in combustion (highest percentage utilization of air in the combustion chamber).
In the following, the invention will be explained in detail with reference to the accompanying drawings in which:

Figure 1 shows the percentage distribution in urban engine operation;
Figure 2 shows the percentage distribution in extra-urban engine operation;
Figure 3 shows the temperature curve in urban engine operation;
Figure 4 shows the temperature curve in extra-urban engine operation;
Figure 5 shows the pressure loss in persistent urban engine operation;
Figure 6 shows the pressure loss in combined operation;
Figure 7 shows the characteristic lambda map of a supercharged diesel engine;
Figure 8 shows the characteristic exhaust temperature map of a supercharged diesel engine;
Figure 9 shows the range of lambda variation at constant engine speed;
Figure 10 shows the exhaust-gas temperature in normal operation and during lambda variation; and
Figure 11 shows the intake pipe pressure and lambda value, respectively, versus load at constant engine speed for ideal and real regeneration on demand.

Figure 9 is a graphic representation of the relationship between exhaust-gas temperature, lambda value and engine load at constant engine speed. Normal engine operation is shown starting from full load at a low lambda value up to lower partial load at a high lambda value. The exhaust-gas temperature is decreasing considerably. During regeneration on demand, operation is at a constant, low lambda value. The exhaust-gas temperature drops only slightly with decreasing load/torque. This is due to the low energy introduced by the decreasing fuel flow rate despite lambda being kept constant. The region between these two curves (the entire area) represents the possible variation between the two operating modes (at constant engine speed).
Using regeneration on demand must not be felt by the driver. This is a general condition applying to all strategies for regenerating diesel particulate filters. This means that at no time power losses may occur. When the driver requires maximum torque, then the maximum air flow rate must be supplied. In normally aspirated engines, no throttling must be active then, and in supercharged engines, the full boost pressure must be available. When the load is reduced by the driver, boost pressure variation and throttling must respectively become active. The driver may be informed of the regeneration operation by corresponding signals in the cockpit.

Similar conditions apply on the test bench. No deviations from normal operation must be measurable for a dynamic test run with varying load requirements. Compared to the vehicle, the test bench makes it possible to apply lambda variation through test bench software. In the vehicle, the corresponding actuators must be operated by the engine electronics in accordance with the driver's request. The driver's request corresponds to the information obtained from the accelerator position at the current engine speed.

Fig. 10 compares the temperature curves of a tested lambda variation to normal operation. The dynamic test presented above to simulate urban operation was conducted in both runs. The curves indicated show the same character as the engine speed and torque curves are identical. A distinct difference in the temperature levels is apparent. The curve with lambda variation represents the highest possible temperature for the corresponding operating point as at any operating point the lowest possible lambda value is used.

Ideal regeneration on demand would be operated at a constant lambda value in the entire characteristic map, e.g., a value of about \( \lambda = 1.8 \); thus, if possible, the lowest lambda value from the entire characteristic map of normal operation (refer to Figure 7). This will be called an ideal lambda value. The first limit/deviation from operation at the ideal lambda value is apparent from Figure 7. If in the higher engine speed ranges this ideal lambda value were used, the air flow rate would have to be reduced. This, however, would re-
duce the engine's power capacity, which is unacceptable. Therefore, every engine speed has its own lowest lambda value, i.e., the lambda value at the full load curve.

The second deviation from this ideal lambda value takes place at lower partial load down to zero load (also idling). In these characteristic map ranges, the engine is operated in a throttled manner. The suction pressure/negative pressure generated cannot be lowered arbitrarily. If it was lowered further in an effort to continue to operate the ideal low lambda value, then too small final compression pressures would occur. The consequence would be failure of self-ignition in the combustion chamber. Combustion does not take place any longer, and the engine would ultimately cease to operate (throttle down/stall).

Thus, there is a minimum intake pipe pressure defining the engine's misfire limit. This pressure depends on the compression of the engine employed and is therefore not indicated here. This minimum intake pipe pressure is reached in the lower partial load range. Generally, this is the case for a range between about 4 and 5 bar. Reducing the load further down to zero load inevitably results in a growing lambda value, i.e., a deviation from the ideal lambda value of ideal regeneration on demand. This situation is depicted in Figure 11 showing the example of a supercharged diesel engine. In this Figure, lambda grows from about 1.8 which is the ideal lambda value to about at least 5.5 at zero load.

The use of diesel particulate filters in vehicles will be an effective technique for exhaust-gas aftertreatment in the near future. As a result, it will be possible to almost completely filter out the particulates contained in the diesel exhaust gas. Filtration of the particulate matter, however, leads to a follow-on problem, i.e., progressive clogging of the filter with particulates. This is called increasing loading. This loading forms a resistance in the exhaust-gas line perceptible through increased backpressure. The backpressure makes exhausting of exhaust gas from the engine difficult, ultimately contributing to increased fuel consumption in driving operation. To keep this increase as small as
possible, the diesel particulate filter must be regenerated from time to time. To do so, the filter loading is burned off. This regeneration is achieved using different strategies known to the art. However, it is a problem to ensure regeneration for every user, i.e., for every mode of operation. When a vehicle is permanently operated at lower partial load only, regeneration cannot be performed without any additional modifications because the exhaust-gas temperature which is the decisive quantity for regeneration is permanently too low. Therefore, solutions producing a temperature-raising effect are needed.

The principle of regeneration using lambda variation presented above is a modification affecting the engine. The diesel engine operating in a quality-controlled fashion in normal operation is operated as a quantity-controlled engine during the actively initiated regeneration phase similar to a gasoline engine. This means, inter alia, that the engine can be operated at a constant lambda value. The resultant advantage is a considerably increased exhaust-gas temperature at partial load, as the high excess of air from normal operation is no longer present.

Implementation and use of this lambda variation permits vehicles which are permanently used at partial load to also perform a regeneration phase on the diesel particulate filter. Thus, a regeneration strategy not relying on additional units (such as a burner system) is provided. This can involve other advantages concerning production expenditure and manufacturing cost.

Using the principle of lambda variation explained above, regeneration conditions on the diesel particulate filter may also be created at lower partial load of the engine. This engine modification may also be supported by bypassing the intercooler, if provided in supercharged diesel engines. In this case, the air flow rate supplied to the engine is not cooled but enters the engine at a correspondingly higher temperature. Thus, the exhaust-gas temperatures will be higher compared to using lambda variation alone. Moreover, the supplied air flow may be heated. This increases the exhaust-gas
temperature even further. From an engine point of view, fuel delivery adjustment and/or re-injection may also be performed. Finally, exhaust-gas recirculation may also be employed.
Claims

1. A method of regenerating a diesel particulate filter in an exhaust-gas purification system of a diesel engine, wherein during regeneration the substantially highest possible exhaust-gas temperature for the corresponding operating point of the diesel engine is reached by adjusting the ratio of air to fuel.

2. The method according to claim 1, wherein the ratio of air to fuel (lambda value) is minimized to achieve the highest possible exhaust-gas temperature.

3. The method according to any of the preceding claims, wherein during regeneration the ratio of air to fuel is maintained substantially constant over the major part of the load range.

4. The method according to any of the preceding claims, wherein during regeneration the engine is operated at full load.

5. The method according to any of the preceding claims, wherein the engine is a diesel engine with or without supercharging.

6. The method according to any of the preceding claims, wherein the adjustment of the ratio of air to fuel is performed by means of a throttle valve for the supply and intake air, respectively.

7. The method according to claim 6, wherein the throttle valve restricts the air flow rate at partial load of the engine.
8. The method according to claim 5, 6 or 7, wherein the adjustment of the ratio of air to fuel in a supercharged diesel engine is further performed by a system for varying the boost pressure.

9. The method according to any of claims 1 to 5, wherein the adjustment of the ratio of air to fuel in a supercharged diesel engine is performed by means of a regulating valve downstream of the supercharger, the regulating valve closing or restricting the air passage to the engine and simultaneously opening a passage to the environment.

10. The method according to any of claims 1 to 5, wherein the entire air flow rate in a supercharged diesel engine is restricted upstream of the supercharger such that the resulting boost pressure is varied through the air flow entering the supercharger.

11. The method according to any of the preceding claims, wherein the air flow supplied to the engine is heated.

12. The method according to any of the preceding claims, wherein, in a supercharged diesel engine having an intercooler downstream of the supercharger, the intercooler is bypassed during regeneration.

13. The method according to any of the preceding claims, wherein the diesel particulate filter is catalytically coated.

14. Device for regenerating a diesel particulate filter in an exhaust-gas purification system of a diesel engine, particularly for performing the method according to any of the preceding claims, which is adapted to achieve the substantially highest possible exhaust-gas temperature for the corresponding operating point of the die-
sel engine during regeneration by adjusting the ratio of air to fuel.
Fig. 5

Pressure loss/exhaust backpressure in urban traffic

Fig. 6

Pressure loss/exhaust backpressure in combined operation
Urban and extra-urban operation
Fig. 9

Regeneration on demand

Normal operation

Temperature

Load/torque

Lambda

Fig. 10

Temperature in urban operation

Temperature with lambda variation

Temperature in normal operation

Time
Fig. 11

Intake pipe pressure and lambda vs. load (constant engine speed)

Lambda during real regeneration on demand
Lambda during normal operation
Lambda during ideal regeneration on demand
Intake pipe pressure during normal operation
Intake pipe pressure during real regeneration on demand
Intake pipe pressure during ideal regeneration on demand
Minimum intake pressure
Ambient pressure

Load
**A. CLASSIFICATION OF SUBJECT MATTER**

| IPC    | FOIN3/023 | FOIN9/00 |

According to International Patent Classification (IPC) or to both national classification and IPC.

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

| IPC    | FOIN |

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched.

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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