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S.I. Engine Operation on Lean Mixtures

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Abstract

The operation of S.I. engines on lean or diluents containing fuel-air mixtures is attractive since it can provide, in principle, improved fuel economy, reduced tendency to knock and extremely low NO_x emissions combined with a possible longer operational life. However, the flame propagation rate then becomes degraded and drops sharply as the operational mixture is leaned or diluted. There is an ever increasing interest in examining the performance of S.I. engines when operated on lean or diluted mixtures and to investigate the deterioration in engine performance.

The paper presents experimental data obtained in a single cylinder, variable compression ratio, S.I., CFR engine when operated on gaseous fuels. A gradual leaning of the operating mixture was demonstrated to affect in turn, CO emissions and cyclic variation, emissions of unburned fuels and would lead eventually to the occurrence of misfire. The deterioration in these parameters was found to correlate well with the key combustion variables, notably the combustion duration. A similar effect was noted when diluents were added increasingly to a stoichiometric CH₄-air mixture. The reasons behind the trends observed will be discussed.

Introduction

The operation of spark ignition (S.I.) engines on lean mixtures is attractive since it can provide, in principle, improved fuel economy and extremely low NO_x emissions with longer operational life. There is also an increasing interest to apply exhaust gas recirculation (EGR) in S.I. engine applications to reduce the engine out NO_x emissions and suppress the onset of knock, [Grandin, et al., 1999]. However, the engine power output drops rapidly when leaning or diluting significantly the operational mixture due mainly to the associated reduction in flame propagation rates and the possible incompleteness of combustion combined with a reduction in the energy density of the intake mixtures. These may also lead to increased emission of unburned fuel, deteriorated power production efficiencies, unacceptably high cycle-to-cycle variation and even the eventual occurrence of misfire [Bade Shrestha, et al., 2000]. Correspondingly, there exist distinct operational limits beyond which satisfactory engine performance can not be maintained. There is increasing recent interest in examining the lean operation performance and extending the operational region of S.I. engines when operated on either gaseous or liquid fuels. For example, Gupta et al., [1996] examined the lean operation performance of a S.I. production engine operated on natural gas and gasoline. Natural gas was shown having superior lean operation performance over gasoline, though relatively lower power outputs were reported at around stoichiometric mixture operation. Søggaard, et al. [2002] investigated exhaust the emissions of unburned hydrocarbon (UHC) and cyclic variations in S.I. engines fuelled with a mixture of natural gas and products of its reforming that were described as Reformed Natural

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Gas (RNG). Such fuel mixtures were shown to have fast flame propagation rates and wider operational regions than with natural gas. The emission of unburned CH_4 could be reduced significantly, especially for lean mixture operation. Al-Fakhri, et al. [2000] examined the cyclic variation of S.I. engines and defined a new parameter called the “completeness of combustion” to describe such degradation of the combustion process with lean operation. Quader et al. [2003] examined the performance of a S.I. engine operated at around the operational limits of reformed gases. These H_2 -rich gases permitted operation of S.I. engines with either extremely lean or with a high level of (EGR) to enhance the power production efficiency and reduce dramatically engine-out NO_x emission. Bade Shreshta et al. [2000] examined in detail the operating limits of a S.I. engines operated on common gaseous fuels. The addition of H_2 to CH_4 was shown to extend the lean operational limits significantly. However, much of the research reported in the open literature tended to focus mainly on only one or some aspects of engine performance affected, which tends to be insufficient to understand fundamentally the detailed effects of lean or diluents operation on the combustion process. Also, the choice of any particular experimental approach is often dictated by the specific needs of the investigation and the availability of experimental facilities needed.

This paper presents results of an experimental investigation into the performance for lean mixture operation of a single cylinder, variable compression ratio, S.I., CFR engine operated with variable equivalence ratio on commercial CH_4 and its mixture with H_2 . These fuels were demonstrated to have superior combustion properties in comparison with liquid fuels in their tolerance for lean and/or diluents presence operation. The effect of lean operation on the indicated power production efficiency, exhaust emissions, cyclic variations and misfire processes was experimentally examined and discussed. The effect of the addition of diluents such as CO_2 and N_2 to CH_4 in stoichiometric mixture operation was also examined. The behaviour of the exhaust emission of unburned fuel and cyclic variation was shown to correlate well with changes in the values of the combustion duration.

Experimental Set-up

A single cylinder, four stroke, S.I., CFR engine of 82.6 mm bore and 114 mm stroke was used while operating unthrottled under atmospheric pressure conditions (about 660 mm Hg). The engine is of variable compression ratio (from 4.5:1 to 16:1) and spark timing (up to 40 °CA before and after top dead centre). The induction system was modified to permit the admission of either single or multi-fuels or diluents simultaneously. The gaseous fuels and diluents employed were supplied from a set of high-pressure cylinders and metered individually using a series of calibrated choked nozzles. Different fuel mixtures were prepared by precisely controlling the flow rates of the pure fuels and diluents and mixing them with the air into the intake manifold just before entry into the cylinder. The flow rate of the air was determined using a laminar flow air meter having a low pressure-drop. Thermocouples were employed to measure the temperatures of the intake mixture and exhaust gas. The intake temperature could be varied by electric heating the intake air. The in-cylinder pressure was measured with a high frequency-response, water-cooled piezoelectric type transducer mounted flush with the pan-shaped cylinder head. The overall combustion duration, which is also indicative of the average flame propagation rate, was determined through analysis of the instantaneous variation of the apparent polytropic index of the compression, combustion and expansion processes, as described by Bade Shrestha and Karim [2001]. The exhaust gases were sampled at a point of around 10 cm beyond the exhaust valve. The exhaust analysis system employed consisted of a range of N.D. infra-red

analyzers that measured the concentrations of CH₄, CO and CO₂ and with a chemiluminescence analyzer for NO/NO_x. Unutilized oxygen was measured using a paramagnetic detector. Unless otherwise indicated, the engine was operated at a constant engine speed of 900 rev./min, a fixed spark timing of 15 °CA BTDC, a compression ratio of 8.5:1, and an ambient intake mixture of 22 °C. The commercial CH₄ employed was processed pipeline natural gas having the following average volumetric composition: 93.07%CH₄, 5.74%C₂H₆, 0.16%CO₂ and 1.03%N₂. The purity values of CO and H₂ were over 99.5% by volume.

Experimental Results and Discussions

The lean mixture operation of S.I. engines has been shown to improve the power production efficiency. For example, Figure 1 shows the indicated power production efficiency with CH₄, H₂ and their mixture, (having a composition of 70%CH₄+30%H₂) with the variation in equivalence ratio. The indicated power production efficiency increases gradually with leaning the mixture but drops rapidly when excessively lean mixtures are employed. Also, it is shown that a much leaner mixture could be tolerated for H₂ and its mixture with methane reflecting the superior lean operational performance of H₂ in comparison to CH₄.

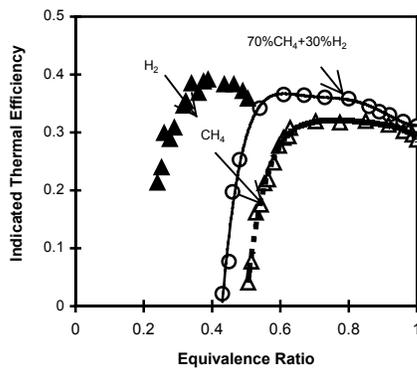


Figure 1 Variation of the indicated power production efficiency with changes in equivalence ratio for H₂, CH₄ and (70%CH₄+30%H₂) operations

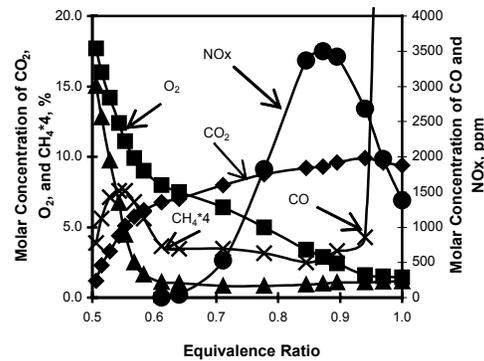


Figure 2 Variations of the exhaust emissions of NO_x, unburned CH₄, CO, CO₂, and O₂ with changes in equivalence ratios, Fuel: CH₄

The emissions of products, CO and unburned fuel, is an important tracer to any incomplete combustion, bulk quenching and the onset of misfire. As shown in Figure 2, when the operating mixture is significantly leaned, both CO and unburned CH₄ emissions increased substantially combined with a sudden drop in CO₂ emissions. These reflect the increasing extent of incomplete combustion and possibly bulk quenching and even failure of flame initiation, [Søgaard et al., 2002]. Such behaviour also was supported by the associated rapid increase in O₂ concentrations in the exhaust gases. The emissions of CO and CH₄ were also evaluated in terms of a relative emission, defined as the molar ratio of these components in the exhaust gases relative to that of CH₄ in the intake mixture. The combustion efficiency is defined as the molar ratio of CO₂ in the exhaust gases relative to intake CH₄. As shown in Figure 3, the emissions of the unburned CH₄ contribute in comparison significantly towards the deterioration of the combustion efficiency at lean operation. Figure 4 shows the corresponding indicated power production efficiency, CO emissions and coefficient of variation (*COV*) in indicated mean effective pressure (*imep*). The CO emission was found to keep pace with the increase in the

value of COV as the operating mixture was leaned gradually reflecting the development of incomplete and unstable combustion. Both of these parameters start to increase when the power production efficiency begins to decrease rapidly. However, as shown in Figure 5, the relative emission of CH_4 starts increasing at relatively leaner mixtures than for the COV in $imep$, which indicates that bulk quenching occurs at a leaner mixture than that associated with significant combustion instability. Leaning the operating mixture further, increases the relative emissions of CH_4 and leads to the occurrence of misfire in some cycles and eventually to a total loss of combustion, as shown in Figure 6.

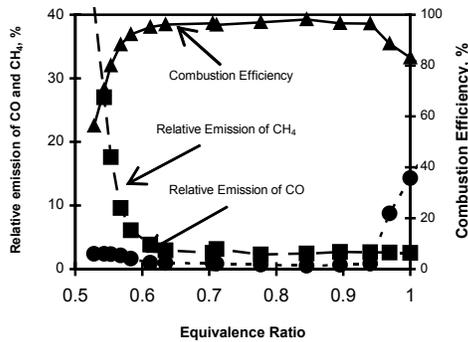


Figure 3 Typical variation of combustion efficiency, and relative emission of CO and CH_4 with changes in equivalence ratio when operated on CH_4

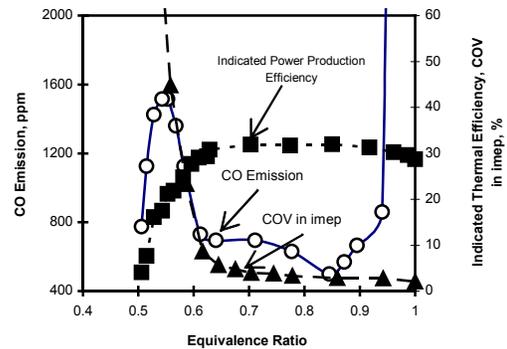


Figure 4 Comparison of the variation trends of the CO emission and COV in $imep$ with leaning operation when operated on CH_4

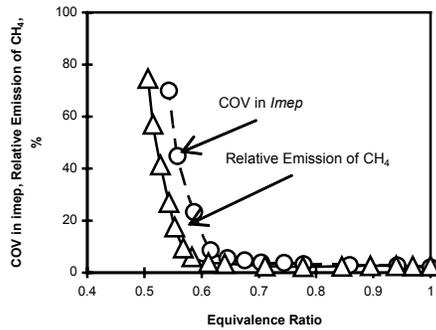


Figure 5 Comparison of the variation trends of the COV in $imep$ and relative emission of CH_4 with leaning operation, fuel: CH_4

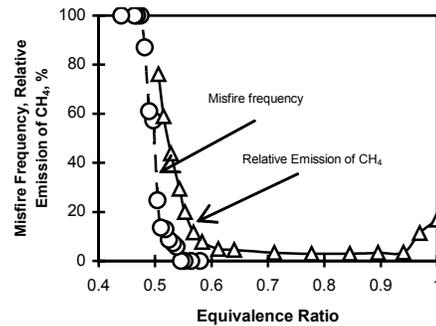


Figure 6 Comparison of the variation trends of the relative emissions of CH_4 and misfire frequency with leaning operation, fuel: CH_4

The deterioration in these processes with leaning operation is shown in Figure 7 and can be summarized by the following steps:

- 1) With a gradual leaning of the operating mixture, significant cyclic variation was first observed and accompanied by a relatively substantial increase in CO emissions.
- 2) Leaning the operating mixture yet further, a dramatic increase in the relative emissions of unburned CH_4 is observed, reflecting the increased contribution of flame quenching or the occasional lack of full flame propagation through the whole mixture.
- 3) A further leaning of the operating mixture leads to a rapid increase in the relative emissions of the unburned CH_4 accompanied by a sudden increase in the frequency of misfire until misfire is observed in all cycles when operated at sufficiently lean mixture. Similar trends were also found when using the other fuels, as shown in Figure 8.

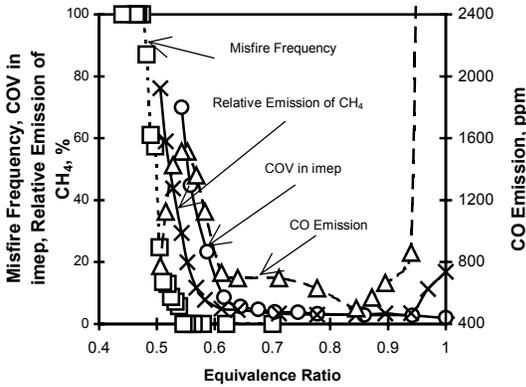


Figure 7 Comparison of the variation trends of the CO emissions, *COV* in *imep*, relative emissions of CH_4 and development of misfire frequency with leaning operation, fuel: CH_4

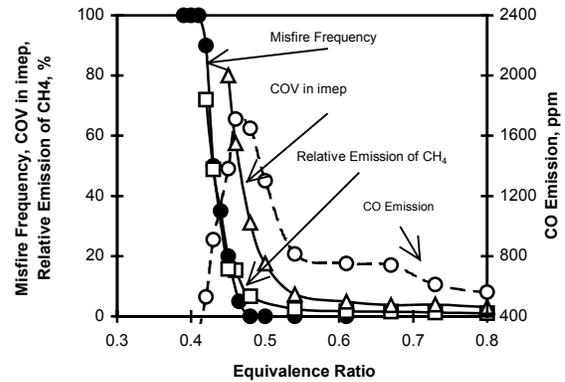


Figure 8 Comparison of the variation trends of the CO emissions, *COV* in *imep*, the relative emission of CH_4 and development of misfire frequency with leaning operation, fuel: $70\%\text{CH}_4+30\%\text{H}_2$

The effect of EGR on the combustion process is evaluated approximately through adding the pure diluents CO_2 and N_2 to a stoichiometric CH_4 -air mixture. As shown in Figure 9, adding these diluents appear not to affect substantially the power production efficiency until an excessive amount of a diluent was added, reflecting a relatively stable combustion process. This was also evident in the cyclic variations, as shown in Figure 10. As expected, distinctly poor and unstable combustion could be observed only when relatively large amounts of diluents were added.

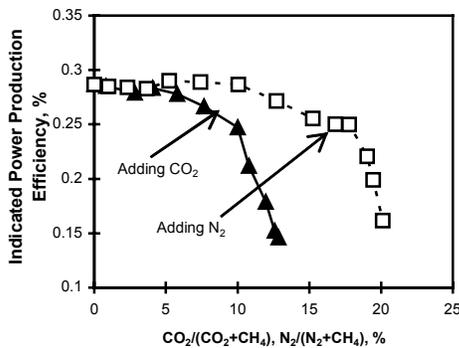


Figure 9 Comparison in variations of the indicated power production efficiency with the amount of CO_2 and N_2 added to stoichiometric CH_4 -air mixture.

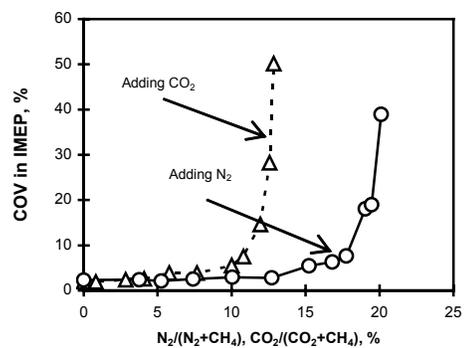


Figure 10 Comparison in variations of the *COV* in *imep* with the amount of CO_2 and N_2 added to stoichiometric CH_4 -air mixture.

The correlation of the extent of deterioration in engine performance with the key combustion parameter, the combustion duration was also made. Figure 11 shows a correlation of the relative emission of unburned fuel with the corresponding value of the combustion duration when operated on lean mixtures of CH_4 , CO and $(70\%\text{CH}_4+30\%\text{H}_2)$ [Li and Karim, 2005]. Significant unburned fuel emissions were obtained only when the combustion duration becomes relatively long as a result of the slow flame propagation. As shown in Figure 12, the values of *COV* in *imep* also correlated well with the combustion duration when varied through either leaning or diluting operation of common gaseous fuels. It appears that keeping a rapidly propagating flame reduces the emission of unburned fuels and the development of cyclic variation.

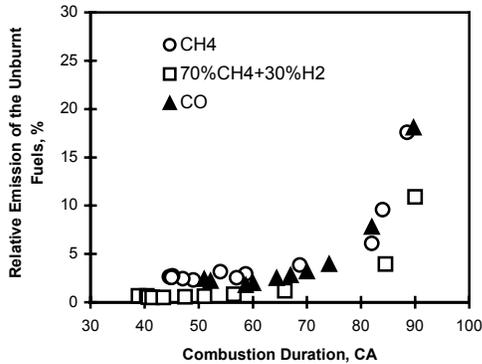


Figure 11 Variations of the relative emissions of the unburnt fuels with changes in combustion duration while operated on CO, CH₄ and 70%CH₄+30%H₂.

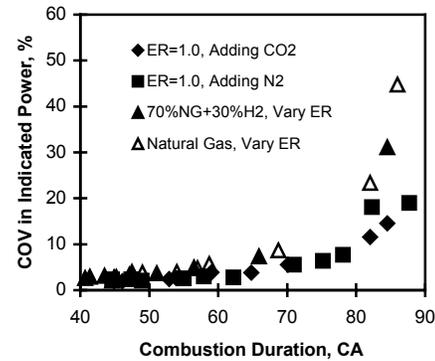


Figure 12 Variations of the COV in imep with changes in combustion duration when varied through either leaning or diluting operation of CH₄ and 70%CH₄+30%H₂

Conclusions

A gradual increase in the leaning of the operating mixture of an S.I. engine operated on gaseous fuels was shown to affect in turn CO emissions, cyclic variation, emissions of unburnt fuel and will lead eventually to the occurrence of misfire. The deterioration in engine performance during lean or diluted operations was found to correlate well with the key combustion variable of the combustion duration. Keeping a relatively fast flame helps to reduce exhaust emissions and suppress the development of cyclic variation.

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