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Imran, S, Emberson, DR, Ihracska, B et al. (3 more authors) (2014) Effect of pilot fuel quantity and type on performance and emissions of natural gas and hydrogen based combustion in a compression ignition engine. International Journal of Hydrogen Energy, 39 (10). pp. 5163-5175. ISSN 0360-3199

https://doi.org/10.1016/j.ijhydene.2013.12.108

Effect of pilot fuel quantity and type on performance and emissions of natural gas and hydrogen based combustion in a compression ignition engine

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Abstract

Natural gas and hydrogen have been extensively tested in dual fuel mode in a compression ignition engine. Many studies conclude that the emissions, especially those oxides of nitrogen (NO_X) are expected to form in the region around the pilot spray where high temperatures exist and the equivalence ratio is close to stoichiometric. The effect of changing the pilot fuel quantity has not been widely reported. This study investigates the effect of changing pilot fuel quantity, and type and the effect of this change on various combustion (ignition delay, in-cylinder pressure and rate of energy release) and emission (specific NO_X and hydrocarbons) parameters. Dual fueling of natural gas and hydrogen exhibit an increased ignition delay compared to the ignition delay exhibited by the pilot fuel at similar operating conditions. For dual fueling cases, the ignition delay is reduced as the quantity of pilot fuel is increased.

Keywords: combustion, emissions, dual fueling, RME, compression ignition, pilot fuels

Nomenclature

γ	specific heat capacity ratio
<u>Abbreviations</u>	
ATDC	after top dead center
BMEP	brake mean effective pressure
CA	crank angle
CI	compression ignition
IC	internal combustion
RME	rape methyl ester

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1. Introduction

Development of alternative fuels to replace the conventional fuels in IC engines is an active area of research. Fuels derived from different resources (especially but not exclusively renewable ones) have been tested in IC engines with their performance and emissions characteristics investigated to assess their suitability as substitute fuels. Both natural gas and hydrogen have long been considered alternative fuels for the transportation sector and have fueled vehicles for decades.

When compared to the reserves of crude oil on volume basis, natural gas has much larger reserves, estimated to be 5288.5 trillion cubic feet [1]. The cleanliness of any burning process is indicated by the amount of soot or smoke produced, natural gas qualifies this test owing to its lower carbon content. Natural gas is generally a mixture of primary alkanes with methane (CH_4) contributing around 95%.

An initial source of ignition is required to ignite both natural gas and hydrogen-air mixtures in unmodified CI engines. This is due to lower cetane number (high octane number) of natural gas [1, 4] and high auto-ignition temperature of hydrogen. To ignite these gaseous fuel in compression ignition engine, various ignition strategies have been employed. A glow plug or a high cetane liquid fuel such as diesel [5–8] or a biodiesel [6, 9–11] have been widely used as an initial source of ignition using the piloted dual fuel concept [12]. All of these studies consider a fixed quantity of pilot fuel, hence the effect of varying quantity of pilot fuel remains to be investigated.

Natural gas has high specific heat capacity ratio (γ). Due to this, the temperature of the in-cylinder charge is lowered and hence ignition is delayed which is critical from an emissions perspective [13, 14]. These studies have considered a variety of pilot fuels but were limited to a fixed quantity of pilot fuel. They present a good comparison of how different pilot fuels perform under certain operating conditions but lack an account on what will be the effect if the pilot fuel quantity is varied.

When compared to baseline single fueling case, the natural gas based dual fueling mode exhibit a slight reduction in brake thermal efficiency at lower loads [5, 7, 15–17]. Higher thermal efficiency values were reported at higher loads for natural gas dual fueling [18].

Hydrogen has been shown to increase flame stability [16] and improve thermal efficiency [19]. It is believed that the high diffusion coefficient of hydrogen leads to highly turbulent flame propagation rate [16]. The addition of hydrogen to increase the flame stability has been studied extensively because of the belief that flame propagation is the key factor in improving combustion [16, 20–23]. All of these studies highlight one or the other important aspect of the natural gas and hydrogen based dual fueling cases but the effect of changing the pilot fuel quantity and type on various combustion and emissions parameters has not been reported.

Concerning total brake specific fuel consumption, it is revealed that it becomes inferior under dual fuel operation compared to normal diesel operation at the same engine operating conditions. At high load, the values of total brake specific fuel consumption under dual fuel operation tend to converge with that of normal diesel operation [5]. The concept of multi ignition centers that result from the pilot fuel igniting the gaseous fuels in case of dual fueling modes requires an investigation on how changing the number of ignition centers (of course by injecting a different quantity of pilot fuel) shall affect the total brake specific fuel consumption and hence power and emissions characteristics. The lower heating value of the fuel also affects brake specific fuel consumption. It is worth investigating how two pilot fuels with different lower heating values shall perform in dual fuel mode from the brake specific fuel consumption perspective.

NO_X is a strong function of local temperatures. It has been reported that most of the NO_X are formed in the region around the pilot spray where high temperatures exist and the equivalence ratio is close to stoichiometric [24]. Natural gas based dual fueling results in lower NO_X emissions when compared to the NO_X concentration under normal single fuel operation. At the same time, a significant decrease in soot emissions under dual fuel operation has also been reported. On the other hand, CO and HC emissions levels have been reported to be considerably higher compared to normal diesel operation [5, 13–15, 25]. How would these different emissions parameters change if both the quantity as well as the type of the pilot fuel are changed, remain to be investigated and reported.

Hydrogen has high burning velocity which can lead to increased in-cylinder pressures and higher temperatures, resulting in increased NO_X emissions. Hydrogen is flammable over a wide range of concentrations in air (from 4% to 75%) [8, 9, 26]. This wider flammability can be used to prepare leaner mixtures resulting in lower in-cylinder temperatures and pressures and hence reduced NO_X emissions [21].

However, the initiation and development of the multiple turbulent flames requires a H_2-air mixture richer than the lean flammability limit [27]. Most studies have limited the enthalpy fraction of hydrogen addition to a maximum of 15% [9, 16]. The upper limit of hydrogen addition with manifold injected hydrogen is determined by the quenching gap of hydrogen flame which can travel past the nearly-closed intake valve and more readily back fires into the engine's intake manifold [28]. Using different quantities of the pilot fuels to achieve a certain BMEP in hydrogen dual fueling can be helpful in quantifying the effect of wider flammability and smaller quenching gap on different performance and emissions parameters.

Most of the studies reported on natural gas and hydrogen dual fueling lack one or the other important aspect. They are either confined to one type of gaseous fuel (either hydrogen or natural gas) or one type of pilot fuel (either diesel or a biodiesel). These two dual fueling cases with two different pilot fuels have hardly been reported in a single study. Changing the quantity of pilot fuel in natural gas and hydrogen based dual fueling is yet to be investigated, compared and reported. This study is an effort to fill all these gaps in the literature on natural gas and hydrogen based dual fueling of compression ignition engines. The study was conducted at two different engine speeds and the effect of variation in engine speed on different performance and emissions parameters has also been discussed.

The same engine can be used as a power source for different power applications, each with its own different load characteristics. For instance the same engine can be used to power: two different-size cars; a small marine vessel; an electricity generator; and in several other applications. The procedure of selecting the engine (prime mover) while considering the engine's contours of thermal efficiency on the power-speed range of the engine, and concurrently the load line of the powered device, has been briefly described in [6]. The engine is a standard test engine, typical of the majority of such engines used in the developing economies of the world; and though more-modern engines may have higher thermal efficiency and lower emissions, the trends of different performance and emissions characteristics presented in this paper are representative of those shapes for typical CI engines.

2. Experimental Set Up

A four-stroke, single-cylinder Gardner 1L2 CI engine was used, the specifications of which are shown in Table 1. Figure 1 shows the schematic layout of the experimental rig showing hydraulic brake, fuel supply lines, various emission analyzers and instrumentation.

Exhaust gas was sampled from the Gardner exhaust manifold through steel and PTFE tubing via a heated filter (maintained at 190 degrees Celsius). A Signal 4000VM chemiluminescence analyzer was used to measure NO and NO_X emissions, while unburnt HC emissions was measured by a Rotork Analysis model 523 flame ionization detector (FID) (both analyzers sampled wet exhaust gas via a heated line at 160 degrees Celsius). A Servomex 4210C exhaust gas analyser measured CO, CO_2 and oxygen (O_2) concentrations (all on a dry-volume basis) using non-dispersive infrared sensors and a paramagnetic sensor respectively. A water trap and silicon oxide moisture filter is used to remove moisture from the Servomex sample gas. The RME used was provided by British Petroleum.

Three different pilot fuel settings were used for the two pilot fuels (diesel and RME) at two different speeds (1000 and 1500 rev/min). The different test conditions can be summarized by a legend A-B-n-X-Y where A and B represent the type of emission and the type of pilot fuel respectively, n represents the BMEP setting of the pilot fuel, D and E represent the type of gaseous fuel and the engine rev/min respectively.

$$A = \left\{ \begin{array}{c} NO_X \\ HC \end{array} \right\}$$

$$B = \left\{ \begin{array}{ll} D & \text{The pilot fuel is diesel} \\ RME & \text{The pilot fuel is biodiesel (RME)} \end{array} \right\}$$

$$n = \left\{ \begin{array}{ll} 1 & \text{BMEP setting for pilot fuel is 0.125 MPa} \\ 2 & \text{BMEP setting for pilot fuel is 0.252 MPa} \\ 3 & \text{BMEP setting for pilot fuel is 0.312 MPa} \end{array} \right\}$$

$$X = \left\{ \begin{array}{ll} NG & \text{The gaseous fuel is natural gas} \\ H2 & \text{The gaseous fuel is hydrogen} \end{array} \right\}$$

$$Y = \left\{ \begin{array}{ll} 1000 & \text{Engine speed is 1000 rev/min} \\ 1500 & \text{Engine speed is 1500 rev/min} \end{array} \right\}$$

So, NO_X-D-1-NG-1000 shall be read as NO_X emissions produced by diesel piloted natural gas combustion when the quantity of liquid fuel (diesel in this case) was fixed at a BMEP value of 0.125 MPa. When the engine was operated on natural gas based dual fueling, only higher BMEP values were considered for the three different pilot fuel settings and different emissions from the three cases were compared against each other. When the engine was run on hydrogen based dual fueling, medium and higher-medium BMEP values were considered. This is because at n=1, the engine was running unstable and knocking was observed with any value of BMEP beyond 0.44 MPa but for n=2,3 it was possible to induct more hydrogen and achieve higher BMEP values. Cylinder pressure as well as first and second cylinder pressure derivatives were

Table 1: Specifications of the Gardner 1L2 diesel engine and Characteristics of RME used

No. of cylinders	1
Bore	107.95mm
Stroke	152.40mm
Swept volume	$1394\times10^{-6}m^3$
Clearance volume	$115.15\ \times10^{-6}m^3$
Compression ratio	13.11:1
Max. power	11kW @ 1500rev/min
IVO	10°BTDC
IVC	40°ABDC
EVO	50°BBDC
EVC	15°ATDC
Heating value of RME	38MJ/Kg
Density of RME	880kg/m^3
Cetane number of RME	54.4
Chemical Formula of RME	$C_{21}H_{38}O_2$

plotted against crank angle at the same engine condition. An inflection in the cylinder pressure trace shows a sudden increase in the pressure-rise rate which indicates the start-of-combustion (ignition). The point where both pressure derivative curves suddenly changes and rises into a steep slope also indicates ignition. This point (in terms of crank angle) is exactly the same as the point where the energy conversion rate plot

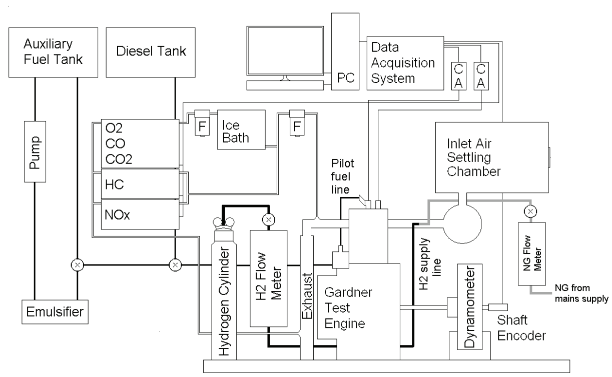


Figure 1: Experimental apparatus lay-out

also suddenly rises above the datum. As all three plots have the same inflection points indicating ignition, the ignition delay values in this work were obtained via a first pressure derivative analysis.

3. Results and Discussion

This section presents the results of natural gas and hydrogen based dual fueling and discusses the implications of changing the quantity of pilot fuel for these two fuels.

3.1. Natural Gas

This section is further divided into two parts. The first part discusses the implications of the change in the pilot fuel quantity and type on in-cylinder pressure, rate of energy release and ignition delay. The second part discusses the effect of change in the pilot fuel quantity and type and engine speed on different emissions.

3.1.1. Ignition Delay and Pressure Data

Figure 2 reflects the effect of pilot fuel quantity on ignition delay for pure diesel and pure RME as well as three natural dual fueling cases piloted by each of these two fuels. When compared to pure diesel and pure RME at 1500 rev/min and 0.503 MPa BMEP, all of the natural gas based dual fueling cases have shown larger ignition delay. For all combinations of the pilot fuel quantity, type and engine speed, the lowest pilot fuel setting (n=1) has exhibited maximum ignition delay and the ignition delay was generally reduced as the quantity of the pilot fuel was increased. This can be attributed to more ignition centers resulting from the injection of greater amount of pilot fuel and hence shortening the time between the fuel injection and the start of the ignition process. RME piloted dual fueling of natural gas at 1000 rev/min showed a slightly different trend where the medium pilot fuel setting (n=2) showed the minimum ignition delay when compared to the two other pilot fuel settings (n=1,3). At lowest pilot fueling setting (n=1), the enthalpy contribution of the natural gas is maximum. As n (the BMEP value where the pilot fuel quantity is fixed) increases, the pilot fuel is set at a relatively higher BMEP resulting in relatively lower enthalpy contribution from the natural gas. The specific heat capacity ratio γ for the natural gas - air mixture is considerably higher than the pure air. This higher specific heat capacity ratio results in lower in-cylinder temperatures and hence an increased ignition delay. The ignition delay for the middle pilot fuel setting

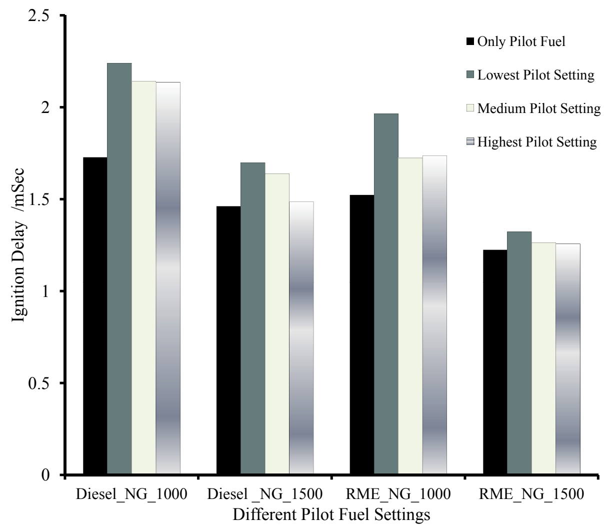


Figure 2: Effect of pilot fuel quantity, type and engine speed on ignition delay for different pilot fuel settings in diesel and RME piloted combustion of natural gas at 1000 rev/min and 1500 rev/min

(n=2) is marginally different from the highest pilot fuel setting (n=3). This can be attributed to the fact that there is only a difference of 0.069 MPa between these two cases when compared to a difference of 0.127 MPa between the lowest (n=1) and the middle pilot fuel setting (n=2). Insignificant difference between the ignition delays of the two higher pilot fuel quantity settings (n=2,3) suggests that increasing the pilot fuel quantity shall not result in proportional reduction in ignition delay. This view seems to hold good for all cases and diesel piloted natural gas combustion at 1500 rev/min is the exception where significant reduction has been observed as quantity of pilot was increased.

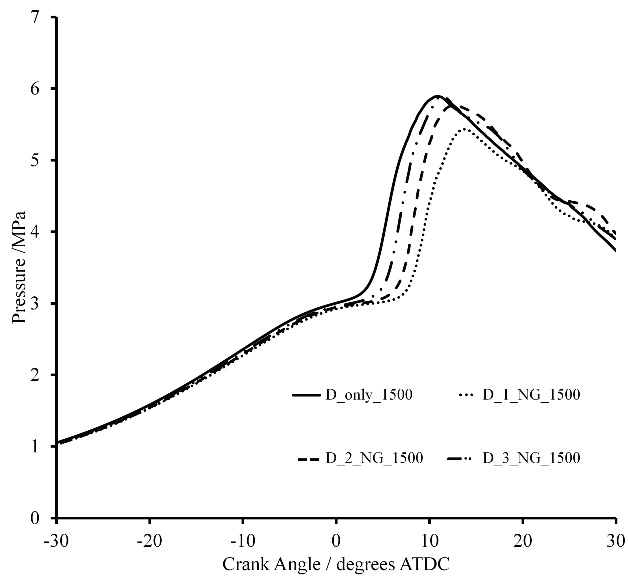
Figure 3(a) shows the in-cylinder pressure and Figure 3(b) shows the corresponding rate of energy release for pure diesel and three cases of natural gas dual fueling with three different diesel pilot fuel settings to achieve a BMEP of 0.503 MPa and 1500 rev/min. Figure 4(a) shows the in-cylinder pressure and Figure 4(b) shows the corresponding rate of energy release for pure RME and three cases of natural gas dual fueling with three different RME pilot fuel settings to achieve BMEP of 0.503 MPa and 1000 rev/min.

As reflected in Figure 3(a), for diesel piloted dual fueling of natural gas, the combustion peaks followed the trend observed for the ignition delays for different fuel combinations. Higher combustion peak was achieved when the ignition delay was reduced. For 1000 rev/min with diesel piloted combustion of natural gas, the ignition delay has shown similar trends as shown at 1500 rev/min as the lowest pilot fuel quantity has shown maximum ignition delay but there was no significant difference noted between the two higher pilot fuel settings. In Figure 3(b), $P_{0,1}$,$P_{0,2}$ and $P_{0,3}$ are the points on the rate of energy release graph pointing towards the first , second and the third (if any) peaks respectively for diesel piloted dual fueling of natural gas. The highest peak for the rate of energy release (indicated by $P_{0,1}$) for different pilot fuel settings has shifted in proportion to the ignition delay observed. The two higher pilot fuel settings (n=2,3) have resulted in higher peaks for the rate of energy release when compared to the lowest pilot fuel setting. Although the two higher pilot fuel settings exhibit similar peaks (point $P_{0,1}$) for the rate of release peaks but the two peaks occur at different crank angles. The first peak for the rate of energy release for pilot setting (n=2) occurs 8.089° CA ATDC whereas for pilot setting (n=3), it occurs at 6.84° CA ATDC. For the lowest pilot fuel setting, the the first peak for the rate of energy release occurs at 9.39° CA ATDC. For the two cases (n=2,3), a relatively longer ignition delay when compared to the diesel based single fueling has retarded the first peak ($P_{0,1}$) for the rate of energy release. The second peak for the rate of energy release (indicated by $P_{0,2}$) at 11.96° is more clear when the pilot fuel is set at the lowest BMEP (n=1) whereas it is not very clear for the higher pilot fuel settings (n=2,3). The third peak (indicated by $P_{0,3}$) is observed for the lowest (n=1) at 27° and for the middle (n=2) pilot fuel settings at 24° whereas the highest pilot fuel setting (n=3) shows the trend similar to what is observed with pure diesel in the latter part of the combustion. The latter peaks in case of relatively lower pilot fuel setting cases can be attributed to the fact that some of the gaseous does not get oxidized in the earlier phase of combustion and hence cause these latter peaks.

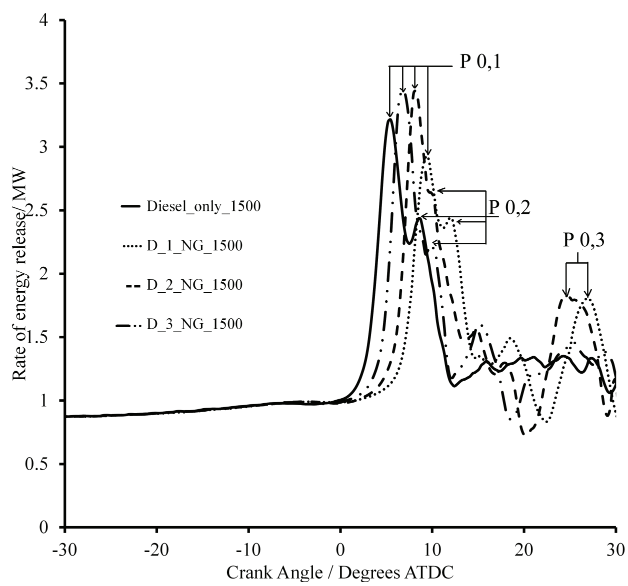
For RME piloted dual fueling of natural gas at 1000 rev/min as shown in Figure 4(a), lower peak pressure was recorded for the lowest pilot fuel setting (n=1) whereas similar rate of pressure rise and the peak pressures were observed with two of the higher pilot fuel settings (n=2,3). In Figure 4(b), $P_{0,4}$, $P_{0,5}$ and $P_{0,6}$ are the points on the rate of energy release diagram pointing towards the first , second and the third peak (if any) respectively for diesel piloted dual fueling of natural gas. The first rate of energy release peak for the three RME piloted dual fueling cases (indicated by $P_{0,4}$) occurs at 4° CA ATDC for the lowest pilot setting whereas 3.2° CA ATDC for the two higher pilot fuel settings (n=2,3). The second rate of energy release peak ($P_{0,5}$) occurring at 10.12° CA ATDC is more clear for the lowest pilot fuel setting whereas the two higher pilot fuel setting cases, the second rate of energy release peak occur at 8.14° CA ATDC. The two higher pilot fuel settings show a noticeable third peak ($P_{0,6}$) in the latter part of the combustion event (24° CA ATDC) which is not observed with the lowest pilot fuel setting case.

3.1.2. Specific NO_X

Figure 5(a) shows specific NO_X emissions for diesel piloted combustion of natural gas at 1500 rev/min. Figure 5(b) shows specific NO_X emissions for RME piloted combustion of natural gas at 1000 rev/min. At 1000 rev/min, apart from the highest load condition, the diesel piloted natural gas combustion produced



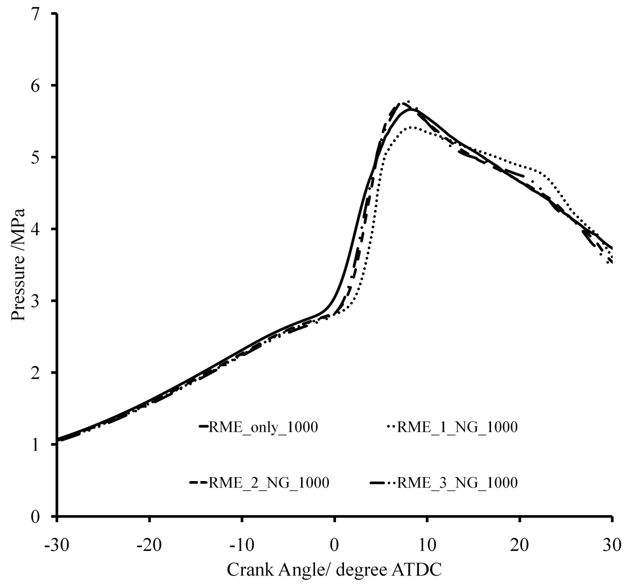
(a)



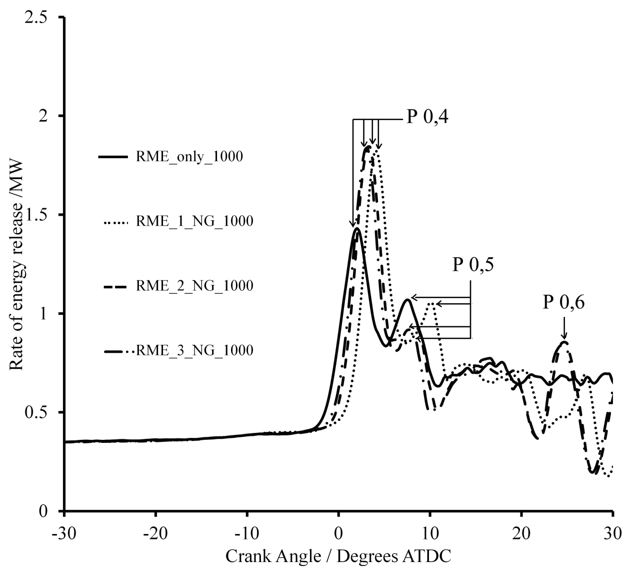
(b)

Figure 3: Effect of the pilot fuel quantity and type on in-cylinder pressure (a) and rate of energy release (b) for pure diesel and three cases of natural gas combustion with different diesel pilot fuel settings at a BMEP of 0.503 MPa and 1500 rev/min

minimum NO_X when the quantity of the pilot fuel was set at a minimum BMEP value(n=1). Maximum NO_X were produced when the diesel pilot was set at a BMEP value of 0.251 MPa. A linear increase in specific NO_X with any increment in BMEP was observed for pilot fuel settings of n=2,3 whereas for n=1, the specific NO_X initially dropped then an increase was observed. At similar speed (1000 rev/min), RME piloted natural gas combustion demonstrated different trends as compared to the diesel piloted case. Any increase in pilot fuel quantity resulted in lower specific NO_X. With pilot fuel set at the minimum (n=1), both



(a)



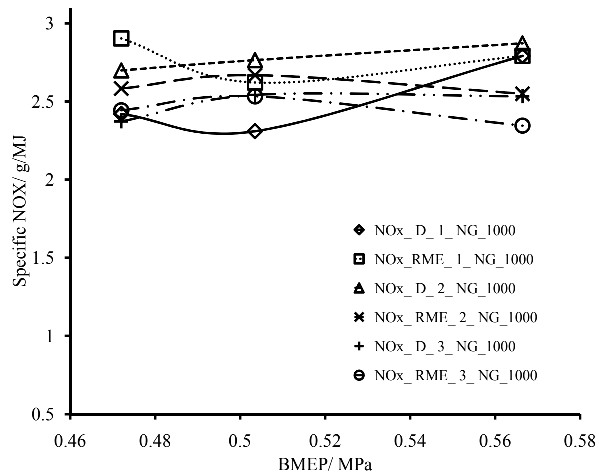
(b)

Figure 4: Effect of the pilot fuel quantity and type on in-cylinder pressure (a) and rate of energy release (b) for pure RME and three cases of natural gas combustion with different RME pilot fuel settings at a BMEP of 0.503 MPa and 1000 rev/min

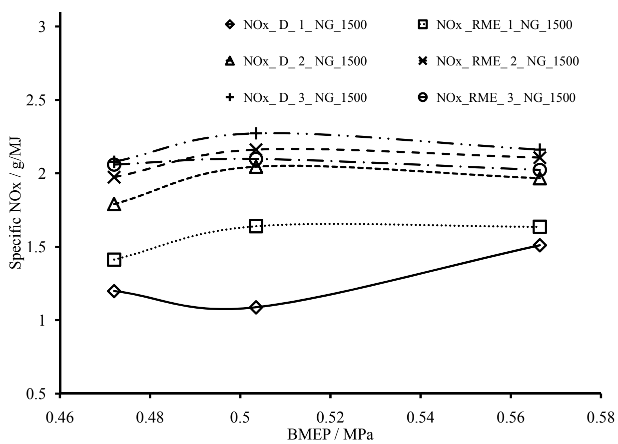
RME as well as diesel based combustion of natural gas showed similar trend as there was an initial decrease and then a serge was observed although they differed in magnitude as RME resulted in higher specific NO_X at the minimum pilot fuel setting. For the two higher pilot fuel settings (n=2,3), RME piloted combustion of natural gas produced lower specific NO_X as compared to the diesel piloted natural gas combustion. Lower specific NO_X resulted for all case six cases at 1500 rev/min when compared to the similar conditions at 1000 rev/min At 1500 rev/min, the diesel based natural gas dual fueling has shown different trends for specific

NO_X when compared to the same fuel settings at 1000 rev/min. The specific NO_X were observed increasing as the quantity of pilot fuel was increased. At minimum pilot fuel setting (n=1) for diesel piloted natural gas combustion, the specific NO_X exhibited similar trend at both speed i.e. an initial decrease and then an increase in specific NO_X. For all other cases at 1500 rev/min, the specific NO_X increased initially and then stayed constant. An offset proportional to the quantity of pilot fuel was observed for NO_X from diesel piloted natural gas whereas RME based natural gas dual fueling produced similar (or slightly different) magnitudes of specific NO_X for the two higher pilot fuel settings (n=2,3). The trends of specific NO_X emissions can be attributed to multi-centered ignition of the dual fueling. At relatively lower BMEP values, lower values of specific NO_X with lower quantity of pilot fuel can be attributed to the failure of the pilot fuel to ignite natural gas and air mixture properly. The increase observed in specific NO_X attributed to relatively higher in-cylinder temperature. The higher in-cylinder temperature can ensure timely evaporation of the pilot fuel and hence better distribution of the ignition centers across the charge. At lower speeds (1000 rev/min in this case), the lower specific NO_X with the highest pilot fuel setting (n=3) can be attributed to the cooling caused as a result of fuel evaporation. Greater quantity of pilot fuel results in large number of ignition centers and the cooling effect of the fuel evaporation is more pronounced at this condition as compared to the lower pilot fuel quantities. The maximum specific NO_X with pilot fuel setting at a medium BMEP suggests that there is a pilot fuel quantity threshold for specific NO_X where these are maximum and there would be lower specific NO_X below or above this threshold. There can be many reasons for this trend. Some of them have been already presented in this section but there may be some other factors playing their roles. Both for diesel and RME piloted dual fueling of natural gas at 1000 rev/min and the highest BMEP values, the specific NO_X resulted from the lowest pilot fuel setting ((n=1) supersedes the specific NO_X resulted from the highest pilot fuel setting. This can be attributed to the subsequent rate of energy release peaks occurring after the highest peak for the lowest pilot fuel quantity case.

Lower values of specific NO_X with RME based natural gas operation when compared to diesel piloted natural gas operation can be explained on the basis of higher cetane number of RME as compared to the diesel fuel. Premixed combustion is strongly affected by ignition delay. Lower cetane number has been reported to result in longer ignition delays and hence more time for premixed combustion, leading to higher in-cylinder temperature. In the pre-mixed combustion phase, fuel and air that have already mixed ignite, causing a rapid rise in temperature and pressure. This temperature and pressure rise depends upon the amount of fuel that has already been injected, which is related to the length of the ignition delay. With shorter ignition delays (related to high cetane number), less fuel is injected and mixed with air before ignition occurs, thus leading to moderate temperature and pressure increases. This ignition delay dependence of specific NO_X explains the trends in most of the cases considered here.



(a)

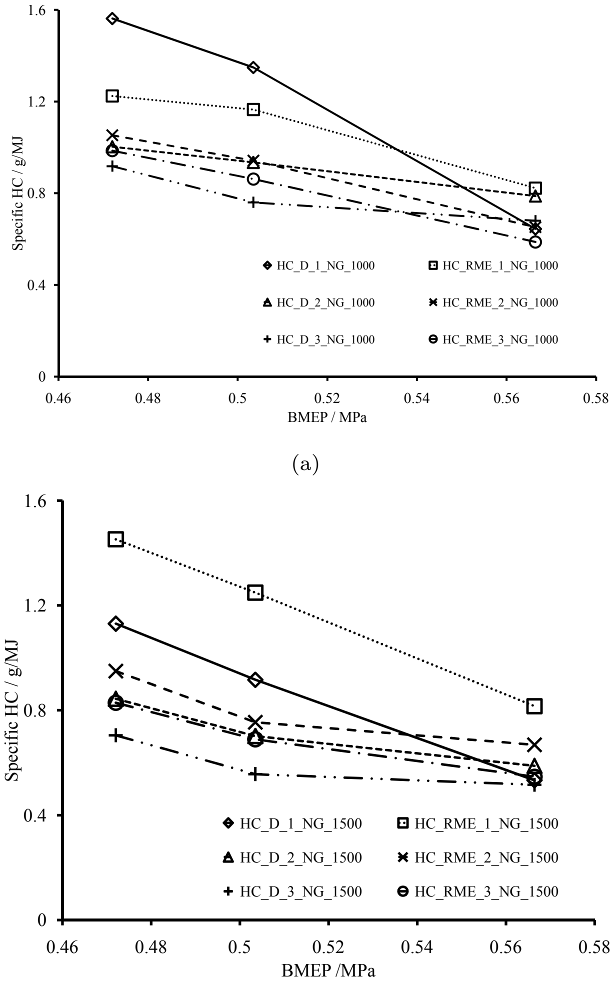


(b)

Figure 5: Effect of pilot fuel quantity and type on specific NO_X emissions for natural gas combustion with three different diesel pilot and RME pilot fuel settings at 1000 rev/min (a) and 1500 rev/min (b)

3.1.3. Specific HC

Figures 6(a) and 6(b) show specific HC emissions for diesel and RME piloted combustion of natural gas at 1000 rev/min and 1500 rev/min respectively. For diesel piloted natural gas combustion at 1000 rev/min, any increase in pilot fuel quantity has resulted in lower specific HC emissions. The highest load condition where the minimum pilot fuel setting (n=1) have produced lower specific HC as compared to the middle pilot fuel setting (n=2) is the only exception to the above mentioned trend. This is consistent with the trends obtained in specific NO_X emissions as the minimum pilot fuel setting produced higher NO_X at the highest load so that it resulted in minimum specific HC emissions at the same operating conditions. Apart from the lowest pilot fuel setting (n=1), the specific HC emissions vary in very small range. This suggests that when the pilot fuel is set constant at a relatively lower value of BMEP, a significant portion of the fuel



(a)

(b)

Figure 6: Effect of pilot fuel quantity and type on specific HC emissions for natural gas combustion with three different diesel pilot and RME pilot fuel settings at 1000 rev/min (a) and 1500 rev/min (b)

escapes unburnt as the pilot fuel fails to provide enough ignition sites to launch natural gas combustion. A comparable (or even lower) value of specific HC emission at the highest load when the pilot is set at a minimum BMEP can be attributed to a relatively higher in-cylinder temperature. This relatively higher in-cylinder temperature can ensure timely evaporation of the pilot fuel and hence better distribution of the ignition centers across the charge.

At 1000 rev/min, RME piloted combustion of natural gas has generally produced lower levels of specific HC emissions when compared to the diesel piloted combustion of natural gas. The highest load condition is the only exception to this trend where diesel piloted natural gas combustion has resulted in lower specific HC numbers for similar operating conditions.

At 1500 rev/min, the specific HC have shown similar trends as observed at 1000 rev/min. The only exception is when RME is used to pilot the natural gas combustion with pilot fuel set at a minimum BMEP value (n=1). RME-1-NG-1500 case has produced higher levels of HC at all operating condition when compared to all other five cases. This can be attributed to poor atomization characteristics of RME which become more evident at lower pilot fuel setting. When the pilot fuel is set at a minimum BMEP value, there is more natural gas present in the combustion chamber. As natural gas has higher heat capacity value, it shall result in a lower temperature charge which can further deteriorate the atomization problems with RME. The effect is more pronounced at higher speed as there is less residence time available at higher speeds. With diesel as pilot fuel at 1000 rev/min, the ignition delay decreased initially as the quantity of pilot fuel was increased and then stayed constant for any further decrease. On the other hand, at 1500 rev/min, a gradual decrease in ignition delay was observed when the quantity of pilot fuel was increased. With RME as a pilot fuel, the ignition delay decreased slightly and then stayed the same as the quantity of pilot fuel was increased. This trend was exhibited at both speeds. Considering the diesel piloted natural combustion at the peak load conditions at 1000 rev/min, lower specific HC emission resulted when the ignition delay was shortened. A shorter ignition delay can afford the fuel mixture and the initial combustion products to have longer residence time at temperature, thereby reducing the specific HC emissions. At 1500 rev/min for similar fuel and operating conditions combination; the ignition delay showed a different trend as it decreased gradually as the quantity of pilot fuel increased. This can be attributed to greater magnitude of vortices of turbulence at higher engine rev/min helping to achieve better mixing and an early start of ignition and hence a greater reduction in specific HC values. Like specific NO_X, specific HC emissions from diesel and RME piloted combustion of natural gas also exhibit the pilot fuel quantity threshold phenomenon. At lower speeds, the specific HC emissions decrease as the quantity of pilot fuel is increased whereas at higher speeds, there exists a pilot fuel quantity threshold below or above which the specific HC emissions increase. Also, at relatively lower values of BMEP, the specific HC emissions vary significantly and the trend lines converge as BMEP is increased. This confirms that higher temperatures at higher BMEP values make better use of the pilot fuel.

3.2. Hydrogen

This section is further divided into two parts. The first part discusses the implications of the change in the pilot fuel quantity and type on in-cylinder pressure, rate of energy release and ignition delay. The second part discusses the effect of change in pilot the fuel quantity and type and engine speed on different emissions.

3.2.1. Ignition Delay and Pressure Data

Figure 7 shows the effect of the pilot fuel quantity, type and the engine speed on the ignition delay of different cases of hydrogen dual fueling piloted by either diesel or RME. Compared to the respective diesel or RME based single fueling, the diesel and RME piloted combustion of hydrogen has shown longer ignition delays for all combinations of the pilot fuel quantity, type and engine speed. When the three diesel piloted

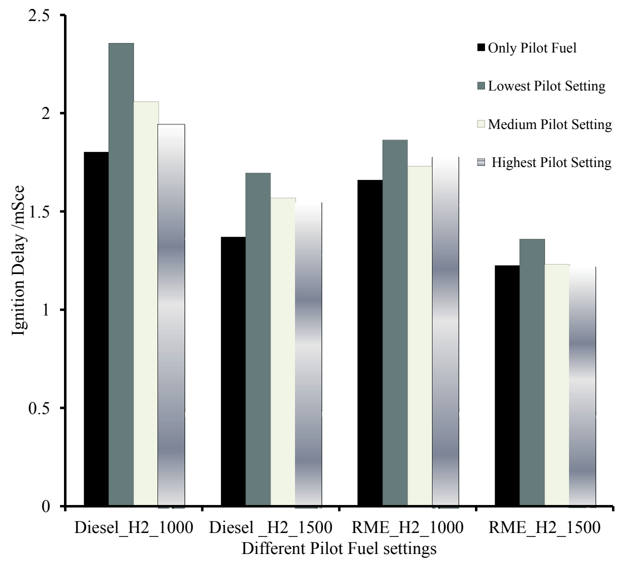


Figure 7: Effect of pilot fuel quantity on ignition delay for different pilot fuel settings in diesel and RME piloted combustion of hydrogen at 1000 rev/min and 1500 rev/min

hydrogen dual fueling cases are compared with each other, the ignition delay was shortened as the quantity of pilot fuel was increased. Relatively smaller difference was observed in terms of ignition delays for the two higher pilot fuel settings (n=2,3) at 1500 rev/min. Greater number of ignition centers when the pilot fuel is set at a higher BMEP (n=2 or 3) value (or when the energy contribution from the hydrogen is lower) causes the ignition delay to be shortened as more ignition sites are available to ignite the available amount of hydrogen. This can explain the difference between different ignition delay values for the different cases especially between the lowest pilot fuel setting and the two higher settings. Smaller difference between the higher pilot fuel setting cases can be attributed to smaller variation in ignition energy for hydrogen. Similar ignition delays in case of the two higher pilot fuel settings suggest that if the quantity of pilot fuel is set at a BMEP higher than a certain value, the ignition delay will not be affected significantly. At 1500 rev/min, the RME piloted dual fueling of natural gas exhibits trends similar to the diesel piloted dual fueling of the natural gas; shortening of the ignition delay as the quantity of pilot fuel was increased. At 1000 rev/min, the RME piloted dual fueling of natural has deviated from the trend observed for the rest of the combinations. When compared to the highest pilot fuel setting (n=3), the medium pilot fuel setting (n=2) exhibited relatively shorter ignition delay. This can be attributed to the poor atomization characteristics of the RME which become more evident at lower speeds due to relatively lower levels of in-cylinder turbulence.

Figures 8(a) and 8(b) show the in-cylinder pressure and the corresponding rate of energy release plotted against the crank angle for pure diesel and the three cases of diesel piloted combustion of natural gas at 1000 rev/min.

In Figure 8(b), the first peak in the rate of energy release diagram for the diesel piloted dual fueling of natural gas at 1000 rev/min is indicated by point ($P_{0,7}$) whereas the points ($P_{0,8}$) indicates the second peak. When the diesel pilot was set at the minimum BMEP value (n=1), two very distinct peaks were observed. The first peak in the rate of energy release diagram for this case occurred at 5.95° CA ATDC which was similar to the diesel based single fueling. There was another very obvious peak observed at 12° CA ATDC. The first peak in the rate of energy release diagram for the two higher diesel pilot settings (n=2,3) occurred at 3.9° CA ATDC. The second peak in the rate of energy release diagram for these two (n=2,3) cases occurred at 7.5° CA ATDC and 9.0° CA ATDC respectively. The medium setting (n=2) of the pilot fuel for the diesel piloted dual fueling of hydrogen produced higher first as well as the second peaks when compared to the highest pilot fuel setting. The medium pilot fuel setting for the diesel piloted dual fueling of hydrogen exhibited the highest first peak when compared to all other diesel piloted dual fueling cases.

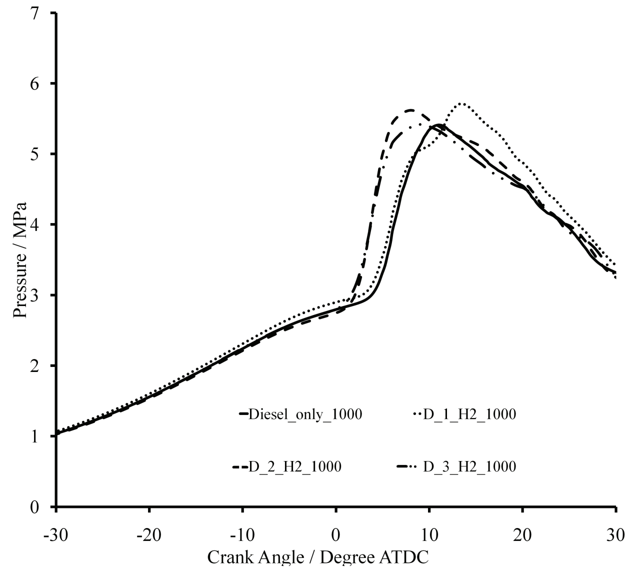
At 1500 rev/min when compared to pure diesel base case, all diesel piloted hydrogen combustion cases have shown shorter ignition delay and higher peak cylinder pressure and higher rate of pressure rise. Relatively smaller difference was observed in terms of ignition delays for the two higher pilot fuel settings (n=2,3) but the medium (n=2) pilot fuel setting case showed the highest peak pressure. The lowest pilot fuel setting, when the amount of hydrogen was maximum, showed the longest ignition delay but the peak pressure in this case was comparable to the maximum pressure obtained for the case n=2. Also the occurrence of the peak pressure for the lowest pilot fuel quantity was delayed proportional to the ignition delay when compared to the other cases with diesel piloted combustion of hydrogen. Similar ignition delays but different peak pressures in case of the two higher pilot fuel settings suggest that if the quantity of pilot fuel is set at a BMEP higher than a certain value, neither ignition delay will be shortened nor a higher peak pressure will be achieved. A higher peak pressure with the lowest pilot fuel setting can be attributed to different combustion properties of hydrogen as a fuel. Higher flame speed and shorter quenching distances seem to play vital role as more hydrogen is present inside the combustion chamber so the combustion can occur near the relatively colder cylinder walls as well due to short quenching distances. Maximum quantity of hydrogen is inducted when the pilot fuel is set at the lowest BMEP (n=1). A higher second peak for the rate of energy release for the lowest pilot fuel setting (n=1) suggests that for the for this particular setting, the hydrogen is burning in two different phases. In the first phase, it is the diesel-air mixture which gets oxidized along with a small quantity of hydrogen. In the second phase, the bulk of hydrogen is burnt.

Figures 9(a) and 9(b) show the in-cylinder pressure and the corresponding rate of energy release plotted against the crank angle for pure RME and the three cases of RME piloted combustion of natural gas at 1500 rev/min. When compared to RME piloted combustion of hydrogen at 1000 rev/min, RME piloted combustion of hydrogen at 1500 rev/min exhibit different trends when the pressure traces of the two modes are compared. The medium pilot fuel quantity setting (n=2) produced the maximum pressure followed by n=1 and n=3 respectively. The comparable peak pressure for the lowest pilot fuel setting when compared to the middle pilot fuel setting (n=2) when RME piloted the hydrogen combustion can be explained on the similar grounds as presented for the similar condition with diesel piloted hydrogen at 1500 rev/min.

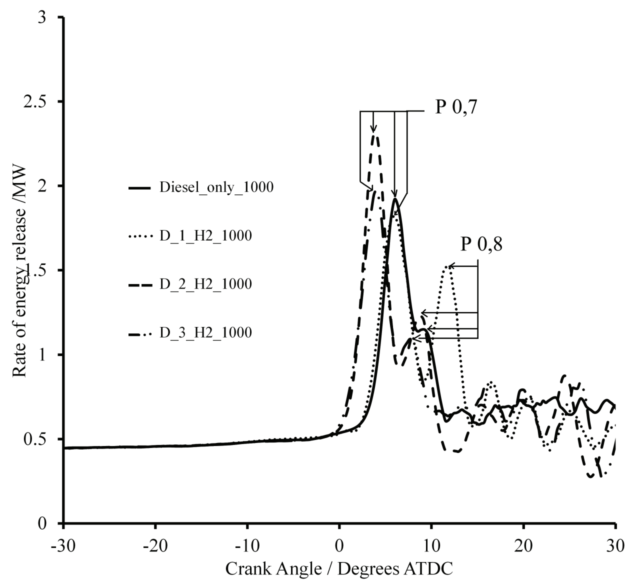
In Figure 9(b), the first peak is the rate of energy release diagram for the diesel piloted dual fueling of hydrogen at 1000 rev/min is indicated by point ($P_{0,9}$) whereas the point ($P_{0,10}$) indicates the second peak for the rate of energy release. At 1500 rev/min, the first peak for the rate of energy release is the highest for the medium pilot fuel setting (n=2) when compared to all other RME piloted hydrogen dual fueling cases hydrogen. It occurs at 5.7° CA ATDC. As the RME pilot fuel quantity was increased, the occurrence of the first rate of energy release peak is delayed. It occurs at 4.5° CA ATDC for the highest pilot fuel quantity whereas at 6.5° CA ATDC the lowest pilot fuel setting shows a relatively clearer second peak at 10.67° CA ATDC when compared to all other cases of RME piloted dual fueling of hydrogen.

3.2.2. Specific NO_X

Figures 10(a) and 10(b) show specific NO_X emissions for diesel and RME piloted combustion of natural gas at 1500 rev/min and 1000 rev/min respectively. At 1000 rev/min when RME pilots hydrogen combustion (Figure 10(a)), there is clear decrease in specific NO_X numbers as the quantity of pilot fuel is increased. For a particular pilot fuels setting, any increase in BMEP resulted in higher specific NO_X for all cases. The three cases with RME as pilot fuel resulted in comparable levels of specific NO_X when compared to the cases with diesel as pilot fuel at similar conditions. For the lowest pilot fuel setting (n=1), higher rate of increase in NO_X was recorded when compared to relative higher pilot fuel settings (n=2,3). This was held for both RME as well as diesel piloted hydrogen combustion cases at 1000 rev/min. Higher specific NO_X at higher BMEP values can be attributed to higher in-cylinder temperature as the engine is running hotter due to more fuel being injected to meet the higher power requirement. The larger gradient of specific NO_X at lowest pilot fuel setting (n=1) could be a result of more hydrogen being inducted at these conditions. Maximum ignition delay was observed when the pilot fuel quantity was set at the minimum so more pilot fuel was injected during this delay period and results in higher temperature and pressure. With longer residence time more fuel is injected and mixed with air before ignition occurs and this explains the higher in-cylinder temperature. Increasing the quantity of pilot fuel has lowered the ignition delay. The specific NO_X seem to be more affected by the quantity of hydrogen being inducted at a particular condition. Lower ignition energy and short quenching distances for hydrogen combustion suggest that it may not depend strongly upon the initial source of ignition to achieve sustainable combustion. The flame travels faster through hydrogen and hence the initial source of ignition becomes irrelevant very quickly. This explains the higher specific NO_X for lower pilot fuel setting case when the hydrogen quantity was maximum.



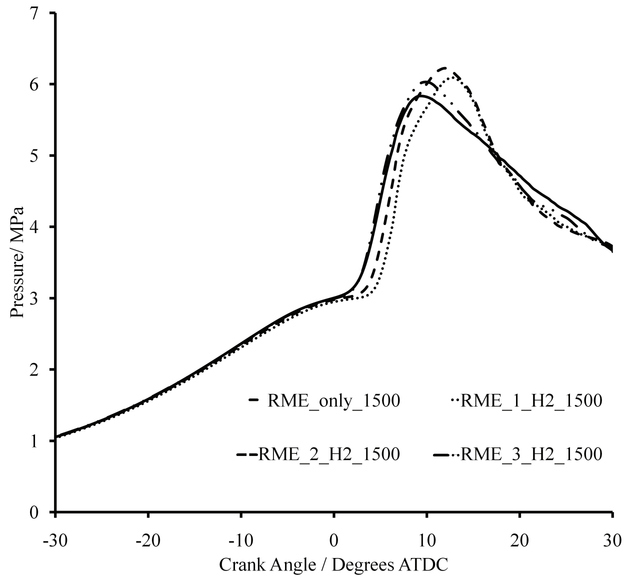
(a)



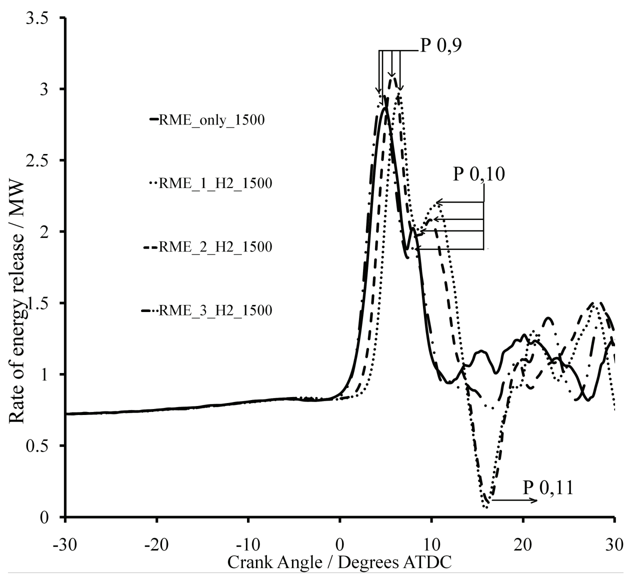
(b)

Figure 8: Effect of the pilot fuel quantity and type on in-cylinder pressure (a) and rate of energy release (b) for pure diesel and three cases of hydrogen with different diesel pilot fuel settings at a BMEP of 0.44 MPa and 1500 rev/min

At 1500 rev/min, the specific NO_X produced by diesel piloted hydrogen combustion exhibit different trends to what is observed at lower speed (1000 rev/min in this case). There is a complete reversal of the orders of the magnitude of the specific NO_X for different cases at these two conditions. At 1500 rev/min, the minimum pilot fuel quantity (n=1) has produced the lowest specific NO_X and these emissions have increased as the quantity of pilot fuel is increased. This trend holds good for the three diesel based cases apart from the highest BMEP value where the two higher pilot fuel settings swap their trends. For the



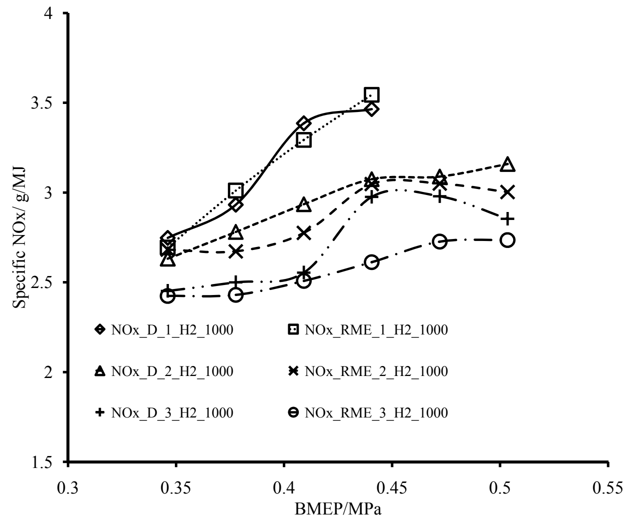
(a)



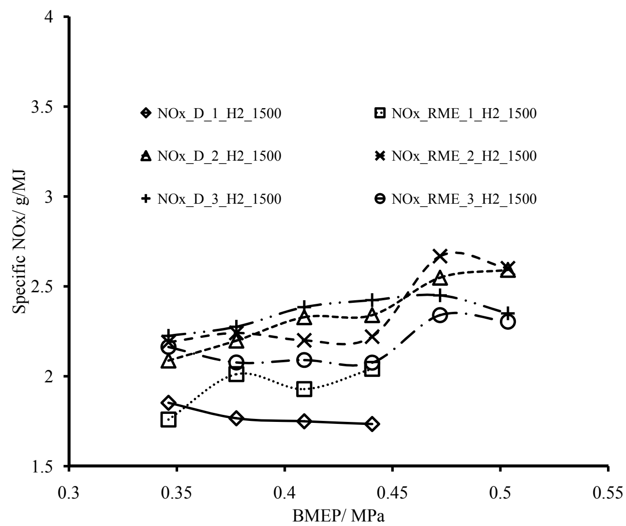
(b)

Figure 9: Effect of the pilot fuel quantity and type on in-cylinder pressure (a) and rate of energy release (b) for pure RME and three cases of hydrogen combustion with different RME pilot fuel settings at a BMEP of 0.503 MPa and 1000 rev/min

lowest pilot fuel setting, specific NO_X are not only lower in magnitude but also vary differently with any change in the BMEP value when compared to the trends observed at 1000 rev/min. Increase in BMEP value has caused the diesel piloted hydrogen specific NO_X to decrease slightly. For the two higher pilot fuel settings, the specific NO_X exhibit similar trend as observed at 1000 rev/min, although the emissions are lower in magnitude when compared diesel piloted hydrogen combustion NO_X at 1000 rev/min. A larger ignition delay is observed with the lowest pilot fuel setting as was the case at 1000 rev/min, but the higher



(a)



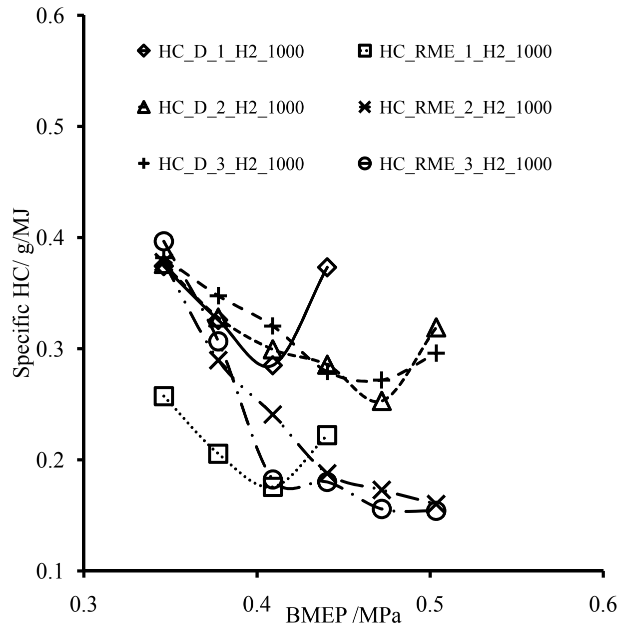
(b)

Figure 10: Effect of pilot fuel quantity and type on specific NO_X emissions for hydrogen combustion with three different diesel pilot and RME pilot fuel settings at 1000 rev/min (a) and 1500 rev/min (b)

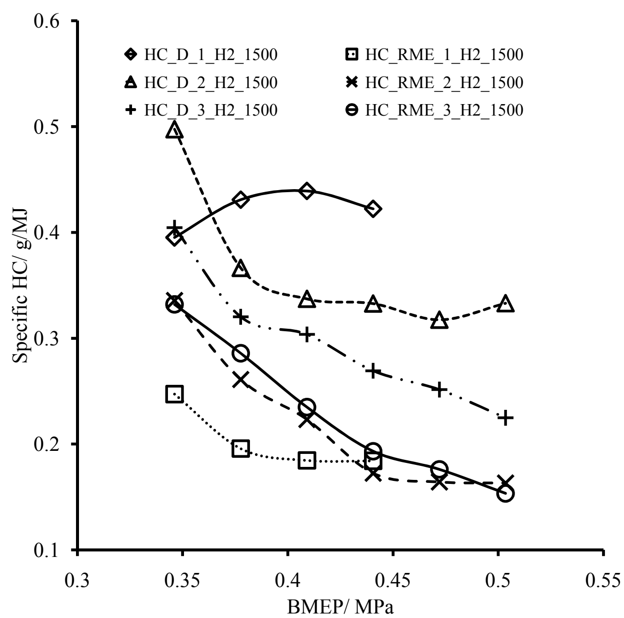
engine speed seems to counter the effect of longer ignition delay. With longer ignition delays, more fuel is supplied during the delay period and causes higher combustion temperature and pressure. At higher speeds the effective residence time is reduced resulting in relatively milder combustion pressure and temperature. The pressure and rate of energy release curves for RME piloted combustion of hydrogen at 1500 rev/min (Figures 9(a) and 9(b)) seem to support this argument. In diesel piloted combustion of hydrogen where the lowest pilot fuel setting (n=1) showed higher maximum in-cylinder pressure and a very strong second rate of energy release peak (point $P_{0,8}$ in Figure 8(b)) when compared to the two higher pilot fuel setting cases (n=2,3), in contrast, with RME piloted combustion of hydrogen at 1500 rev/min, all three pilot fuel settings show similar peak cylinder pressure and the second rate of energy release peak for the lowest pilot fuel quantity is also less strong (point $P_{0,10}$ in Figure 9(b)). Hydrogen combustion characteristics (shorter quenching distances, faster flame speeds and smaller variation in ignition energy that helped the lowest pilot fuel settings case at 1000 rev/min exhibit maximum peak cylinder pressure) seem to be downplayed by this shorter residence at higher engine rev/min. Although the turbulence levels are increased at higher engine rev/min, but the smaller residence time at these conditions seems to dominate combustion phenomenon. The variation in specific NO_X with different pilot fuel setting cases can also be explained on this basis. When the ignition is delayed and overall residence is shortened, it results in relatively lower combustion peak pressure and temperature and hence lower specific NO_X. For the lowest pilot fuel setting, RME piloted combustion of hydrogen has produced higher NO_X as compared to the diesel piloted combustion of hydrogen. The trend is reversed for the highest pilot fuel setting. For the medium pilot fuel setting, the specific NO_X are comparable for both of the cases. This can be attributed to relatively poor injection and atomization characteristics of RME, which become more evident as the combustible mixture become relatively more RME-enriched and a shorter residence time.

3.2.3. Specific HC

Figures 11(a) and 11(b) show specific HC emissions for diesel and RME piloted combustion of natural gas at 1000 rev/min and 1500 rev/min respectively. While operating at 1000 rev/min, the diesel and RME piloted hydrogen combustion resulted in sharp decrease in specific HC emissions before an increase is observed at the highest BMEP. For the lowest pilot fuel setting (n=1), RME and diesel piloted combustion of hydrogen produced similar trends with the diesel piloted case producing higher specific HC numbers for range of BMEP in investigation. The three diesel cases have produced comparable specific HC emissions apart from the BMEP value where the lowest pilot fuel setting has increased. For the lowest pilot fuel setting, the increase in specific HC numbers is consistent with a drop in specific NO_X at the same condition for this case. This can be attributed to some part of the pilot fuel escaping the combustion event due to lack of oxygen and lower turbulence levels in the combustion chamber at higher BMEP values. Another valid observation would be to consider the range of specific HC emissions for the diesel and RME piloted combustion. It is 0.1 g/MJ for diesel and 0.22 g/MJ for RME piloted combustion H_2 across all values of BMEP. Generally lower values of specific HC emissions with lower pilot fuel setting can be attributed to the fact that there are no specific HC emissions from H_2 combustion. These specific HC emissions result from the combustion of the pilot fuel and hence are proportional to the pilot fuel quantity. At 1500 rev/min the specific HC emissions are decreased when there is any increase in BMEP apart from the lowest pilot fuel setting with diesel piloted hydrogen combustion. For diesel piloted hydrogen combustion cases, the specific HC emissions decreased as the quantity of pilot fuel was increased. The reasons presented to explain higher specific NO_X with higher pilot fuel setting hold for lower specific HC emissions with higher pilot fuel setting. As observed at 1000 rev/min, the diesel piloted combustion of hydrogen produce higher specific HC emissions when compared RME piloted combustion of hydrogen.



(a)



(b)

Figure 11: Effect of pilot fuel quantity and type on specific HC emissions for hydrogen combustion with three different diesel pilot and RME pilot fuel settings at 1000 rev/min (a) and 1500 rev/min (b)

4. Conclusions

A study was conducted on diesel and RME piloted dual fueling of natural gas and hydrogen in direct injection diesel engine. Dual fueling of both the natural gas as well as hydrogen were investigated by varying the quantity of the pilot fuel. Diesel and RME were used as pilot fuels. Tests were conducted at two engine speeds. Three different settings were used for pilot fuel were used for each of the gaseous fuel at each engine speed. The key findings of the study are listed below

- Dual fueling of natural gas exhibits an increased ignition delay when compared to the ignition delay exhibited by the pilot fuel when tested in single fueling mode at similar operating conditions. For dual fueling cases, the ignition delay is reduced as the quantity of pilot fuel in increased.

- For a certain operating conditions, there exists a pilot fuel quantity threshold beyond which any increment in the pilot fuel quantity shall not result in reduced ignition delay and higher maximum in cylinder pressure.

- Both for diesel as well as RME piloted combustion of natural gas at higher speeds, the specific NO_X have been generally found proportional to the quantity of pilot fuel where as at lower speeds, there exists a pilot fuel quantity threshold where maximum specific NO_X are produced and any pilot fuel setting below or above the threshold shall result in lower specific NO_X.

- Like specific NO_X, specific HC emissions from diesel and RME piloted combustion of natural gas also exhibit the pilot fuel quantity threshold phenomenon. At lower speeds, the specific HC emissions decrease as the quantity of pilot fuel is increased. At higher speeds, there exists a pilot fuel quantity threshold below or above which the specific HC emissions increase with any increase in the pilot fuel quantity.

- At relatively lower values of BMEP, the specific HC emissions vary significantly and the trend lines converge as BMEP is increased.

- For diesel as well as RME piloted hydrogen combustion, the ignition delay is shortened as the quantity of pilot fuel increased but the peak cylinder pressure does not seem to be a very strong function of ignition delay. Similar peak pressure is achieved even when the pilot fuel is set at a minimum BMEP for diesel piloted hydrogen combustion at 1000 rev/min.

- Specific NO_X has shown different trends at different speeds when hydrogen dual fueling is piloted by either diesel or RME. At lower speeds , the specific NO_X decrease as the quantity of pilot fuel is increased. At higher speeds, the specific NO_X increase as the quantity of pilot fuels is increased.

- Diesel piloted combustion of hydrogen has shown higher specific HC emissions when compared to the RME piloted combustion of hydrogen at both speeds. Lower BMEP values are an exception to this trend. At 1000 rev/min, smaller variation is observed in specific HC emissions when diesel pilots the hydrogen combustion. At higher engine speed, lower specific HC emissions were resulted when the quantity of pilot fuel was increased. This trend was held for both pilot fuels.

Acknowledgments

We thank Steve Warren of BP Marine Ltd (Fuels) UK for coordinating the donation of the RME used in this work

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List of Figures

List of Tables