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An experimental study of the effect of a homogeneous combustion catalyst on fuel consumption and smoke emission in a diesel engine

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ABSTRACT

This paper presents the results of an experimental investigation into the influence of a ferrous picrate based homogeneous combustion catalyst on fuel consumption and smoke emission of a laboratory diesel engine. The catalyst used in this study was supplied by Fuel Technology Pty. Ltd. The fuel consumption and smoke emission were measured as a function of engine load, speed and catalyst dosing ratio. The brake specific fuel consumption and smoke emission decreased as the dosing ratio of the catalyst doped in the diesel fuel increased. At the catalyst dosing ratio of 1:3200, the brake specific fuel consumption was reduced by from 2.1% to 2.7% and the smoke emission was reduced by from 6.7% to 26.2% at the full engine load at speeds from 2600 rpm to 3400 rpm. The results also indicated that the potential of the fuel saving seems to be greater when the engine was run under light load.

1. Introduction

Due to an increase in the price of petroleum and more stringent emissions regulations, many studies have been conducted to develop cleaner and more efficient diesel engines over the past few decades [1–7]. Adding additives into diesel without the modification of diesel engines is an emerging area which is considered to be beneficial to the performance of diesel engine in terms of fuel consumption and emissions [8]. Homogeneous combustion catalysts are those additives which are dissolved into diesel fuels homogeneously to play a catalytic role during the engine combustion process. They are often added into diesel in tiny amounts at ppm levels, which means these catalysts would not alter the fuel specifications and generate significant secondary emissions.

Two groups of combustion catalysts are often used: metal-containing catalysts and ash-free catalysts [9]. Compared to the ash-free catalysts, metal-containing compounds are claimed to be more effective [9]. A number of metal ions are found to be able to reduce the fuel consumption and engine emissions such as Iron [10,11], Cerium [12], Platinum [13], Copper [14], Barium [15], Sodium [16] and Manganese [17]. Kelso et al. [18] studied the effect of platinum-based additives on diesel engines and the results in the literature indicate that the use of catalysts reduced CO and HC emissions and improved the engine fuel consumption, which is often characterized by the brake specific fuel consumption. The brake specific fuel consumption is defined as the rate of the fuel consumption divided by the power produced, allowing the energy conversion efficiency of different engines to be compared directly [1]. Such work was continued by Caton et al. [19]. After 236 h of engine operation, the brake specific fuel consumption was shown to be reduced by an average of 9% at 1300 rpm and 5% at 1600 rpm with an uncertainty of 1.7%. May et al. [20] studied the influence of an iron-magnesium catalyst on diesel engines and the measurements showed that the catalyst promoted more complete and efficient combustion in the engines resulting in higher power output and lower brake specific fuel consumption. Sajith et al. [21] studied the effect of Cerium-based catalysts on the performance of diesel engines and found that the application of the catalyst reduced the brake specific fuel consumption and the emissions of HC and NO_x. Keskin et al. [22] studied biodiesel combustion with Mn and Mo based additives in diesel engines and their results indicated that the CO emissions and smoke opacity decreased up to 64.3% and 30.9% respectively. Many studies of the influences of homogeneous combustion catalysts have been continuing.

The homogeneous combustion catalyst used in the present study was supplied by the Fuel Technology Pty Ltd in Australia. The catalyst is a ferrous picrate based compound. It was found to reduce the brake specific fuel consumption and smoke emission based on field trials and laboratory observations [8,23]. It was also claimed to

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Table 1
Specifications of Yanmar L48AE-DG diesel engine.

Engine type	Four stoke, direct injection, single cylinder
Bore (mm) × Stroke (mm)	70 × 55
Total displacement (L)	0.211
Compression ratio	19.9
Injection Timing	14 ± 1 BTDC (Before Top Dead Centre)
Maximum output (kW)	3.5

improve engine performance such as less abrasive wear, less carbon deposit and no detrimental effect on fuel quality [23]. However, the reported fuel savings and smoke reductions with the application of the catalyst in diesel engines were inconsistent and discrepant. In order to systematically study the effects of the homogeneous combustion catalyst on the brake specific fuel consumption and smoke emission as a function of catalyst dosing ratio, engine load and speed, experimental tests were performed on a single cylinder compression ignition engine in the present study.

2. Experimental setup

The experiments were conducted using an air-cooled, single cylinder, four-stroke diesel engine. Major specifications of the engine are listed in Table 1.

The engine was mounted on an automated bed and coupled with an eddy-current dynamometer which was equipped with a load cell for engine torque measurement. There were two sensors placed in the load cell, one for engine torque and the other for engine speed. These signals were fed into the controller through which the operator can set speed and load of the dynamometer. Coolant and lube-oil systems were assured by electronically driven pumps to control the operation temperature of the dynamometer and engine. Instantaneous engine oil temperature, engine cylinder head temperature and intake air temperature were recorded and acquired by a computer to monitor combustion quality within the engine. A schematic diagram of the engine test bench is illustrated in Fig. 1.

Table 2
Properties of diesel fuel.

Fuel Parameters	Caltax No.2 Diesel Fuel	Analytical Method
Viscosity, cSt (@ 40 °C)	2.03	ASTM D445
Flash Point (°C)	80	ASTM D93
Pour Point (°C)	−10	ASTM D97
Distillation Range (°C)	180–360	ASTM D86
Density, g/mL (15 °C)	0.8435	ASTM D1298
Sulfur Content (ppm)	<10	ASTM D1266

A 1 L tank and a digital weighing scale on the top deck of the fuel system frame measured the amount of fuel consumed at a fixed time interval of engine operation (5 min in the present experimentation). The fuel tank was refilled automatically from a fuel reservoir of 4 L in volume. The digital scale was connected to the data acquisition system so that the brake specific fuel consumption during each test can be calculated and displayed on a computer. Instantaneous pressure within the cylinder, fuel injection pressure and needle lift were measured by Kistler piezoelectric sensors. The cylinder head temperature, dynamometer coolant temperature and exhaust gas temperature were measured by thermocouples. All these signals were connected to the input of an A/D board installed on an IBM compatible Pentium PC. This board can acquire input data at a high rate which was capable of recording these high frequency engine signals with an acceptable resolution.

A Bosch RTM 430 infrared opacimeter was used to measure the smoke level with the degree of opacity to which the light is weakened or absorbed by soot particles.

3. Experimental procedure

Caltax No.2 diesel was used as the baseline fuel and its specifications are listed in Table 2. The catalyst dosing ratio is defined as a ratio between the amount of the catalyst and the amount of the diesel by volume. The dosing ratios of 1:5000, 1:3200, 1:2000, and 1:1000 were used in the present study.

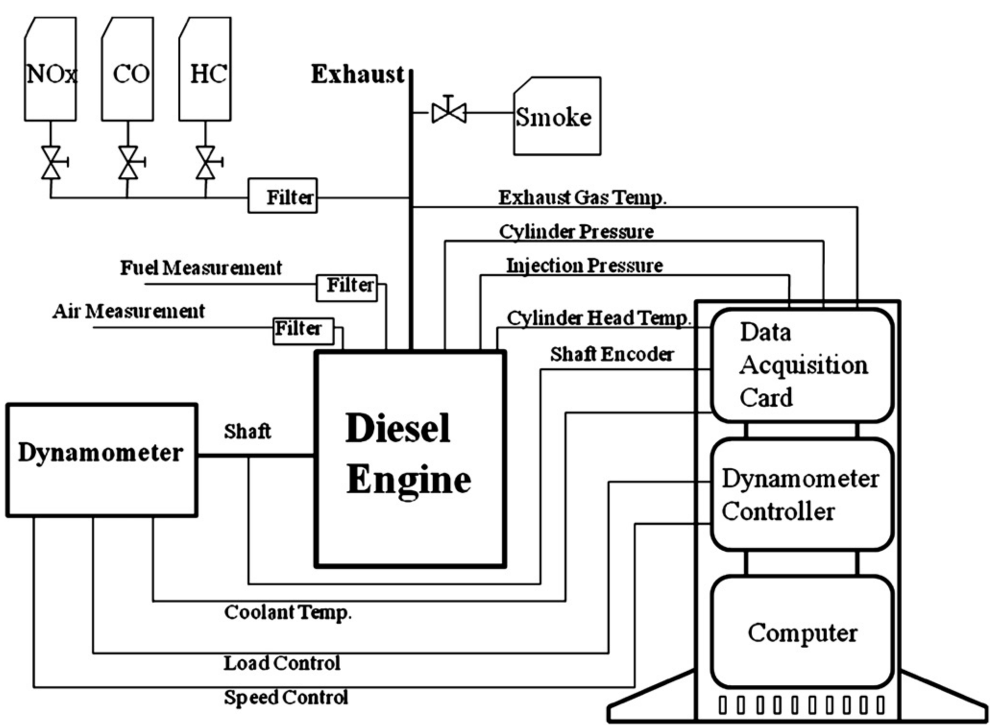

Fig. 1. A schematic diagram of the diesel engine test bench.

In order to systematically study the ability of the FPC-3 catalyst to decrease the brake specific fuel consumption and reduce smoke emission as a function of catalyst dosing ratio, engine load and speed, the following experimental procedure was performed:

1. A series of tests were conducted using each of the above catalyst dosing ratios with the engine working at a speed of 3000 rpm and brake mean effective pressure (BMEP) of −0.43 MPa.
2. A series of tests were conducted using pure diesel and diesel doped with the catalyst at a dosing ratio of 1:3200 with the engine working under four load conditions corresponding to approximately 25%, 50%, 75% and 100% of the full load at a speed of 3000 rpm.
3. A series of tests were conducted using pure diesel and diesel doped with the catalyst at a dosing ratio of 1:3200 with the engine working at speeds from 2600 rpm to 3400 rpm with a 200 rpm interval under full loads conditions, which are 0.4 MPa, 0.4 MPa, 0.43 MPa, 0.43 MPa, and 0.42 MPa for speeds 2600 rpm, 2800 rpm, 3000 rpm, 3200 rpm and 3400 rpm, respectively.

All experimental work started with the investigation into the engine running on pure diesel fuel in order to determine the engine's brake specific fuel consumption and smoke emission level, forming the baseline that was compared with the corresponding cases when applying the homogeneous combustion catalyst in the diesel engine. The same procedure was repeated for each fuel with a different catalyst dosing ratio while maintaining the same operating conditions. At each fuel change with a different catalyst dosing ratio, the engine was left to run for at least 30 min to purge the remaining previously tested fuel in the engine's fuel system. In each test, the brake specific fuel consumption (BSFC) and smoke emission were measured and the measurements were repeated for five times. All results presented in this research were obtained from the average of the five repeated measurements with error bars showing the standard deviation of these measurements.

4. Results and discussion

4.1. Brake specific fuel consumption

The plots of the brake specific fuel consumption at an engine speed of 3000 rpm and engine BMEP of 0.43 MPa as a function of the catalyst dosing ratio are shown in Fig. 2. It is observed that the application of the homogeneous combustion catalyst reduces the brake specific fuel consumption. At the 1:3200 catalyst dosing ratio, the mean brake specific fuel consumption decreases from 320.9 g/kW h to 314.2 g/kW h, reaching 2.1% of fuel saving. It is also found that the brake specific fuel consumption decreases with increasing the catalyst dosing ratio but the level of fuel saving is not linearly proportional to the catalyst dosing ratio. When the catalyst dosing ratio is greater than 1:3200, increasing catalyst dosing ratio does not change the brake specific fuel consumption significantly any more.

To determine whether the effect of the different catalyst dosing ratio on the brake specific fuel consumption were statistically significant, a statistical analysis was conducted by software SPSS (SPSS Inc, Chicago). The procedure was consisted of an one-way analysis of variance (ANOVA) and Fisher's least significant difference (LSD) analysis [24]. A statistical level of significance was defined by a (p) value less than or equal to 0.05 which would indicate that the mean value of at least one of the fuels was not equal to the others. Statistical non-significance was defined by (p) value greater than 0.05.

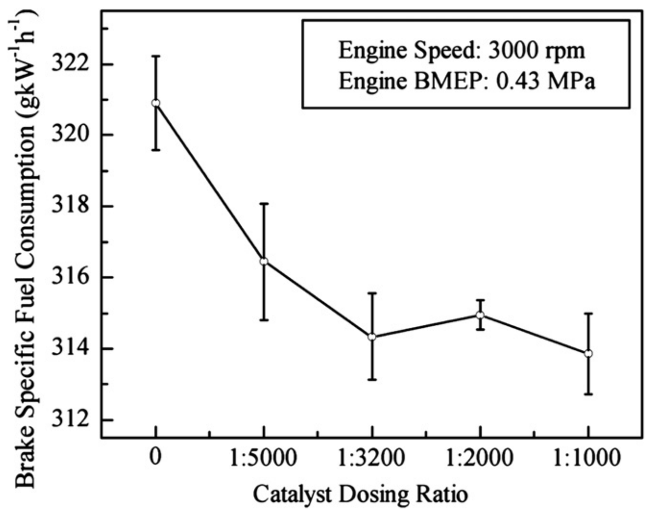

Fig. 2. Effect of the catalyst dosing ratio on the brake specific fuel consumption.

The statistical results are presented in Table 3 including the differences in mean values of the brake specific fuel consumption of any two compared fuels, standard errors and the associated p value. It can be seen that the differences between the mean values of BSFC of pure diesel and diesel dosed with the catalyst were greater than 4.47 with standard deviations of less than 0.84 and p-values of less than 0.05. This suggests that there are statistically significant difference in the brake specific fuel consumption between pure diesel and diesel dosed with the catalyst. It is also seen from the p-value that the brake specific fuel consumption does not change significantly when the catalyst dosing ratio is greater than 1:3200.

Fig. 3 illustrates the effect of the catalyst on the brake specific fuel consumption at various engine loads at a constant engine speed of 3000 rpm. It is seen that the brake specific fuel consumption decreases with increasing engine load. The higher the engine load, the higher the gas temperature in the cylinder and the better the fuel rich mixture combustion conditions, leading to higher energy conversion efficiency and lower brake specific fuel consumption. With the homogeneous combustion catalyst added in the diesel, the brake specific fuel consumption decreases significantly under all tested engine load conditions with fuel saving ranging from 2.2% to 2.4%. The greatest improvement is obtained when the engine was run at light load, with the brake specific fuel consumption dropping from 451.8 g/kW h to 440.8 g/kW h under the engine load of 0.17 MPa. Under the light load

Table 3
Results of AVOVA and LSD analysis.

Catalyst Dosing ratio (A)	Catalyst Dosing ratio (B)	Difference in mean values of BSFC (A-B)	Standard error	p-Value
Pure Diesel	1:5000	4.47	0.79	<0.0001
	1:32,000	6.58	0.75	<0.0001
	1:2000	5.96	0.84	<0.0001
	1:1000	7.05	0.69	<0.0001
1:5000	1:3200	2.1	0.81	0.016
	1:2000	1.49	0.9	0.112
	1:1000	2.58	0.76	0.003
1:3200	1:2000	−0.61	0.86	0.485
	1:1000	0.47	0.72	0.523
1:2000	1:1000	1.08	0.82	0.199

(Note: Column 3 refers to the difference between the mean values of BSFC of the two fuels compared. P-Value indicates the significance of the difference at the 95% confidence level).

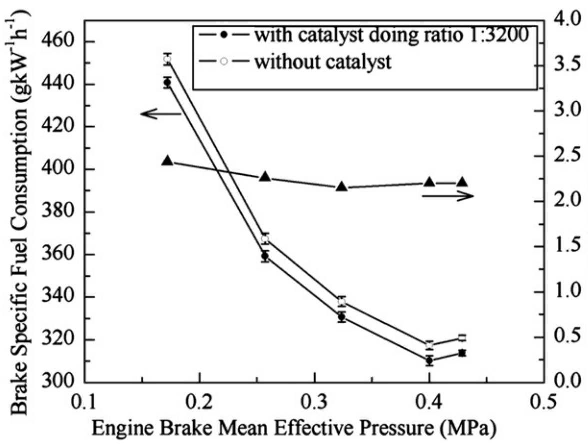

Fig. 3. Brake specific fuel consumption for pure diesel and diesel dosed with the catalyst ratio of 1:3200 under different loads conditions at engine speed of 3000 rpm.

conditions, the ability of the homogeneous combustion catalyst to promote ignition and combustion of fuel mixture seems to be stronger. As a result, the influence of homogeneous combustion catalyst on the brake specific fuel consumption was more significant.

Fig. 4 shows the brake specific fuel consumption of the tested engine with and without the catalyst dosed in the diesel at engine speeds from 2600 rpm to 3400 rpm with a 200 rpm interval under full loads conditions. The catalyst dosing ratio was 1:3200. It is evident that the homogeneous combustion catalyst reduces the brake specific fuel consumption regardless of engine speed with fuel saving ranging from 2.1% to 2.7%. It is observed that the lower the engine speed, the greater the fuel saving, which implies that the benefit of adding the homogeneous combustion catalyst is more significant when the engine operates in the region of low speed. With the addition of the catalyst dosing ratio of 1:3200, the brake specific fuel consumption decreases from 376.3 g/kW h to 366.2 g/kW h with 2.7% fuel saving at the engine speed 2600 rpm and from 325.2 g/kW h to 318.6 g/kW h with 2.1% fuel saving at the engine speed of 3200 rpm.

Fig. 5 shows the effect of the running time on the brake specific fuel consumption under the engine load of 0.4 MPa and speed of 3000 rpm with and without the catalyst. In this set of tests, the engine was initially run with Caltex No.2 diesel without being dosed with the catalyst for 150 min before switching to the fuel dosed with the catalyst with dosing ratio 1:3200 catalysts for

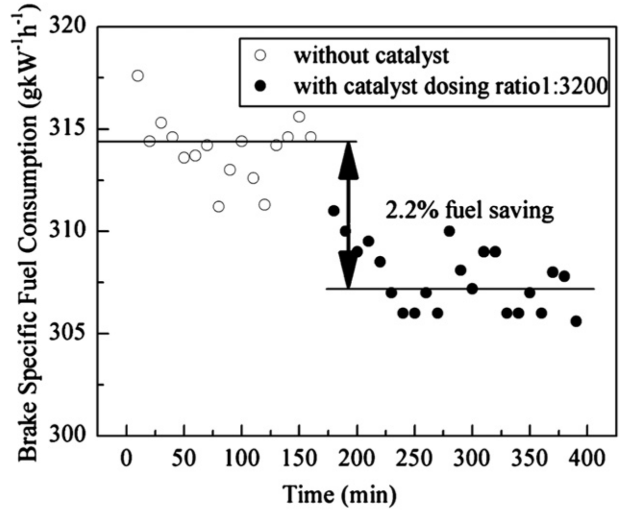

Fig. 5. Brake specific fuel consumption for pure diesel and diesel dosed with the catalyst ratio 1:3200 under engine of 0.4 MPa and engine speed of 3000 rpm.

250 min without stopping the engine. During the entire test period, the engine condition was kept constant and stable. From Fig. 5, it can be seen that the mean value of brake specific fuel consumption decreased from 314.1 g/kW h for pure diesel (with a standard deviation 1.5) to 307.1 g/kW h for diesel dosed with the catalyst at the dosing ratio of 1:3200 (with a standard deviation 1.6), with a 2.2% fuel saving -. It is also worth mentioning that the engine reached a stable condition in terms of the brake specific fuel consumption within half an hour after switching from the pure diesel to diesel dosed with the catalyst. Extending the test time does not change the brake specific fuel consumption significantly in this study. Therefore, when the engine was switched from one condition to another condition, data was only collected for analysis after half an hour later.

4.2. Smoke emission

The effect of the homogeneous combustion catalyst on the smoke emission was indicated by the smoke reduction ratio which was defined using the following formula:

$$\eta = (\omega_1 - \omega_2)/\omega_1 * 100\% \quad (1)$$

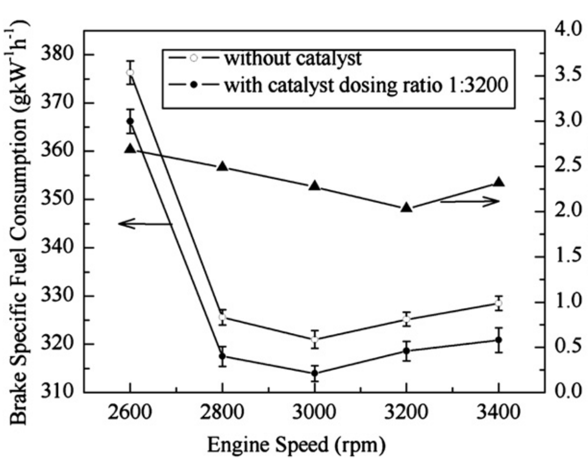

Fig. 4. Brake specific fuel consumption for pure diesel and diesel dosed with the catalyst ratio of 1:3200 at various speed under full loads conditions.

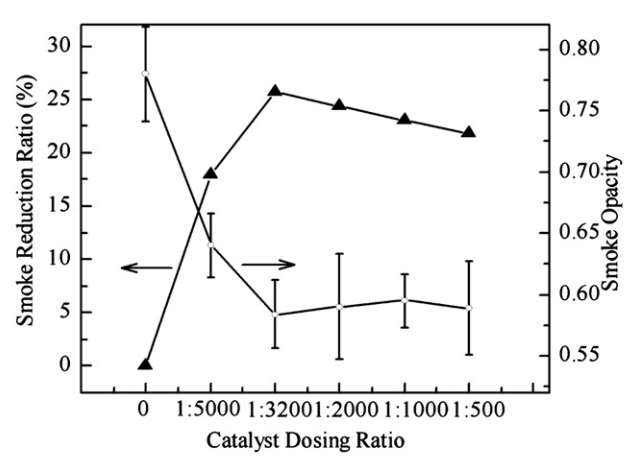

Fig. 6. Smoke opacity and smoke reduction ratio of engine at different catalyst dosing ratio at a constant speed of 3000 rpm and engine load of 0.43 MPa.

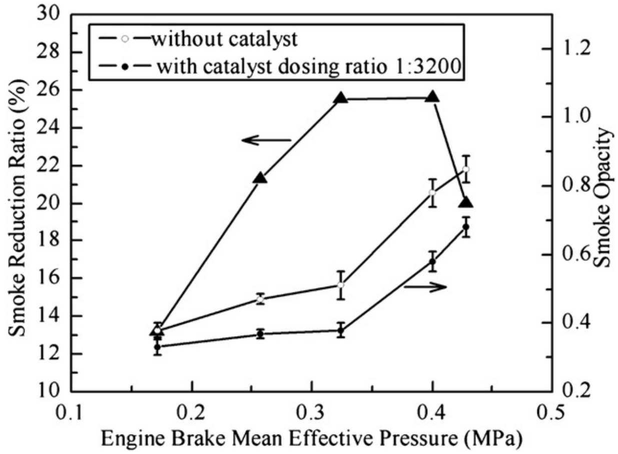

Fig. 7. Smoke opacity and smoke reduction ratio under different engine load condition with engine speed of 3000 rpm and catalyst dosing ratio of 1:3200.

where: η – smoke reduction ratio, ω_1 – smoke opacity of pure diesel, ω_2 – smoke opacity of diesel doped with the catalyst.

Fig. 6 presents the smoke reduction ratio of the diesel engine with different catalyst dosing ratio at a fixed engine speed of 3000 rpm and engine load of –0.43 MPa. It is seen that the homogeneous combustion catalyst is able to reduce the smoke emission significantly, with the smoke reduction ratio from 17.9% to 25.6%. When the catalyst was dosed at a dosing ratio of 1:3200, the mean value of smoke opacity dropped from 0.78 to 0.58, reaching a smoke reduction ratio of 25.6%. It is also clear that the smoke reduction ratio did not change remarkably when the catalyst dosing ratio increased above 1:3200 up to 1:500 if we take the measurement uncertainties into consideration. For instance, when the catalyst dosing ratio is greater than 1:3200, the smoke opacity only varied between 0.58 and 0.59.

Fig. 7 shows the results of the smoke emission and the smoke reduction ratio of the diesel engine under different engine load conditions at the constant engine speed of 3000 rpm when the diesel was dosed with the catalyst at the ratio of 1:3200. It is seen that the smoke emission increased with increasing engine load. The higher the engine load is, the higher is the brake specific fuel consumption, and hence, the higher is the total smoke emission. It is evident that the smoke is reduced by 13.2%–25.6% regardless of the engine load. The smoke reduction ratio seems to be greater at higher engine loads, which indicates that the catalyst is more effective to reduce smoke emission at higher engine load in this case.

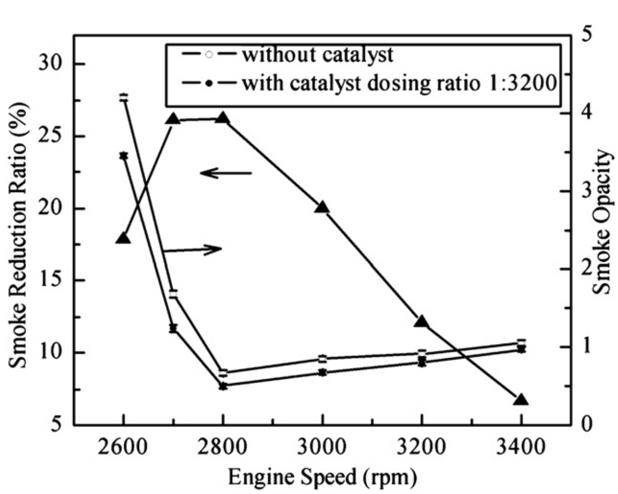

Fig. 8. Smoke opacity and smoke reduction ratio with engine speed under full loads conditions and catalyst dosing ratio of 1:3200.

Fig. 8 shows the result of the smoke reduction ratio when the engine speed varies from 2600 rpm to 3400 rpm under the full load conditions and the catalyst dosing ratio of 1:3200. It is seen that the smoke emission is higher at lower speed for the diesel fuel and the fuel dosed with the catalyst. It is shown that the smoke emission is reduced regardless of the engine speed and the highest reduction ratio reached 26.2% at engine speed of 2800 rpm. It is also observed that when the engine operated under low speeds (at speeds from 2600 rpm to 2800 rpm) the smoke reduction ratio is relatively higher compared to those when the engine was running at high speeds (at speeds from 2800 rpm to 3400 rpm).

5. Conclusions

The effect of the homogeneous combustion catalyst on the brake specific fuel consumption and smoke emission of a diesel engine was studied experimentally as a function of engine load, speed and catalyst dosing ratio.

The brake specific fuel consumption and the smoke emission were reduced with the use of the homogeneous combustion catalyst with respect to that of the pure diesel fuel but the level of fuel saving was not linearly proportional to the catalyst dosing ratio. When the catalyst dosing ratio was greater than 1:3200, increasing catalyst dosing ratio did not change the brake specific fuel consumption and the smoke emission significantly any more.

With the catalyst dosing ratio of 1:3200 in the fuel, the brake specific fuel consumption was reduced by 2.1%–2.7% under controlled engine conditions and the maximum fuel saving was achieved when the engine was run at speed of 2600 rpm under load of 0.4 MPa.

With the catalyst dosing ratio of 1:3200 in the fuel, the smoke emission was reduced by 6.7%–26.2% under the controlled engine conditions, and the maximum reduction ratio was obtained when the engine was run at speed of 2800 rpm under load of 0.4 MPa.

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