

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijhydene

The effect of reformer gas mixture on the performance and emissions of an HSDI diesel engine

Fanos Christodoulou*, Athanasios Megaritis

Centre for Advanced Powertrain and Fuels Research, School of Engineering and Design,
Brunel University, Uxbridge UB8 3PH, UK

ARTICLE INFO

Article history:

Received 10 January 2014

Received in revised form

28 February 2014

Accepted 7 March 2014

Available online 10 May 2014

Keywords:

Compression ignition engine

Diesel engine

Diesel reforming

Reformer gas mixture

Syngas

ABSTRACT

Exhaust gas assisted fuel reforming is an attractive on-board hydrogen production method, which can open new frontiers in diesel engines. Apart from hydrogen, and depending on the reactions promoted, the reformatte typically contains a significant amount of carbon monoxide, which is produced as a by-product. Moreover, admission of reformed gas into the engine, through the inlet pipe, leads to an increase of intake air nitrogen to oxygen ratio. It is therefore necessary to study how a mixture of syngas and nitrogen affects the performance and emissions of a diesel engine, in order to gain a better understanding of the effects of supplying fuel reformer products into the engine.

In the current research work, a bottled gas mixture with H₂ and CO contents resembling those of typical diesel reformer product gas was injected into the inlet pipe of an HSDI diesel engine. Nitrogen (drawn from a separate bottle) at the same volumetric fraction to syngas was simultaneously admitted into the inlet pipe.

Exhaust analysis and performance calculation was carried out and compared to a neat diesel operation. Introduction of syngas + N₂ gas mixture resulted in simultaneous reduction of the formation of NO_x and smoke emissions over a broad range of the engine operating window. Estimation of the bottled carbon monoxide utilisation showed that by increasing either the load or the speed the admitted carbon monoxide is utilised more efficiently. As a general rule, CO₂ emissions increase when the bottled carbon monoxide utilisation is approximately over 88%. Isolation of the H₂ and N₂ effect revealed that a CO diluted flame promotes the formation of smoke. When the intake air is enriched with syngas + N₂, an increase of engine speed results in reduction of maximum pressure rise rate (dp/da). The effect of load on dp/da varies depending on engine speed. Finally, the engine is more fuel efficient when running on neat diesel.

Copyright © 2014, The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications, LLC. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>).

* Corresponding author. Tel.: +44 7907 450 486.

E-mail addresses: fanos.christodoulou@brunel.ac.uk, fanosc@hotmail.com (F. Christodoulou).
<http://dx.doi.org/10.1016/j.ijhydene.2014.03.090>

0360-3199/Copyright © 2014, The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications, LLC. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>).

Introduction

The production of hydrogen is classified into three categories: thermochemical, electrochemical and biological [1]. In the first category (most hydrogen is derived from this method), separation of hydrogen from a feedstock is achieved through endothermic chemical reactions. The electrochemical method involves water decomposition into H₂ and O₂ by passing an electric current through the water. Concerning the biological method, hydrogen can be produced from renewable sources by microorganisms using carbohydrate-rich and non-toxic raw materials.

The hydrogen produced from the methods described above can be stored in an automobile either as a gas dissolved in a metal, as a cryogenic liquid or as a compressed gas [2]. Nevertheless, on-board hydrogen storage is deemed challenging as practical issues (weight increase, volume occupation, hydrogen infrastructure and safety) need to be overcome.

A widely acceptable alternative that is currently under research and development stage is the on-board hydrogen production. Adoption of this technique requires the integration of a fuel reformer within the exhaust pipe in order to generate hydrogen through a catalytic interaction of the fuel with hot exhaust gases. The basic idea is to liberate the hydrogen held in the fuel and exhaust steam and direct it into the combustion chamber. The chemical reactions (1–7) may take place in a reformer supplied with exhaust gas and diesel [2–4]. Details about reforming reactions can also be found in articles [5] and [6]. It should be clarified that the following reactions do not refer to engine combustion.

Diesel fuel steam reforming:

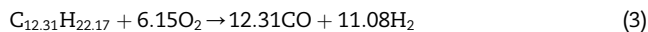


This reaction is largely endothermic and to be efficient it requires temperatures 600–800 °C [7]. Typical diesel exhaust gas temperatures vary from approx. 200–700 °C, depending on the operating condition.

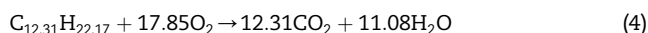
Water-gas shift:



Diesel fuel partial oxidation:



Diesel fuel complete oxidation:

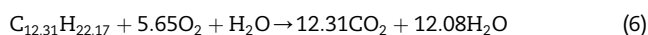


The reactions (3) and (4) although not desirable, due to the drop of product gas calorific value, being exothermic can raise the exhaust temperature in case it is not adequate to drive the steam reforming reaction.

‘Dry reforming’ reaction:



Temperatures over 800 °C are required in reaction (5).
Autothermal reforming:



Hydrocarbon thermal decomposition:



In fact, during a fuel reformation process more than one reaction may take place, however, promotion of the most desirable can be achieved by tuning the reformation process.

Tsolakis et al. [8] experimentally investigated the effect of REGR on a diesel engine. The authors concluded that, in the majority of the test conditions, dual-fuel operation (diesel and REGR) resulted in improved NO_x, smoke and engine fuel consumption. The concentration of H₂ and CO in the exhaust gas was found relatively high at low engine load, and as a result BSFC deteriorated due to the incomplete gaseous fuel utilisation. Singh Bika used a single-cylinder CI engine fuelled on syngas-diesel in order to study the effect of varying syngas proportions on the cycle efficiency, NO_x and CO emissions [9]. It was demonstrated that cycle efficiency reduced when the equivalence ratio of the gaseous fuel was increased. Moreover, it was shown that NO_x emissions remained relatively constant under 2 bar IMEP operation, while under 4 bar IMEP they increased with diesel fuel substitution. Also, it was proven that CO was utilized more efficiently at the high load condition. Abu-Jrai et al. [10] introduced simulated REGR into a diesel engine and found, among others, that the unburned H₂ in the exhaust gas can benefit the performance of a SCR catalyst.

A typical diesel exhaust gas fuel reforming produces a gas mixture that is mostly composed of hydrogen and carbon monoxide. Although the effect of providing syngas into a diesel engine has been investigated by many researchers [11–14], no papers were found dealing with the effect of syngas + N₂. In previous studies, the effect of enriching the intake air with separate and simultaneous hydrogen and nitrogen on the combustion and emissions of an HSDI diesel engine has been investigated [15,16]. The current experimental work aims to take this research effort further by introducing syngas and nitrogen (at varying concentrations) into the engine. Syngas composition resembled that of typical diesel fuel reformation, while the introduction of nitrogen simulated the effect of oxygen concentration reduction in the inlet charge, that is, the increased N₂ to O₂ ratio.

Methodology

Engine

The experiments were performed using a Ford Puma direct injection diesel engine. The main specifications of the engine were: bore 86 mm, stroke 86 mm, compression ratio 18.2:1, number of cylinders 4, swept volume 1.998 L. The engine was equipped with a common rail system, a turbocharger and an EGR valve. Throughout the experiments diesel injection pressure was set to 800 bar. The engine was run in naturally aspirated mode by disconnecting the turbocharger, whereas the EGR valve was maintained hermetically closed.

Fuel

The baseline data was obtained by fuelling the engine on ultra-low sulphur diesel (ULSD). The dual-fuel operation was

Table 1 – Gaseous fuel concentration, mass flow rate and energy ratio.

Syngas concentration [% vol.]	2	4	6
H ₂ fraction [% vol.]	1.2	2.4	3.6
CO fraction [% vol.]	0.8	1.6	2.4
H ₂ mass flow rate (1500 rpm) [g/sec]	0.0204	0.0408	0.0612
CO mass flow rate (1500 rpm) [g/sec]	0.1717	0.3434	0.5151
H ₂ mass flow rate (2500 rpm) [g/sec]	0.0324	0.0648	0.0972
CO mass flow rate (2500 rpm) [g/sec]	0.2760	0.5520	0.8280
H ₂ /CO energy ratio (1500 rpm)	1.4116	1.4116	1.4116
H ₂ /CO energy ratio (2500 rpm)	1.3947	1.3947	1.3947

realised by substituting an amount of diesel fuel with gaseous H₂ + CO, while the engine speed and load were maintained constant. The concentration of the syngas was 60% H₂–CO balance. Table 1 details the concentration of the syngas in the intake charge as well as the mass flow rate and the energy ratio of the gases it was composed of.

Intake charge

The gases were stored in two separate bottles, as shown in the schematic representation of the experimental set up, Fig. 1. The first bottle contained the gaseous fuel (syngas), whereas the second bottle was filled with high-purity nitrogen gas. Both bottles had lines connected to the inlet pipe. Table 2 illustrates the concentration of the individual gases in the intake charge, while the schematic representation of the intake charge composition is illustrated in Fig. 2.

Emissions measurement

A small quantity of the exhaust gas was directed into the analysers, which provided measurements of carbon monoxide and carbon dioxide (through non-dispersive infrared, NDIR), NO_x (chemiluminescence technique) and BSN (optical evaluation of the soot collected on a paper filter). The excess air ratio measured by the Horiba analyser was also recorded.

Table 2 – Intake charge composition.

Syngas + N ₂ [% vol. of intake air]	Intake charge composition [% vol.]			
	N ₂	O ₂	H ₂	CO
0	79	21	0	0
2 + 2	77.84	20.16	1.2	0.8
4 + 4	76.68	19.32	2.4	1.6
6 + 6	75.52	18.48	3.6	2.4

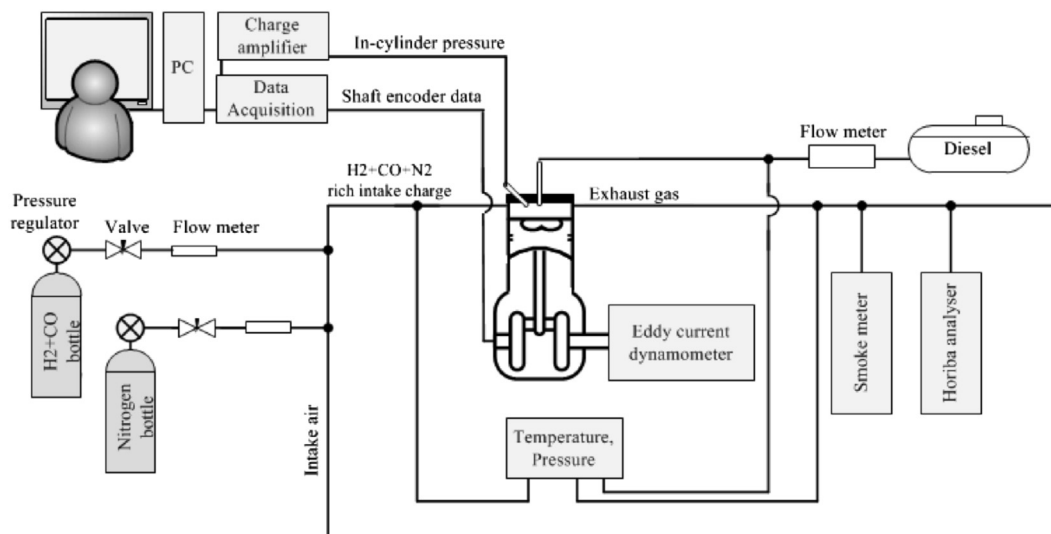
Experimental

Experiments were performed at four different operating conditions, which included two different speeds (1500 and 2500 rpm) and two different loads (2.5 and 5 bar BMEP). Start of injection was swept from 12 to 3 CAD BTDC in three degree increments, while an amount of intake air was gradually replaced by the bottled gases in 4% steps (2% syngas + 2% N₂), starting from 4% up to 12%. Diesel fuel was delivered into the cylinder through a single injection event at 800 bar. Cylinder pressure data as a function of crank angle was stored in a PC for off-line analysis. Temperature and pressure readings at various points (intake pipe, fuel line, exhaust pipe) were provided. Before taking any measurements, the engine was allowed to warm up until water temperature and emissions had settled to an acceptable steady state. Day-to-day variation in the results was minimized by ensuring that the data produced at specific operating conditions was within the accepted limits.

Results

NO_x-BSN

The effect of syngas + N₂ enrichment on NO_x-smoke trade-off is presented in Figs. 3 and 4. The tests were repeated four times and the values reported are mean values. Tables 3 and 4 show the standard deviation of NO_x and BSN at 8% syngas + N₂ concentration. Inclusion of error bars in the figures was proven impractical because standard deviation values were too small compared to the values of the axes.

**Fig. 1 – Experimental set up.**

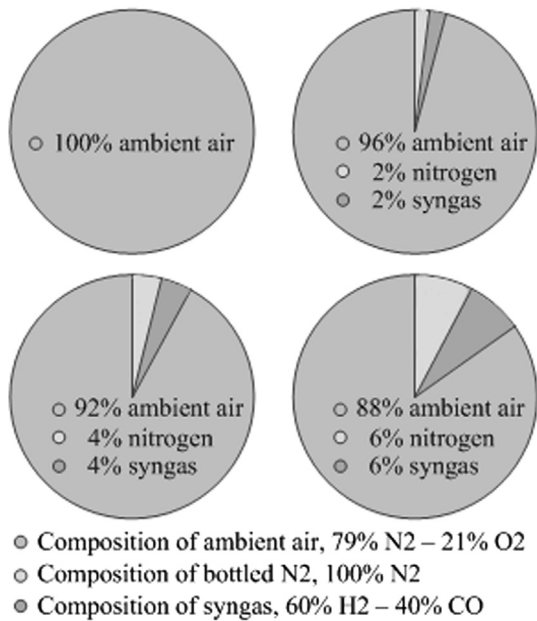


Fig. 2 – Schematic representation of intake charge composition.

Before providing discussion on the results, it should be mentioned that due to zero BSN values in Fig. 3(a), and in order to better illustrate the results, a secondary y axis was used. Simultaneous reduction of both NO_x and BSN was achieved over a broad range of the operating window of the engine. In particular, this desirable NO_x-BSN trend was observed under: (i) low speed low load, (ii) low speed medium load and (iii) high speed low load at syngas + N₂ concentration over 4%. Fig. 4(b) shows that under high speed medium load operation the added gas had an adverse effect on BSN, although neither the combustion of H₂ nor the combustion of carbon monoxide generates smoke. The high dilution level of the intake charge was probably the main contributor to the increased BSN, as

there was less oxygen within the cylinder to react with the diesel fuel. Isolation of the effect of N₂ and H₂ can clarify whether the admission of carbon monoxide (in addition to the dilution effect) contributed to smoke formation. According to Guo et al. [17], the concentration of OH (which contributes to soot oxidation) is lower and the concentration of H (which intensifies soot surface growth rate) is higher in a CO diluted flame due to the reaction $\text{CO} + \text{OH} = \text{CO}_2 + \text{H}$, whose forward rate is increased when CO is supplied into the engine. Fig. 5 shows the results obtained when a mixture of H₂ + CO (w/o N₂) was admitted into the engine. BSN dropped below the values recorded at baseline operation, and this suggests that under this operating condition smoke formation is very sensitive to the admission of N₂. Isolation of the CO effect (i.e. enrichment of intake air with H₂ only) can extend this investigation in order to assess whether a dilution with CO affects soot oxidation, as mentioned by Guo et al. The effect of H₂ enriched intake air on BSN has been presented in previously published work [15]. Comparison of the data collected at identical operating conditions and gas admission indicated lower BSN levels when fuelling on diesel-H₂. This verifies that a CO diluted flame promotes the formation of smoke. Since smoke exclusively originates from diesel, the above comparison is valid only if a comparable amount of diesel was delivered into the cylinder when fuelling on (i) H₂ + CO-diesel and (ii) H₂-diesel. The diesel flow rate measurements revealed that in the first case (i.e. when fuelling on H₂ + CO-diesel), the amount of diesel was slightly lower compared to the second case (when fuelling on H₂-diesel). This finding can be verified by comparing the energy density (energy per unit volume) of the two gases. The combustion of 1 L of H₂ releases 3.4% less energy compared to that released from the combustion of a gas mixture composed of 60% H₂ + 40% CO. From this, it is clear that more diesel fuel is required in the diesel-H₂ mode in order to achieve the same speed and load. This reinforces the conclusion drawn from the above comparison as in the higher smoke case (that is, fuelling on H₂ + CO-diesel) a smaller quantity of diesel (the smoke producing fuel) was supplied into the engine.

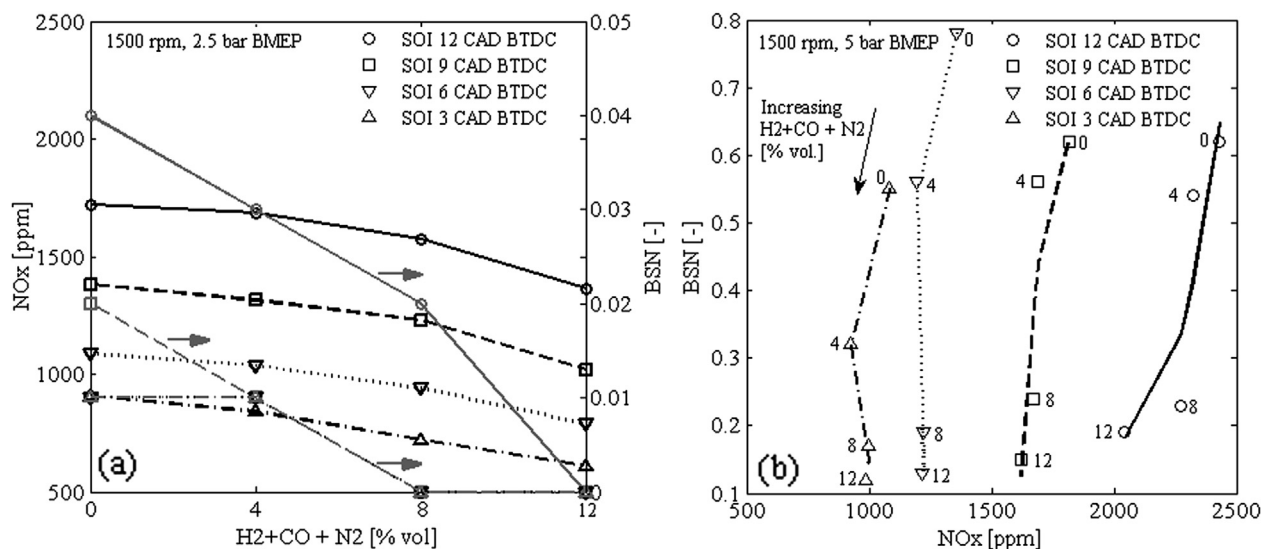


Fig. 3 – Effect of syngas + N₂ on NO_x-smoke trade-off. Engine speed: 1500 rpm, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP.

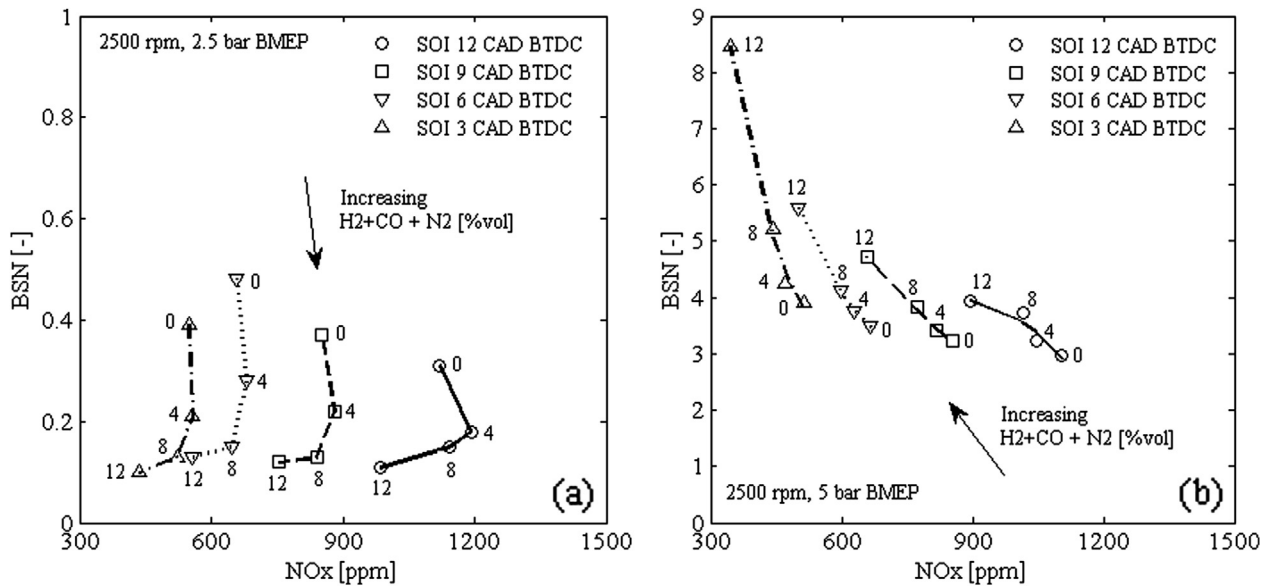


Fig. 4 – Effect of syngas + N₂ on NO_x-smoke trade-off. Engine speed: 2500 rpm, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP.

Table 3 – Standard deviation of NO_x emissions and BSN. Engine speed 1500 rpm, load 2.5 and 5 bar BMEP, syngas + N₂ concentration 8%.

SOI	1500 rpm, 2.5 bar BMEP		1500 rpm, 5 bar BMEP	
	Standard deviation of NO _x emissions	Standard deviation of BSN	Standard deviation of NO _x emissions	Standard deviation of BSN
12	9.98	0.00	15.24	0.008
9	7.88	0.00	13.00	0.005
6	5.24	0.00	6.48	0.001
3	6.14	0.00	8.42	0.00

Enrichment of the intake air with syngas + N₂ resulted in reduction of oxygen concentration, which led to a decrease of lambda. From Figs. 6 and 7, it can be concluded that, in the majority of the operating conditions, drop of lambda resulted in simultaneous NO_x and BSN decrease with a parallel rise in CO emissions. Replacement of part of diesel fuel with syngas was possibly the dominant factor that led to BSN drop, as intake charge dilution has typically a detrimental effect on smoke emissions. In Fig. 7(b), the increase of BSN may have been caused by both the high CO utilisation (as presented in the following section) and the relatively low lambda value. Reduction of NO_x with lambda is not unexpected as oxygen concentration is a dominant NO_x formation factor. Increase of CO with the reduction of lambda was caused, on the one hand,

by the reduction of oxygen concentration and, on the other, by the increase of the amount of the bottled CO that was introduced into the engine.

Carbon monoxide, carbon monoxide utilisation and carbon dioxide emissions

Enrichment of the intake air with a carbon monoxide-containing mixture inherently increases the concentration of this pollutant in the exhaust gas. In essence, the increase of CO levels is attributed to the next two factors. The first is the incomplete combustion of the admitted gas, while the second is the slip of the carbon monoxide-rich intake charge during the valve overlap period. Figs. 8 and 9 depict the carbon

Table 4 – Standard deviation of NO_x emissions and BSN. Engine speed 2500 rpm, load 2.5 and 5 bar BMEP, syngas + N₂ concentration 8%.

SOI	2500 rpm, 2.5 bar BMEP		2500 rpm, 5 bar BMEP	
	Standard deviation of NO _x emissions	Standard deviation of BSN	Standard deviation of NO _x emissions	Standard deviation of BSN
12	7.56	0.008	7.13	0.037
9	6.06	0.00	5.79	0.045
6	8.41	0.001	5.63	0.034
3	6.12	0.008	5.15	0.059

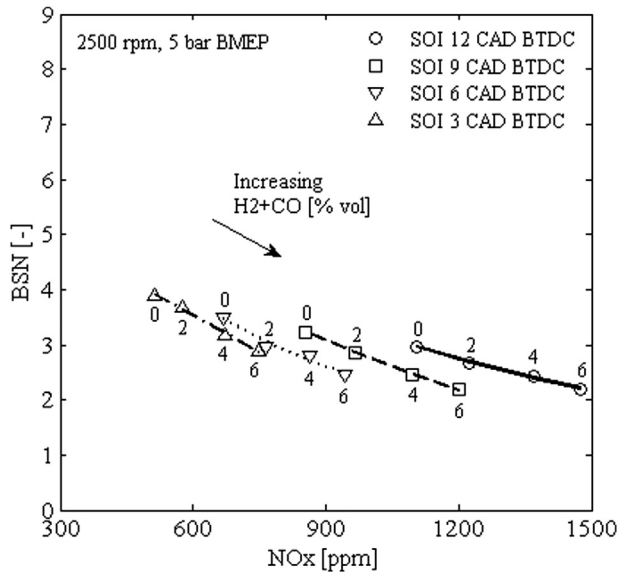


Fig. 5 – Effect of H₂ + CO on NO_x-smoke trade-off. Engine speed 2500 rpm, load 5 bar BMEP.

monoxide emissions collected at low and high speed, respectively. Inset in each of the main figures is an estimation of the carbon monoxide utilisation in the combustion chamber, the calculation of which is explained later on in this section.

Under low load operation, the bottled carbon monoxide was not utilised as efficiently as in medium load, resulting in significantly high engine-out carbon monoxide emissions. For instance, comparison of Fig. 8(a) with Fig. 8(b) indicates that under low load operation, the minimum carbon monoxide utilisation was 72.6% and the maximum 82.8%, whereas under medium load, it ranged from 88.1% to 92.4%. Concerning the engine speed, it is clear that the high speed operation was more favourable in terms of carbon monoxide utilisation. In essence, the above results indicate that the carbon monoxide

was more completely burned at high temperatures. This can be linked, among others, with the drop of the lower flammability limit (LFL) of the gas at elevated temperatures [18,19]. Using Le Chatelier's mixing rule [20], the LFL of the combustible gas mixture (that is, H₂ + CO) was found to be 5.45%, Equation (8).

$$LFL_{\text{mix}} = \frac{1}{\sum \frac{x_i}{LFL_i}} \quad (8)$$

Where LFL_{mix} is the lower flammability limit of the mixture, x_i denotes the concentration of component i in the gas mixture, LFL_i denotes the lower flammability limit of component i .

Due to variations in temperature, pressure and oxygen concentration, to name a few, the actual LFL is expected to differ from the calculated value. Nevertheless, the fact that carbon monoxide utilisation, in the majority of the points tested, improved at 12% bottled gas mixture (6% combustible gas mixture) suggests that the calculated LFL should not be far from the actual value. Gatts et al. [21] described a mechanism for the combustion of lean hydrogen, which probably holds true for the combustion of lean H₂ + CO. In particular, it was proposed that when the concentration of hydrogen is below its LFL, it simultaneously burns with diesel fuel by entraining into diesel vapour, since the flame cannot propagate in the lean gas. In addition, it was suggested that a wider diesel spray plume enhances the combustion of the gaseous fuel.

The calculation process of the bottled carbon monoxide utilisation is presented in this paragraph. Equation (9) is a simplified one but gives a good indication of the carbon monoxide utilisation in the combustion chamber.

$$CO_{\text{utilisation}} = 1 - \frac{CO_{\text{meas H}_2+\text{CO}+\text{N}_2} - CO_{\text{est H}_2+\text{N}_2}}{CO_{\text{sup}}} \times 100 \quad (9)$$

Where $CO_{\text{utilisation}}$ is the percentage of carbon monoxide being utilised [%], $CO_{\text{meas H}_2+\text{CO}+\text{N}_2}$ is the carbon monoxide measured in the exhaust gas when H₂ + CO + N₂ is admitted into the intake pipe [ppm], $CO_{\text{est H}_2+\text{N}_2}$ is the estimated carbon monoxide (estimation at equivalent H₂ fraction) in the exhaust gas

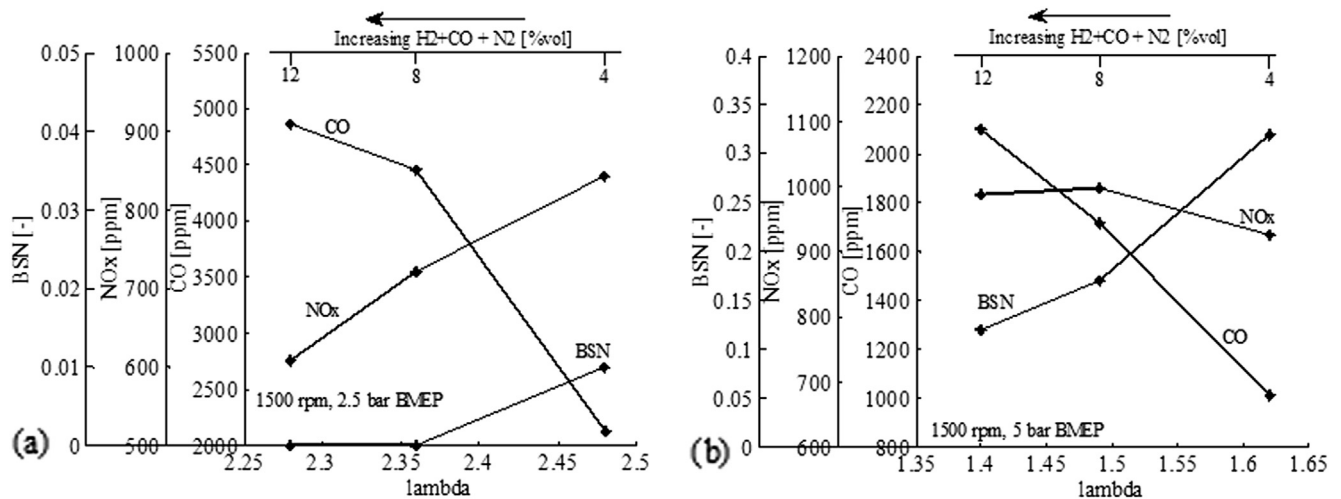


Fig. 6 – Effect of lambda coefficient on BSN, NO_x and CO emissions. Engine speed: 1500 rpm, SOI: 3 CAD BTDC, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP.

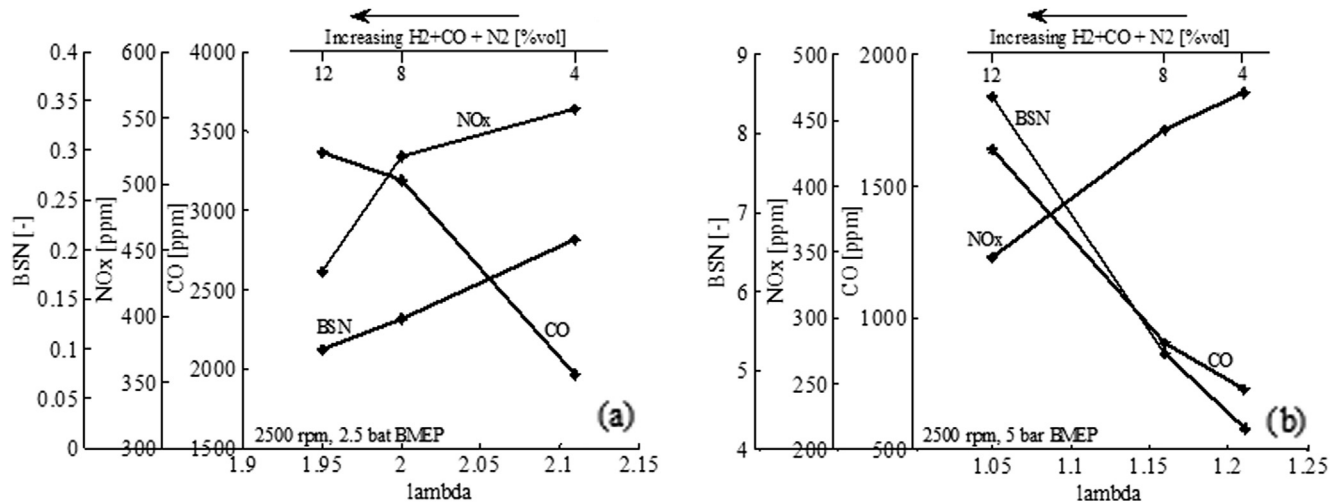


Fig. 7 – Effect of lambda coefficient on BSN, NO_x and CO emissions. Engine speed: 2500 rpm, SOI: 3 CAD BTDC, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP.

when H₂ + N₂ is introduced into the intake pipe [ppm], CO_{sup} represents the bottled carbon monoxide supplied into the engine [ppm].

In order to isolate the contribution from diesel fuel on the carbon monoxide measured in the exhaust gas, the values obtained when a mixture of H₂ + N₂ was introduced into the engine were subtracted from those obtained when a mixture of H₂ + CO + N₂ was supplied. Since the H₂ content in the two gas mixtures (4% H₂ + N₂ contained 2% H₂, whereas 4% H₂ + CO + N₂ contained 1.2% H₂ taking into account that the composition of the syngas was 60% H₂–CO balance) was not the same, an estimation of carbon monoxide (through the linear interpolation method) that would be measured in the exhaust gas if the amount of H₂ was the same is required. The calculation is based on certain assumptions such as possible dissociation reactions that produce carbon monoxide are still

the same when changing H₂ + N₂ with H₂ + CO + N₂ in the cylinder, carbon monoxide generated from diesel fuel is similar when changing H₂ + N₂ with H₂ + CO + N₂ and assuming a linear relationship between carbon monoxide emissions and %H₂ to get the values at 1.2, 2.4 and 3.6 %H₂. As mentioned in the NO_x-BSN section, the two distinct gaseous fuels (H₂ and H₂ + CO) release similar amounts of energy; hence, this implies that the amount of diesel fuel required to keep the speed and the load constant when changing H₂ + N₂ with H₂ + CO + N₂ in the cylinder is also similar.

Fig. 10 illustrates the CO₂ emissions as a function of the gas mixture delivered into the engine. Taking into account Figs. 8 and 9, it can be deduced (as a general rule) that CO₂ emissions increase when the utilisation of bottled carbon monoxide is approximately over 88%. That holds true under medium load operation. Poorer utilisation of the bottled carbon monoxide

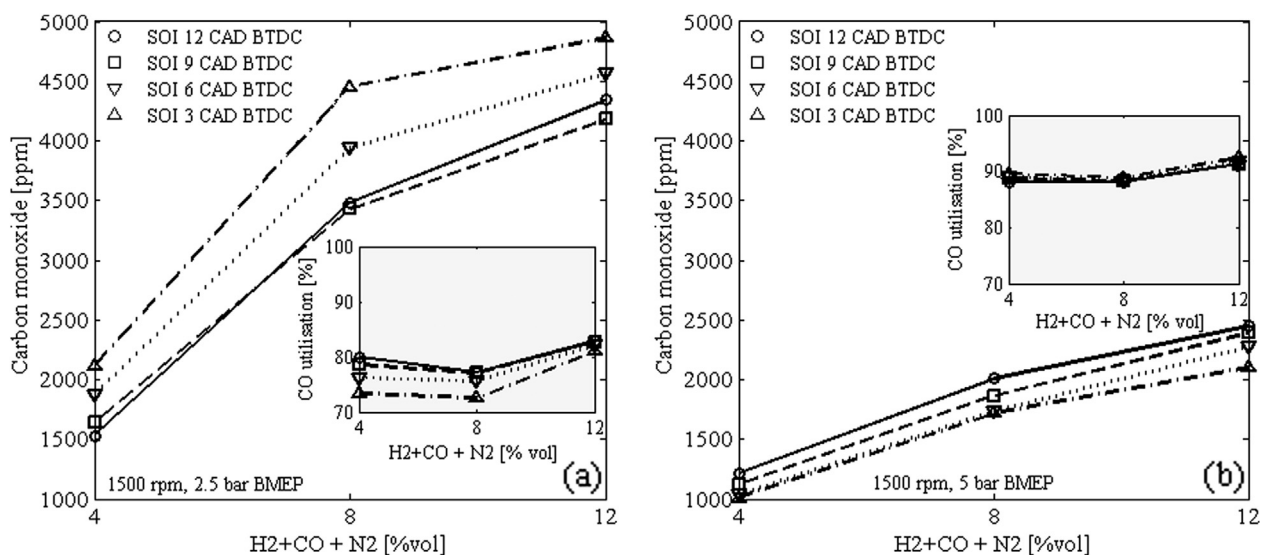


Fig. 8 – Effect of syngas + N₂ on carbon monoxide emissions. Engine speed: 1500 rpm, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP. Inset is the estimated carbon monoxide utilisation.

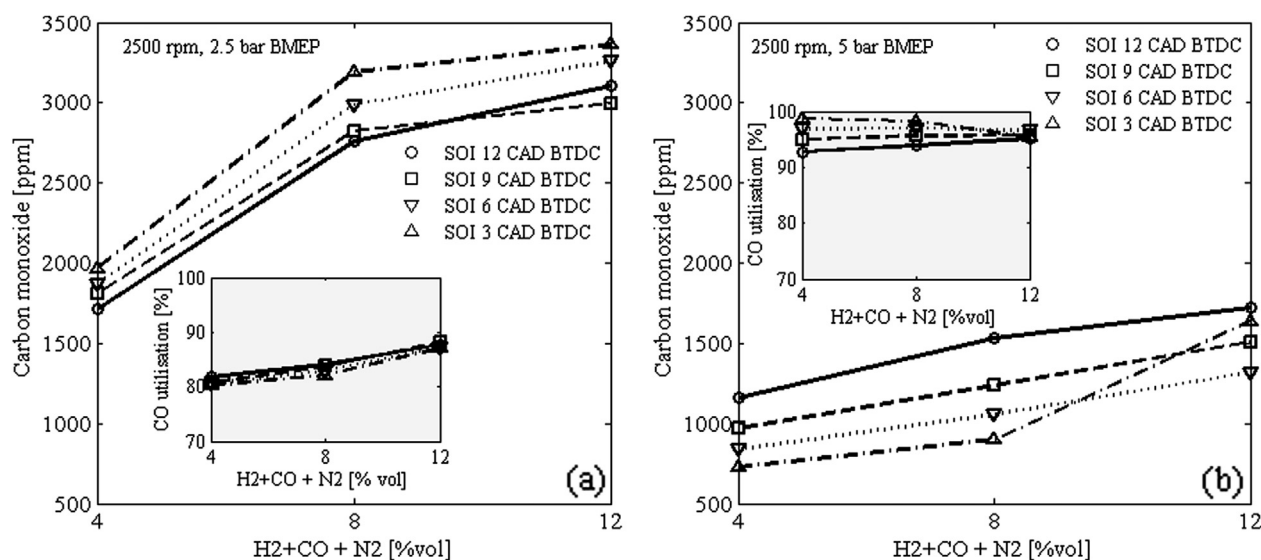


Fig. 9 – Effect of syngas + N₂ on carbon monoxide emissions. Engine speed: 2500 rpm, load: (a) 2.5 bar BMEP, (b) 5 bar BMEP. Inset is the estimated carbon monoxide utilisation.

under low load run resulted in slight CO₂ decrease, since a considerable amount of the bottled carbon monoxide was not burned.

Combustion analysis

A combustion analysis in the two extreme operating conditions (cond. 1 and 4) is illustrated in Figs. 11 and 12. The mass fraction burned (MFB), the maximum pressure rise rate and the maximum in-cylinder pressure obtained at the three different gas mixture concentrations adopted throughout the experiments are presented. Under low speed low load operation, the heat release increased sharply after the onset of combustion, resulting in high pressure rise rate values. As shown in Fig. 11, the maximum pressure rise rate

was always located in between CA 10 and CA 50 (CA 10 and CA 50 is the crank angle at which 10% and 50% of fuel mass has been burned, respectively). The inset figure reveals that both maximum dp/da and maximum in-cylinder pressure decreased as the concentration of the gas mixture was increased. The maximum pressure was located after the CA 50 and was always approximately one fifth of the distance, in crank angle degrees, from CA 50 to CA 90. Furthermore, the combustion duration (CA 10 to CA 90) increased with the fraction of the gas mixture. This result can be linked to the reduction of NO_x emissions when the concentration of the bottled gas mixture was increased, Fig. 3(a). Under certain conditions, the fuel which is burned faster is the most NO_x emitting one [16,22,23]. However, when syngas + N₂ is used, this is not the sole contributor to the reduction of NO_x

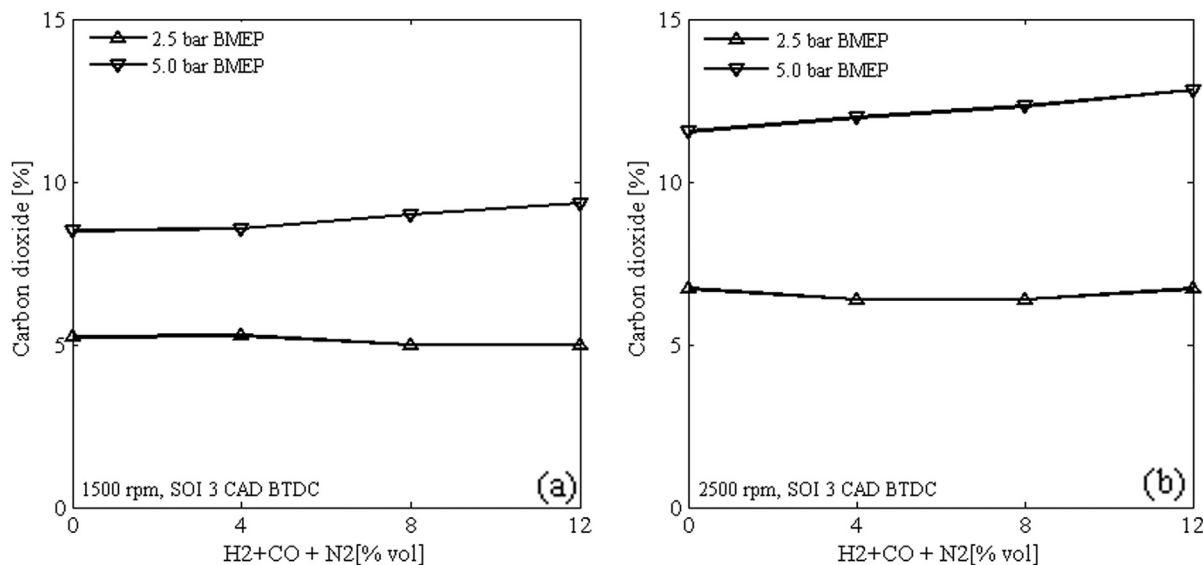


Fig. 10 – Effect of syngas + N₂ on carbon dioxide emissions. (a) 1500 rpm 2.5 and 5 bar BMEP, (b) 2500 rpm 2.5 and 5 bar BMEP. SOI 3 CAD BTDC.

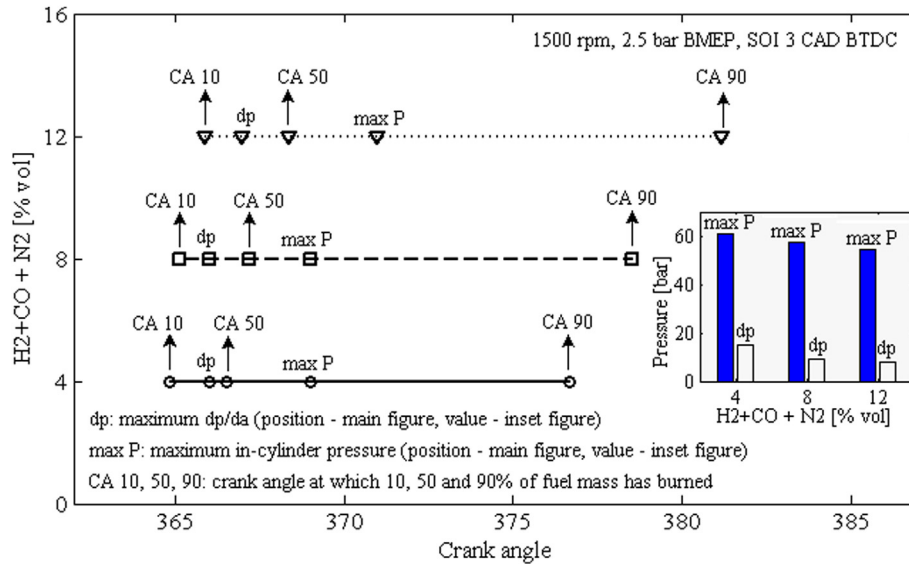


Fig. 11 – Mass fraction burned, maximum pressure rise rate and maximum pressure. Engine speed 1500 rpm, load 2.5 bar BMEP, SOI 3 CAD BTDC.

emissions, since the reduction of in-cylinder pressure with syngas + N₂ fraction is associated with in-cylinder temperature decrease, which leads to reduced NO_x formation.

Fig. 12 shows the combustion analysis data that corresponds to high speed medium load operation. The maximum pressure rise rate was located straight after the CA 10 and was smaller to that obtained under low speed low load run. When the intake air was enriched with a mixture of syngas + N₂, increase of engine speed resulted in a reduction of maximum dp/da, whereas the effect of load on dp/da varied, depending on engine speed. Under low speed operation, dp/da increased with load, whereas under high speed operation, dp/da dropped with increase in the load. Selim [24] performed experiments on a Ricardo E6 engine running on diesel-CNG. It was proven that as the engine speed is increased the pressure rise

rate is decreased. Furthermore, it was shown that the pressure rise rate at low speed (1200 rpm) is increased with the load. Referring again to Fig. 12, the maximum in-cylinder pressure almost coincided with the CA 50 and was lower to that obtained at low speed low load operation. However, in contrast to low speed low load operation, increase of syngas + N₂ proportion resulted in higher in-cylinder pressure. The reduction of NO_x emissions at this operating condition may have been caused by the soot radiative heat loss [25], as BSN was significantly increased when the amount of syngas + N₂ introduced into the engine was increased (Fig. 4(b)). Finally, comparison with Fig. 11 reveals that under high speed operation, the combustion took longer to complete (in terms of crank angle degrees).

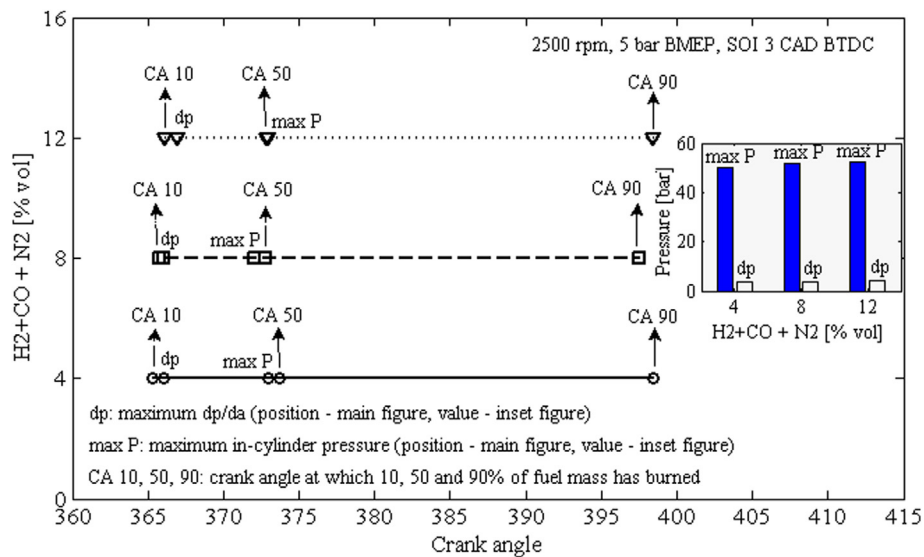


Fig. 12 – Mass fraction burned, maximum pressure rise rate and maximum pressure. Engine speed 2500 rpm, load 5 bar BMEP, SOI 3 CAD BTDC.

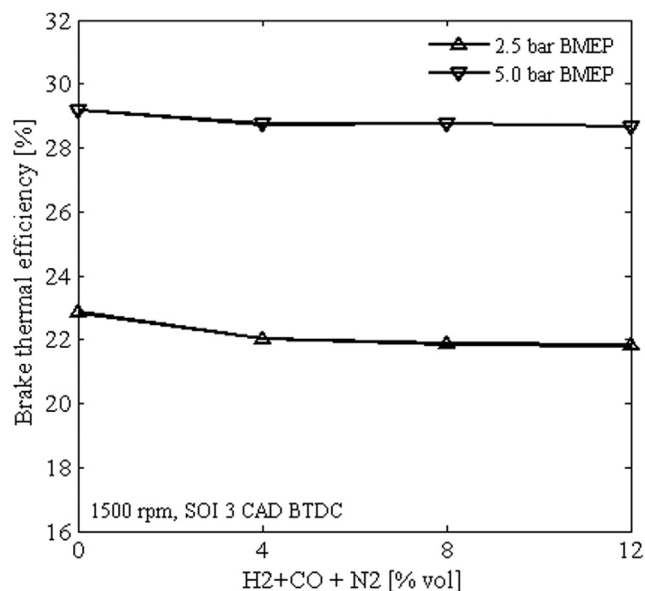


Fig. 13 – Effect of syngas + N₂ on brake thermal efficiency. Engine speed: 1500 rpm, load: 2.5 and 5 bar BMEP, SOI: 3 CAD BTDC.

Brake thermal efficiency

Figs. 13 and 14 illustrate the effect of enriching the intake air with a mixture of syngas + N₂ on brake thermal efficiency under low and high speed operation, respectively. At the operating conditions tested, the engine was more efficient when fuelled on neat diesel. Fig. 13 reveals that thermal efficiency dropped when a 4% gas mixture was admitted into the engine and remained relatively unaffected as the volume of the bottled gas was increased. A more intense fuel consumption penalty was observed under high speed run. The engine became very inefficient under high speed medium

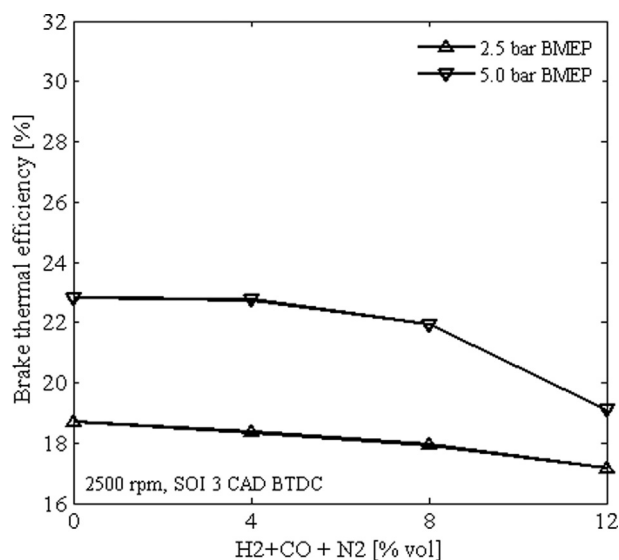


Fig. 14 – Effect of syngas + N₂ on brake thermal efficiency. Engine speed: 2500 rpm, load: 2.5 and 5 bar BMEP, SOI: 3 CAD BTDC.

load operation at 12% gas mixture, although the utilisation of carbon monoxide was over 95% and hydrogen combustion efficiency was almost 100% [15]. The flow rate of diesel fuel (not shown separately) was considerably increased under this operating point. The high dilution of the intake air probably led to poor diesel utilisation, which was reflected in the unacceptably high BSN values (Fig. 4(b)).

Conclusions

The effect of enriching the intake air with simulated reformer gas mixture on the performance and emissions of an HSDI diesel engine has been presented. The flammable gas was composed of H₂ + CO at a concentration resembling that of a typical fuel reformer. The introduction of bottled nitrogen aimed to simulate the increase in N₂/O₂ proportion in the intake charge. From the results presented the following conclusions can be drawn.

1. Simultaneous reduction of NO_x and BSN was achieved over a broad range of the operating window of the engine. In particular, when the intake air is enriched with a mixture of syngas + N₂, the engine is less NO_x-smoke emitting (compared to baseline values) when operating at low speed low load, low speed medium load and high speed low load at syngas + N₂ concentration over 4%.
2. Under high speed medium load operation, BSN is very sensitive to the admission of nitrogen. Moreover, although in-cylinder pressure was increased with syngas + N₂ concentration, NO_x emissions exhibited a decreasing trend. This may have been caused by the soot radiative heat loss as BSN was unacceptably high. Isolation of H₂ and N₂ effect revealed that a CO diluted flame promotes the formation of smoke.
3. Enrichment of the intake air with a carbon monoxide-containing mixture increases the concentration of that pollutant in the exhaust. Estimation of bottled carbon monoxide utilisation revealed that by increasing either the load or the speed of the engine carbon monoxide is more efficiently utilised. In essence, this suggests that the combustion of carbon monoxide is affected, among others, by the in-cylinder temperature.
4. Increase of engine speed leads to a reduction of maximum dp/da, whereas the effect of load on dp/da varies depending on engine speed. Under low speed operation, dp/da increases with load, while under high speed operation, dp/da drops when the load is increased.
5. The engine is more fuel efficient when operating on neat diesel. Under low speed run, brake thermal efficiency dropped when a 4% gas mixture was admitted into the engine and remained relatively unaffected as the amount of the gas mixture increased. A significant thermal efficiency reduction was observed under high speed run.

Acknowledgement

The authors would like to thank the UK Engineering and Physical Science Research Council (EPSRC) for supporting this

work (grant EP/H050248/1). Thanks are also due to colleagues David Peirce, Mohammed Abahussain and Nehemiah Alozie for their assistance.

Nomenclature

BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BSN	Bosch smoke number
BTDC	Before top dead centre
CA 10, 50, 90	Crank angle at which 10%, 50%, 90% of fuel mass has been burned
CAD	Crank angle degrees
CI	Compression ignition
CO	Carbon monoxide
CO ₂	Carbon dioxide
dp/da	Pressure rise rate
EGR	Exhaust gas recirculation
HSDI	High speed direct injection
IMEP	Indicated mean effective pressure
LFL	Lower flammability limit
MFB	Mass fraction burned
NDIR	Non-dispersive infrared
NO _x	Nitrogen oxides
REGR	Reformed exhaust gas recirculation
Rpm	Revolutions per minute
SCR	Selective catalytic reduction
SOI	Start of injection
ULSD	Ultra-low sulphur diesel

REFERENCES

- [1] Chaubey R, Sahu S, James O, Sudip M. A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources. *Renew Sust Energy Rev* 2013;23:443–62.
- [2] Jamal Y, Wyszynski M. On-board generation of hydrogen-rich gaseous fuels – a review. *Int J Hydrogen Energy* 1994;19:557–72.
- [3] Tsolakis A, Megaritis A, Wyszynski M. Low temperature exhaust gas fuel reforming of diesel. *Fuel* 2004;83:1837–45.
- [4] Hemmings S, Megaritis A. The effect of a H₂/CO mixture at varying ratios on the diesel particulate filter regeneration process: towards an optimised fuel reformer design – diesel engine after treatment system. *Int J Hydrogen Energy* 2012;37:12332–41.
- [5] Tsolakis A, Megaritis A, Golunski SE. Reaction profiles during exhaust assisted reforming of diesel engine fuels. *Energy Fuels* 2005;19:744–52.
- [6] Megaritis A, Tsolakis A, Golunski SE, Wyszynski ML. In: Zhao H, editor. 'Fuel reforming for diesel engines', chapter in 'Advanced direct injection combustion engine technologies and development: diesel engines (volume 2)' Woodhead Publishing Ltd and CRC Press; 2009, ISBN 1 84569 744 8. ISBN-13: 978 1 84569 744 0.
- [7] Kopasz J, Wilkenhoener R, Ahmed S, Carter J, Krumpelt M. Fuel flexible reforming of hydrocarbons for automotive applications. In: Gregoire Padro CE, Lau F, editors. *Advances in hydrogen energy*. New York: Springer; 2002. pp. 47–56.
- [8] Tsolakis A, Megaritis A, Yap D, Abu-Jrai A. Combustion characteristics and exhaust gas emissions of a diesel engine supplied with reformed REGR. *SAE Paper*; 2005. 2005-01-2087.
- [9] Singh Bika A. Synthesis gas use in internal combustion engines. Minnesota: University of Minnesota; 2010 [dissertation].
- [10] Abu-Jrai A, Tsolakis A, Megaritis A. The influence of H₂ and CO on diesel engine combustion characteristics, exhaust gas emissions, and after treatment selective catalytic NO_x reduction. *Int J Hydrogen Energy* 2007;32:3565–71.
- [11] Sahoo BB, Sahoo N, Saha UK. Effect of H₂:CO ratio in syngas on the performance of a dual fuel diesel engine operation. *Appl Therm Eng* 2012;49:139–46.
- [12] Sahoo BB, Saha UK, Sahoo N. Theoretical performance limits of a syngas-diesel fueled compression ignition engine from second law analysis. *Energy* 2011;36:760–9.
- [13] Azimov U, Okuno M, Tsuboi K, Kawahara N, Tomita E. Multidimensional CFD simulation of syngas combustion in a micro-pilot-ignited dual-fuel engine using a constructed chemical kinetics mechanism. *Int J Hydrogen Energy* 2011;36:13793–807.
- [14] Garnier C, Bilcan A, Le Corre O, Rahmouni C. Characterisation of a syngas-diesel fuelled CI engine. *SAE Paper*; 2005. 2005-01-1731.
- [15] Christodoulou F, Megaritis A. Experimental investigation of the effects of separate hydrogen and nitrogen addition on the emissions and combustion of a diesel engine. *Int J Hydrogen Energy* 2013;38:10126–40.
- [16] Christodoulou F, Megaritis A. Experimental investigation of the effects of simultaneous hydrogen and nitrogen addition on the emissions and combustion of a diesel engine. *Int J Hydrogen Energy* 2014;39(6):2692–702.
- [17] Guo H, Thomson KA, Smallwood GJ. On the effect of carbon monoxide addition on soot formation in a laminar ethylene/air coflow diffusion flame. *Combust Flame* 2009;156:1135–42.
- [18] Wierzbka I, Kilchyk V. Flammability limits of hydrogen-carbon monoxide mixtures at moderately elevated temperatures. *Int J Hydrogen Energy* 2001;26:639–43.
- [19] Kondo S, Takizawa K, Takahashi A, Tokuhashi K. On the temperature dependence of flammability limits of gases. *J Hazard Mater* 2011;187:585–90.
- [20] Mashuga CV, Crowl DA. Derivation of Le Chatelier's mixing rule for flammable limits. *Process Saf Prog* 2000;19:112–7.
- [21] Gatts T, Liu S, Liew C, Ralston B, Bell C, Li H. An experimental investigation of incomplete combustion of gaseous fuels of a heavy-duty diesel engine supplemented with hydrogen and natural gas. *Int J Hydrogen Energy* 2012;37:7848–59.
- [22] Peirce DM, Alozie NS, Hatherill DW, Ganippa LC. Premixed burn fraction: its relation to the variation in NO_x emissions between petro- and biodiesel. *Energy Fuels* 2013;27:3838–52.
- [23] Shin B, Cho Y, Han D, Song S, Min Chun K. Investigation of the effect of hydrogen on cylinder pressure in a split-injection diesel engine at heavy EGR. *Int J Hydrogen Energy* 2011;36:13158–70.
- [24] Selim M. Pressure-time characteristics in diesel engine fueled with natural gas. *Renew Energy* 2001;22:473–89.
- [25] Musculus MP. Measurements of the influence of soot radiation on in-cylinder temperatures and exhaust NO_x in a heavy-duty DI diesel engine. *SAE Paper*; 2005. 2005-01-0925.