EXPERIMENTAL STUDY ON EXHAUST GAS AFTER TREATMENT USING LIMESTONE

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In this study a simple low-cost exhaust gas after-treatment filter using limestone was developed and tested on a four cylinder DI diesel engine coupled with dynamometer under variable engine running conditions. Limestone was placed in cast iron housing through which exhaust gases passes. The concentration of both carbon dioxide and nitrogen oxides were measured with and without the filter in place. It was found that both pollutants were decreased significantly when the filter is in place, with no increase in the fuel consumption rate.

Key words: diesel engine, after treatment, limestone, NO\textsubscript{X} reduction

1. Introduction

Diesel engines are widely used for commercial and public transportation due to their good fuel efficiency and durability. However, diesel engine emissions are harmful to human health and to the environment and are targets for reduction [1]. Emission control regulations have been introduced in all industrialized countries in order to reduce the emissions of vehicles powered by internal combustion engines. The pollutants that are limited today are Hydrocarbons (HC), carbon monoxide (CO) oxides of nitrogen (NO\textsubscript{X}) and particulate matter (PM). Additional reduction in these emissions is mandatory to comply with upcoming stringent emission standards, such as EURO V, US 2010 as shown in Figure 1 [2].

The available methods of diesel engine emissions reduction include engine modification or improvement, using emulsified diesel fuel [3], increasing the boost pressure [4] and after-treatment of exhaust gas. There are many reports of oxidation catalysts in the exhaust system of diesel engines [5–8]. That caused significant reductions in HC, PM and CO with oxidation catalysts [5, 8]. However, the benefits are somewhat dependent upon engine loads/exhaust temperatures. The light-off temperature of diesel oxidation catalyst is usually around 200 °C [6–8].

The search for after-treatment of exhaust gas in diesel engines to reduce emissions has attracted increasing research efforts [2, 9–11]. Diesel engines represent the state of the art regarding fuel consumption. Within the last 15 years the diesel emissions were reduced by approx. 95% using mainly combustion optimization measures [9]. However, further improvements are necessary in the area of emission control focusing now on exhaust treatment components like filters and catalytic converters in order to reduce particulate and
NOX emissions. This requires further research and development in the area of emission control systems and components like filters, catalytic converters and sensors [2]. The combination of NOX storage and reduction catalyst (NSRC) and selective catalytic reduction (SCR) of NOX offers the potential to significantly increase the efficiency of NSRC-based exhaust gas after treatment systems [10]. A simple low-cost exhaust gas after treatment system called water-scrubbing and air-dilution to reduce exhaust odor and smoke of stationary DI diesel engines to acceptable level by water-scrubbing and air-dilution system was developed in Bangladesh [11]. Diesel exhaust was diluted with air and washed by sprayed water and passed through a silica gel-absorber. Moderate-to-strong exhaust odor reduced to almost no odor level and strong smoke level reduced to almost no smoke or very slight smoke level. Other emissions like carbon monoxide (CO), carbon dioxide (CO2) and oxides of nitrogen (NOX) were significantly reduced. Irritants in exhaust gases were also significantly reduced making almost no eye irritation. There was no fuel penalty by using the system as compared to without system. Development of a test cell setup for concurrent running of a real engine and a simulation of the vehicle system, and its use for investigating highly-dynamic engine-in-vehicle operation and its effect on diesel engine emissions is presented in this paper [12]. The results shed light on critical transients in a conventional powertrain and their effect on NOx and soot emissions. Measurements demonstrate very large spikes of particulate concentration at the initiation of vehicle acceleration events. The analysis of the energetic performances of structured and pelletized aftertreatment systems in flow-through and reverse-flow designs (passive and active flow control, respectively) for diesel internal combustion engines is carried out in this research [13]. To this purpose, the influence of the engine operating conditions on the system performances has been investigated adopting a one-dimensional transient model. Specifically, the thermal behavior and the fuel saving capability of several arrangements have been characterized. The analysis has shown that the active emission control system with pelletized design guarantees higher heat retention capability. Furthermore, the numerical model has revealed the significant influence of the solid and exhaust gas temperature on the energy efficiency of the aftertreatment systems and the large effect of exhaust mass flow rate and un-burned hydrocarbons concentration.

![Figure. 1. Emission control regulations for passenger cars in the European union.](image-url)
Limestone has been used by several researchers to reduce exhaust gas emissions [14, 15]. The emissions of particulate matter PM1 are effectively reduced by kaolin or limestone addition during O2/CO2 coal oxy-fuel combustion, because kaolin captures alkali metal compounds, while limestone reacts with sulfur effectively. In a coal-fired circulating fluidized bed combustor limestone addition at either position always results in a decrease in N2O and CO emissions and increases in NO/NOX emissions [14]. Potential of particle emission reduction from combustion of oat grain by addition of limestone or kaolin was the aim of the study done by Bäfver et al. [15]. Experiments were performed on a residential boiler, using filter sampling and low-pressure impactors to measure the mass and number concentrations and size distributions of the emitted particles. The particles and the bottom ash were subsequently analyzed for inorganic material.

In this project a limestone, which is a very common sedimentary rock of biochemical origin, was used as a main agent to reduce emissions such as NOX, and COX caused by diesel engines. The limestone was installed in a special box designed to prevent a high pressure drop. Several experiments were conducted to study the effect of using limestone on engine performance and exhaust gas emissions. To the best of the author knowledge this is the first work done to study the effect of implementing limestone as catalytic converter to reduce emissions from a diesel engine. The term “without limestone” implies that the engine was operated using the conventional catalytic converter. The term “with limestone” implies that the conventional catalytic converter was replaced by the limestone catalytic converter.

2. Experimental Setup and Procedure

2.1 Experimental Setup

A four cylinder Tempest Engine coupled with dynamometer was used for data collection. The engine is a water-cooled engine, naturally aspirated, four stroke, and direct injection (DI) diesel engine. The main engine specifications are given in Table 1. The engine is a completely self-contained test bed incorporating a swinging field DC dynamometer. The dynamometer which is capable of absorbing 22 kW (30 hp) is supplied in standard form for absorbing power only. The dynamometer casing is restrained by a combination of spring balance and masses where the spring balance is anchored to the overhead frame. Two stops restrict the movement of the dynamometer but when it is in use the torque arm should float between the stops. The engine speed was measured using a tachometer. The tachometer sends a constant infrared radiation signal that intercepts a reflector placed on the crank-shaft counting each revolution per minute. A suitable load (weighting pieces) to balance the engine and minimize the vibration of the engine was adjusted. To measure the exhaust gas emissions, a gas analyzer is used. The specifications of the gas analyzer are given in table 2. The values of voltage and ampere were taken by armature, also a multi-point thermometer was used to measure the values of inlet water, outlet water and exhaust temperatures.
Table 1: Engine Details

<table>
<thead>
<tr>
<th>Name of the engine</th>
<th>Tempest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force arm</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Bore and stroke</td>
<td>72.25 mm ×88.2 mm</td>
</tr>
<tr>
<td>Connecting rod length</td>
<td>156.0 mm</td>
</tr>
<tr>
<td>Swept volume</td>
<td>1447 cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>22:1</td>
</tr>
<tr>
<td>Orifice area</td>
<td>0.00181 m²</td>
</tr>
<tr>
<td>Injection timing</td>
<td>15° CA (deg crank angle) BTDC</td>
</tr>
<tr>
<td>Maximum power</td>
<td>22 kW at 3000 rpm</td>
</tr>
</tbody>
</table>

Table 2: gas analyzer specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide (Infrared)</td>
<td>0.01%</td>
<td>±5% of reading *1 ±0.06% volume *1</td>
<td>0-10% Over-range 20%</td>
</tr>
<tr>
<td>Oxygen (Fuel Cell)</td>
<td>0.01%</td>
<td>±5% of reading *1 ±0.1% volume *1</td>
<td>0-21%</td>
</tr>
<tr>
<td>Hydrocarbon (Infrared)</td>
<td>1 ppm</td>
<td>±5% of reading *1 ±12% volume *1</td>
<td>0-5,000ppm, Over-range 20,000ppm</td>
</tr>
<tr>
<td>Carbon Dioxide (Infrared)</td>
<td>0.1%</td>
<td>±5% of reading *1 ±0.5% volume *1</td>
<td>0-16% Over-range 20%</td>
</tr>
<tr>
<td>NOx (Electro-Chemical)</td>
<td>1 ppm</td>
<td>0-4,000ppm ±4% or 25ppm *1 4,000-5,000ppm ±8% *1</td>
<td>0-5,000ppm</td>
</tr>
</tbody>
</table>

2.2 Limestone catalytic converter

Cast iron housing for the limestone was designed. The housing has 600 mm length, 100 mm diameter and 5 mm thickness. It consists of a diffuser, a nozzle and the main cylinder. The main cylinder has 2 grooves with a width of 2 inch, each. The limestone is placed in these grooves as shown in Fig. 2. The limestone housing is connected to the engine manifold.
2.3 Procedure

The engine runs for a period of time until the water and lubricating oil have been brought to definite operating temperatures. Brake load is introduced and the throttle is opened to its widest setting. The test is started when the engine is operating in approximate temperature equilibrium. The engine speed then was varied from 2000 to 3000 rpm with an increment of 250 rpm. Voltage, current, time needed to consume 50 ml of fuel and weights added to balance the dynamometer, are recorded at each engine speed. Fuel flow rate is measured by simple gravity pipette type gauge with two bulbs calibrated for 50 and 100 ml. The field control unit is enclosed in a steel cabinet located on a platform in the overhead frame. The control unit is for use with 220/240 V single phase 50/50 HZ supplies. The instruments incorporated in the control are voltmeter; ammeter; Field voltage control and a Tachometer. The entire procedure is repeated three times using the conventional catalytic converter and the limestone catalytic converter. From the collected data, brake power, brake torque, BSFC and thermal efficiency are calculated.

The torque (T) produced by drive –shaft is opposed by a turning moment equal to the product of the length of the moment arm (R) and the coupling force (F) according to eq. 1

\[ T = R \times F \]  

(1)

Where moment arm=0.4 m

Equation 2 can be used to calculate the brake power, BP,

\[ BP = \frac{2 \pi N T}{60000} \]  

(2)

Where N is the engine speed. After that Brake Specific Fuel Consumption (BSFC) has been calculated according to eq.3
Where is shown in calculated according to eq. 4

\[ \dot{m}_f = \frac{\eta_{SG}}{c} \]  

(4)

The thermal efficiency of the engine is the ratio between the output and input power

\[ \eta_{ther} = \frac{\text{Power}_{out}}{\text{Power}_{in}} \]

Where \( \text{Power}_{out} = BP \); \( \text{Power}_{in} = \dot{m}_f \times \text{calorific value} \)

Where calorific value is 39000 kJ/kg for diesel

These experiments are performed with and without using the limestone filter. Gas analysis included measurement of carbon dioxide CO\(_2\), carbon monoxide CO, nitric oxide NO, nitrogen oxides NO\(_X\) and oxygen O\(_2\). Figure 3 shows limestone before and after running the experiment.

![Limestone before and after running the experiment](image)

**Figure 3: Limestone before and after running the experiment**

3. **Results and discussion**

The purpose of this study is to show the effect of using limestone on exhaust gas emissions taking into consideration the effect of limestone on the engine performance. The results obtained are potted in Figures. 4-9. In Figures 4-6, the engine performance is shown for both cases with
and without using limestone filter. Figures 4 to 6 were presented in this work to prove that there was no fuel penalties by using limestone filter to reduce exhaust gas emissions as compared to without limestone filter. Figures 7-9 show the effect of using limestone on exhaust gas emissions.

The brake power output versus engine speed over the range from 2000 to 3000 rpm for both cases with and without using limestone filter is shown in Figure 4. It is clear that the brake power increases with velocity in both cases. Only in the case of using a limestone filter the engine produced more brake power at the specified engine speeds. This is due to the enhancement of the exhaust system leading to a decrease in the pressure drop.

![Figure 4: Effect of limestone on brake power due to engine speed](image)

Figure 4 shows the effect of using limestone filter on the BSFC. As indicated the BSFC drops down from 320 down to 300 g/kWh when the filter is used, with the engine runs at a speed of 2000 rpm. On average, using limestone filter leads to a 3 -5% decrease in the BSFC when the filter is in place. Finally, the minimum values of the BSFC were found to be 260 and 280 g/kWh with and without the filter in place respectively and a speed of 2750 rpm.

The relationship between thermal efficiency and engine speed is shown in Fig. 6. The results indicate that using limestone filter improved the thermal efficiency of the engine. A maximum efficiency value of 37% was achieved when limestone filter is used at an engine speed of 3000 rpm, while a maximum engine efficiency without limestone filter in place was 33% at 2750 rpm.
Figure 7 shows CO\textsubscript{2} emission variation engine brake power. At a maximum brake power, a maximum CO\textsubscript{2} concentration (8.5\%) is produced without using limestone filter. Installing limestone filter reduces the CO\textsubscript{2} emission to 2.2\% at the same maximum brake power. CO\textsubscript{2} production is directly proportional to fuel consumption. With the increase in brake power, fuel consumption was also increased producing higher amounts of CO\textsubscript{2}. On average, installing limestone filter reduces CO\textsubscript{2} emission by about 85 percent over the whole operation range. Also
it can be noted that the percentage of CO\textsubscript{2} reduction is inversely related to engine brake power where more CO\textsubscript{2} is produced at higher brake power values. The reduction of CO\textsubscript{2} is attributed to the ability of limestone to absorb CO\textsubscript{2} from the flue gases producing calcium hydrogen carbonate

\[
\text{CaCO}_3(s) + \text{H}_2\text{O}(l) + \text{CO}_2(g) \rightarrow \text{Ca(HCO}_3\text{)}_2(aq)
\]

![Figure 7: Effect of limestone on CO\textsubscript{2} due to engine speed](image)

Figures 8 and 9 summarize the effect of introducing limestone filter on NO and NO\textsubscript{X}. It is clear that installing the limestone filter reduces both NO and NO\textsubscript{X}. NO\textsubscript{X} production is directly proportional to temperature if the engine is not starved for oxygen. With the increase speed, temperature was also increased producing higher amounts of NO\textsubscript{X}, which increased from 288 ppm at 2000 rpm to 416 ppm at 3000 rpm for the case of not using limestone filter. Installing the limestone filter reduced NO and NO\textsubscript{X} on the average by 65 % and 60%, respectively. The reduction of both NO and NO\textsubscript{X} is inversely related with speed. Limestone reacts with NO to produce calcium nitrite Ca(NO\textsubscript{2}).

\[
\begin{align*}
\text{CaCO}_3(s) + 2\text{NO}(g) + \frac{1}{2}\text{O}_2(g) & \leftrightarrow \text{Ca(NO}_2\text{)}_2(s) + \text{CO}_2(g) \\
\text{Ca(OH)}_2(s) + 2\text{NO}(g) + + \frac{1}{2}\text{O}_2(g) & \leftrightarrow \text{Ca(NO}_2\text{)}_2(s) + \text{H}_2\text{O}(l)
\end{align*}
\]
4. Conclusions

This study introduced a simple low cost technique to reduce diesel engine exhaust gases. A limestone filter was designed, manufactured and tested on a four cylinder Tempest DI diesel Engine coupled with dynamometer. The installation of the limestone filter results in reducing
both NOx and CO2 by 60% and 85% respectively. There was no fuel penalty by using the limestone filter.

5. References


