EXPERIMENTAL STUDY ON EXHAUST GAS AFTER TREATMENT USING LIMESTONE

by

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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 direct injection 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_x reduction*

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_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 fig. 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].

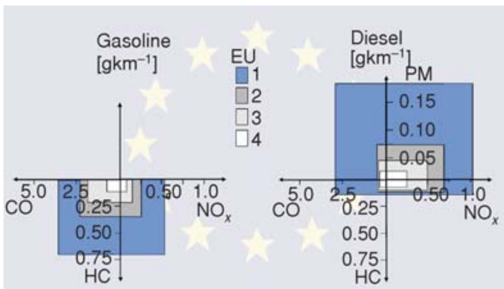

Figure. 1. Emission control regulations for passenger cars in the European union

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 re-

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garding 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 NO_x 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 NO_x storage and reduction catalyst (NSRC) and selective catalytic reduction (SCR) of NO_x 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 direct injection (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 CO, carbon dioxide (CO_2), and NO_x 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 NO_x 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 1-D 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 HC concentration.

Limestone has been used by several researchers to reduce exhaust gas emissions [14, 15]. The emissions of PM are effectively reduced by kaolin or limestone addition during O_2/CO_2 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 N_2O and CO emissions and increases in NO/NO_x 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 Bafver *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 NO_x, and CO_x 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 lime stone" 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 lime stone catalytic converter.

Experimental set-up and procedure

Experimental set-up

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 DI diesel engine. The main engine specifications are given in tab. 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 tab. 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

Name of the engine	Tempest
Force arm	0.4 m
Bore and stroke	72.25 mm × 88.2 mm
Connecting rod length	156.0 mm
Swept volume	1447 cm^3
Compression ratio	22:1
Orifice area	0.00181 m^2
Injection timing	15° CA bTDC
Maximum power	22 kW at 3000 rpm

Table 2. Gas analyzer specifications

Parameter	Resolution	Accuracy	Range
Carbon monoxide (infrared)	0.01%	±5% of reading·1 ±0.06% volume·1	0-10% over-range 20%
Oxygen (fuel cell)	0.01%	±5% of reading·1 ±0.1% volume·1	0-21%
Hydrocarbon (infrared)	1 ppm	±5% of reading·1 ±12% volume·1	0-5.000 ppm, over-range 20,000 ppm
Carbon dioxide (infrared)	0.1%	±5% of reading·1 ±0.5% volume·1	0-16% over-range 20%
NO_x (electro-chemical)	1 ppm	0-4.000 ppm ±4% or 25 ppm·1 4.000-5.000 ppm ±8%·1	0-5.000 ppm

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 two 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.

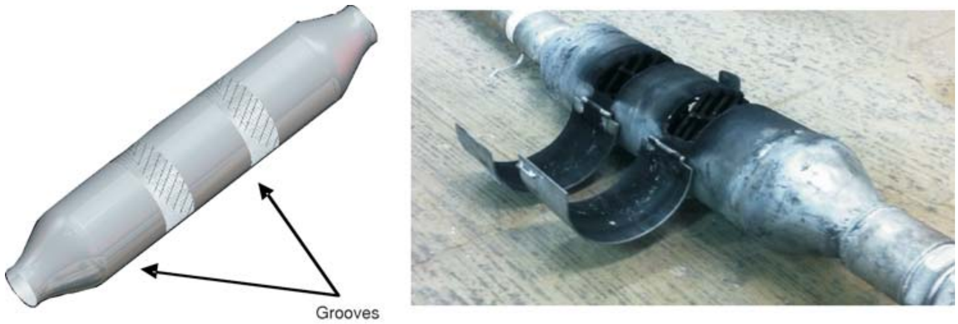

Figure 2. Limestone filter

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 (BP), brake torque, brake specific fuel consumption (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:

$$T = R \cdot F \tag{1}$$

where R = 0.4 m.

Equation 2 can be used to calculate the BP:

$$BP = \frac{2\pi NT}{60000} \tag{2}$$

where N is the engine speed. BSFC has been calculated according to eq. 3:

$$BSFC = \frac{\dot{m}_{\mathrm{f}}}{BP} \tag{3}$$

where $\dot{m}_{\mathrm{f}}$ is:

$$\dot{m} = \frac{V\rho}{t} \tag{4}$$

where ρ is the fuel density, V – the volume, and t – the time.

The thermal efficiency of the engine is the ratio between the output and input power η_{therm} = power$_{out}$/power$_{in}$ where power$_{out}$ = BP, power$_{in}$ = $\dot{m}_f \times$ 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 CO_2, CO, nitric oxide (NO), NO_x, and oxygen (O_2). Figure 3 shows limestone before and after running the experiment.

(a) Before the experiment (b) After the experiment

Figure 3. Limestone before and after running the experiment

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

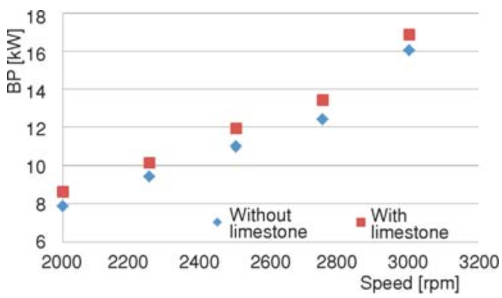

Figure 4. Effect of limestone on BP due to engine speed

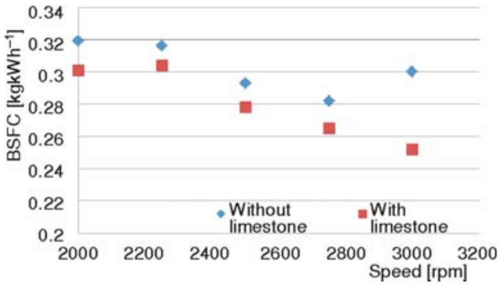

Figure 5. Effect of limestone on BSFC due to engine speed

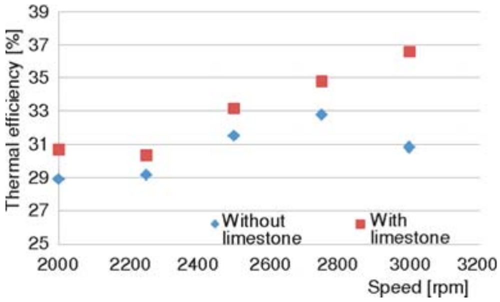

Figure 6. Effect of limestone on thermal efficiency due to engine speed

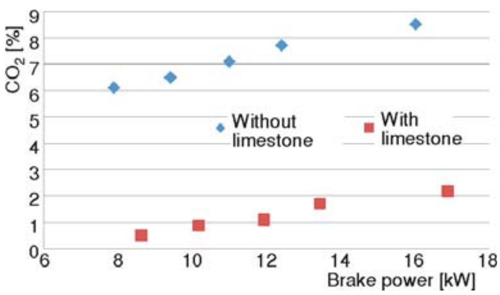

Figure 7. Effect of limestone on CO_2 due to engine speed

Figure 5 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_2 emission variation engine BP. At a maximum BP, a maximum CO_2 concentration (8.5%) is produced without using limestone filter. Instal- ling lime stone filter reduces the CO_2 emission to 2.2% at the same maximum BP. CO_2 production is directly proportional to fuel consumption. With the increase in BP, fuel consumption was also increased producing higher amounts of CO_2. On average, installing limestone filter reduces CO_2 emission by about 85% over the whole operation range. Also it can be noted that the percentage of CO_2 reduction is inversely related to engine BP where more CO_2 is produced at higher BP values. The reduction of CO_2 is attributed to the ability of limestone to absorb CO_2 from the flue gases producing calcium hydrogencarbonate:

$$CaCO_3(s) + H_2O\ (l) + CO_2(g) \rightarrow Ca(HCO_3)_2(aq)$$

Figures 8 and 9 summarize the effect of introducing limestone filter on NO and NO_x. It is clear that installing the limestone filter reduces both NO and NO_x. NO_x production is directly proportional to temperature if the engine is not starved for O_2. With the increase speed, temperature was also increased producing higher amounts of NO_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_x on the average by 65% and 60%, respectively. The reduction of

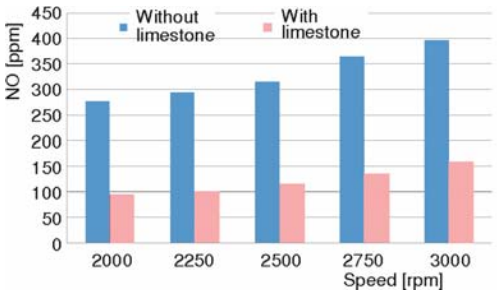

Figure 8. Effect of limestone on NO_x due to engine speed

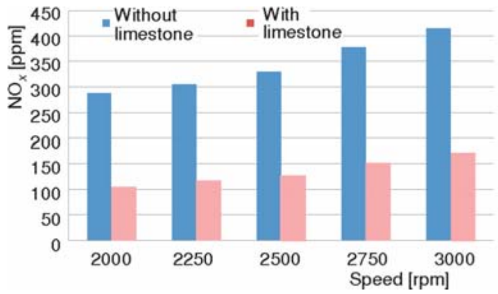

Figure 9. Effect of limestone on NO due to engine speed

both NO and NO_x is inversely relate with speed. Limestone reacts with NO to produce calcium nitrite $Ca(NO_2)$:

$$CaCO_3(s) + 2NO(g) + \frac{1}{2}O_2(g) \leftrightarrow Ca(NO_2)_2(s) + CO_2(g)$$

$$Ca(OH)_2(s) + 2NO(g) + \frac{1}{2}O_2(g) \leftrightarrow Ca(NO_2)_2(s) + H_2O(l)$$

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 NO_x and CO_2 by 60% and 85%, respectively. There was no fuel penalty by using the limestone filter.

Nomenclature

BP – brake power, [kW]
BSFC – brake specific fuel consumtpion, [$gkW^{-1}h^{-1}$]
CV – calorific value, [$kJkg^{-1}$]
F – coupling force, [N]
$\dot{m}_f$ – mass flow rate, [kgs^{-1}]
N – engine speed, [rpm]
R – moment arm, [m]
T – torque, [Nm]
t – time, [s]
V – volume, [m^3]

Greek symbol

ρ – density, [kgm^{-3}]

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