Indian Journal of Science and Technology Vol. 4 No. 6 (June 2011) ISSN: 0974- 6846

Effect of dual fuel homogenous charge diesel combustion for simultaneous reduction of NOx and smoke –an experimental study

M.Himabindu[1] and N.V. Mahalakshmi[2]
[1] *Department of Mechanical Engineering, Indian Institute of Science, Bangalore-560012, India*
[2] *Department of Mechanical Engineering, Anna University, Chennai- 600 025, India*
buddi_hb@yahoo.com; nvmal2001@yahoo.co.in

Abstract

The present work focuses on reducing oxides of nitrogen (NOx) and smoke emissions significantly and simultaneously without much compromise in efficiency by involving simple and cost-effective in-cylinder modifications i.e., Homogeneous Charge Diesel Combustion (HCDC) using dual fuels (mixture of gasoline- diesel (G-D) and gasoline-sarasol (G-S)). The experiments have been carried out on a single-cylinder, four-stroke, direct injection diesel engine developing 4.4 kW at 1500 rpm. The study had been carried out by fabricating a diesel engine into HCDC mode to install a port fuel injector at intake manifold to create a homogenous charge. The injection timing and duration of the premixed charge was electronically controlled for which electronic fuel injection controller was developed. Gasoline was premixed and port injected before ignition whereas the diesel/sarasol was injected by the conventional injector directly into the cylinder and tested for various premixed percentages, however 10% and 40% was optimized in case of lower and upper limits. It was found that the effect of reduction in NOx and smoke with sarasol in HCDC mode is appreciable than diesel as secondary fuel. With G-S NOx and smoke was reduced by 56.15% and 2.1 BSU respectively whereas with G-D NOx and smoke was reduced by 51.09% and 1.9 BSU respectively. This significant reduction in emissions is due to the thermodynamic physical and chemical properties of sarasol 175/360 apart from HCDC contribution.

Keywords: HCDC engine, port injection timing, premixed charge, NOx emissions

Introduction

Generally, HCCI is achieved by homogeneous mixture, which gets auto-ignited throughout the cylinder volume (Thring, 1989; Allen Gray & Thomas Ryan, 1997) Previous investigators (Odaka *et al.*, 1999) reported that premixed HCCI is achieved by dual injection strategies, i.e., primary fuel (premixed) is injected well before top dead center (TDC) and burns in HCCI mode while secondary injection occurs near TDC and burns similar to conventional diesel combustion whereby NOx is reduced (Yokota *et al.*, 1997). Also some investigators used dual-fuel or a fuel reformer to control the mixture auto-ignition temperature (Fuquan Zhao *et al.*, 1994; Chang Sik Lee *et al.*, 2003; Charles Mueller *et al.*, 2004).

The potential of HCCI is limited by the availability of appropriate fuel. Fuel selection is one of the important aspects of HCCI engine development. Fuel volatility and auto-ignition characteristics are key parameters. The focus of HCCI research is driven by the potential for diesel-like efficiency with simultaneous reduction of NOx and smoke emissions. A large amount of research has been performed to investigate the influence of fuels on HCCI combustion using primary reference fuels, natural gas etc but not many or no HCCI experiments with neat F-T diesel have been reported (Fuquan Zhao *et al.*, 1994; Yokota *et al.*, 1997; Chang Sik Lee *et al.*, 2003; Charles Mueller *et al.*, 2004). One such efficient alternative can be the use of synthetic fuels, which is the prime attempt in this investigation to meet the shortage of fossil fuels and the alarming environmental degradation caused due to their emissions.

The goal of the present study is to investigate the possibility of using sarasol (175/360), a mixture made of C_{12}-C_{26} hydrocarbons. It consists of linear and branched isomers, substituting for commercial diesel as a secondary fuel in Homogeneous Charge Diesel Combustion (HCDC) system along with premixed gasoline to operate continuously and smoothly even at higher loads.

Hence, the main aim of the present work is to reduce NOx and smoke simultaneously without efficiency being jeopardized much in a DI diesel engine. Research effort is focused on using HCDC concept with minimum modifications to the existing engine structure in achieving the above-mentioned results. For this purpose, the homogeneous charge diesel combustion concept was employed in which a portion of fuel is supplied into the intake port to form a homogeneous mixture. This fuel is referred as premixed fuel. It is introduced into the cylinder during suction stroke, where it is compressed and ignited by the main DI diesel fuel.

Table 1. Details of engine specifications

Engine Type	Single cylinder 4 stroke, CIE
Bore/Stroke	87.5/110 mm
Cubic Capacity	661 cc
Compression Ratio	17.5:1
Rated Speed	1500 rpm
DI fuel injection timing	23° BTDC
Diesel injector opening pressure	200-205 bar
Port injector type	Single hole pencil spray
Port injection timing	4.5° BTDC
Port injection pressure	3 bar

Experimental program and test procedure

The test engine used for the experimental investigation is a single-cylinder air-cooled vertical direct injection diesel engine capable of developing 4.4 kW at a constant speed of 1500 rpm, coupled to an electrical dynamometer of 5 KVA. The detailed specifications of the engine are given in Table 1.

Fig.1a. Experimental set-up

The test methodology involved the fabrication of partially stabilized zirconia (PSZ) coated cylinder head to allow port fuel injection through which the premixed charge was sent during suction stroke when the intake valve opens. With the modified head in place, the tests were conducted with neat diesel and later in HCDC mode, i.e., various premixed percentages of gasoline was injected just when the intake valve opened for better mixing. Electronic controller circuit (ECU) controlled the injection timing and duration of the premixed fuel. Gasoline was premixed and port injected before ignition whereas diesel fuel was injected by the conventional injector directly into the cylinder. The PFI is a single-hole pencil spray of 0.5 mm orifice diameter. Experiments were conducted in HCDC mode with inlet valve-opening timings (port injection timing) of 4.5° BTDC (1ms), for better atomization. The quantity of premixed charge was increased gradually from 10 to 50% in steps of 10%, and the amount of diesel injected was correspondingly decreased. When the premixed charge percentage is 50% and above, knocking was observed. Hence, from the preliminary tests it was found that 40% premixed charge is optimized in terms of performance and emissions.

Tests were conducted with six cases namely; base diesel, neat sarasol (base readings), initially with 10% and 40% premixed charge of gasoline to diesel and later with gasoline to sarasol in HCDC mode from no load to full load conditions. The premixed fuel quantity for different premixed ratios was calculated on the energy basis. The premixed ratio is defined as the ratio of the energy of premixed fuel to the total energy from diesel and premixed fuel (equation 2.1). The premixed fuel quantity for different premixed ratio was obtained by adjusting injection duration (2 to 18 ms) controller in ECU and fuel injection pressure in the range of 0.5 to 2.5 bar. The predetermined quantity of gasoline premixed charge was injected as the inlet valve opens and thus compressed inside the cylinder, which was ignited by direct-injected diesel/sarasol (175/360) nearer to TDC in HCDC mode. Oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO) measurements were measured with non-dispersive infrared (NDIR) analyzer accurate to within ±2% while smoke was measured through Bosch smoke meter. Exhaust gas temperature was measured by chromel-alumel thermocouple accurate to within ±0.25ºC. Photographic view and schematic diagram of the experimental set-up is presented as Fig. 1 and 2.

Fig.1b. Experimental set-up

$$PR = \frac{\left(m_p \text{ x } CV_p\right)}{\left[\left(m_p \text{ x } CV_p\right) + \left(m_d \text{x } CV_d\right)\right]} \quad (2.1)$$

Where m_p and m_d indicate the mass consumption rate of premixed petrol and directly injected diesel fuel, respectively, and CV_p and CV_d indicate the calorific values of petrol and diesel. m_p and m_d are measured quantity.

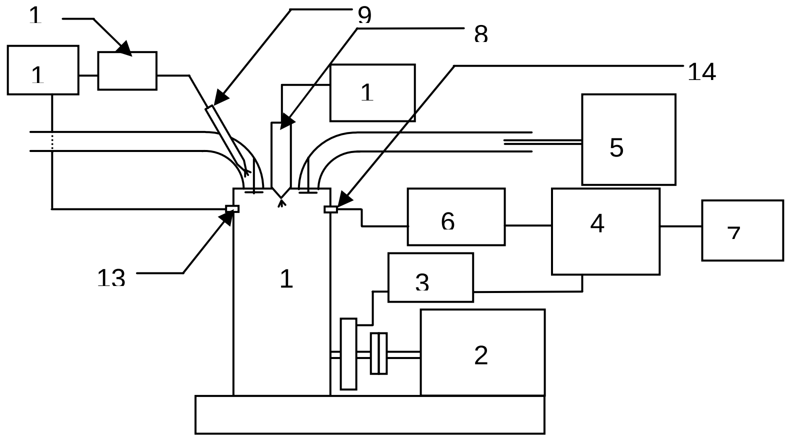
Selection of fuel

Fuel selection is an important aspect of HCDC engine development. HCDC operation is flexible for any octane or cetane rated fuel. Regarding fuel efficiency and emissions, low octane (high cetane) fuel, high octane (low cetane) fuel or a medium octane fuel are suitable for HCDC operation (Magnus Christensen *et al*., 1999) i.e., it is flexible to operate with any fuel. Modifying the fuel can control HCDC auto-ignition. Combustion initiation and heat release rates are achieved by auto-ignition chemistry of fuel-air mixture. Both fuel volatility and auto-ignition characteristics are two fundamental requirements for fuels in HCDC engines.

Hence, in this study, two different fuels i.e., gasoline as primary fuel (premixed fuel) and diesel as secondary or DI fuel, were combined to optimize the operating range and have a better control of combustion phasing. It is difficult to use diesel as premixed fuel because as the pre-mixture auto-ignites rapidly at relatively low temperatures unable to maintain ignition timing near TDC, thus limiting the engine operating condition, and also because of its low volatility. This incomplete fuel vaporization and poor mixture preparation leads to PM and NOx emission, whereas the volatility

1	Engine	8	D.I. Injector
2	Dynamometer	9	Port fuel injector
3	Interrupt circuit	10	Fuel injection circuit
4	Digitalstorage oscilloscope	11	Premixed fuel tank
5	Exhaust gas analyzer	12	D.I. fuel tank
6	Charge meter	13	Camshaft position sensor
7	Printer	14	Pressure sensor

Fig.2. Schematic diagram of experimental set-up



of gasoline makes it relatively easy to form homogeneous charge. In the present study, gasoline was used as a premixed fuel with compression ratio of 17.5:1 without any modification in the engine.

Synthetic fuels

Synthetic fuels (SF) generally include liquid and gaseous fuels as well as clean solid fuels, produced by the conversion of coal, oil shale or tar sands, and various forms of biomass. This experimental investigation involved the study of sarasol (175/360), a synthetic fuel, produced through Gas-To-Liquid process and has been proposed as a substitute for diesel fuel. Sarasol is a mixture made of C_{12}-C_{26} hydrocarbons. It consists of linear and branched isomers. The percentage of carbon and hydrogen content is 85% and 15% respectively. Sarasol initial and final boiling point is 175°C and 360°C.

Table 2. Characteristics of Sarasol (175/360) and diesel fuel

Properties	Sarasol (175/360)	Diesel	Gasoline
Density	780 kg/m³ at 15°C	830 kg/m³	780 kg/m³
Kinematic viscosity	3.45 mm²/s	4.7 mm²/s	0.5 mm²/s
Cetane number	73-74	45-55	----------
Flash point	Typically 92°C	56-65°C	-65°C
Sulphur	<1 ppm	0.05% by weight	----------
Heating value	47,000 kJ/kg	42,500 kJ/kg	43,000 kJ/kg
Autoignition temperature	>220°C	210°C	280°C

Over the conventional diesel fuels F-T fuels have significant advantages in reducing engine emissions. Sarasol has been selected due to its unique physical and chemical properties, which influence the performance and emission characteristics in HCDC operation. Also, HCDC is flexible for any grade of fuel and not many research efforts are focused so far on the study of synthetic fuels in this mode. The physical and chemical properties of this fuel are shown in the Table 2. Sarasol (175/360) has high cetane number, low aromatics, low C/H ratio and relatively low specific gravity.

Electronic fuel injection controller

Premixed fuel injector location and fuel injection timing controller

The premixed fuel injector orientation is found to have a significant effect on the performance and exhaust emission characteristics. Hence, at most care was taken in the injector orientation while fabricating the intake manifold using special purpose machines by trial and error. The angle at which the port fuel injector was positioned was determined in such a way that the spray (pencil type) impinges on the valve seat as the inlet valve opens, so that better homogeneous mixture is formed while using the swirl present at the inlet manifold. The injector orientation was critical to allow formation of homogenous mixture and to avoid wall wetting, which induces high CO emissions. The location of the port fuel injector on the cylinder head is shown in Fig. 3.

The injection timing and duration of the port injector was controlled by an electronically controlled fuel injection circuit or a timing circuit, which was developed for this study (Fig.4). This injection controller consists of two integrated circuits, one for injection duration and the other for injection delay. The optical sensor was fixed with respect to the position of the pointer of camshaft on the engine. When the pointer fixed on the camshaft crosses the sensor, it sends a pulse to the electronic controller unit (ECU). The signal from the sensor is amplified and sent to the input of the first IC, which is meant for injection delay. The output of the first IC is given to the input of the second IC that is meant for injection duration. Injection duration was varied by adjusting the corresponding potentiometer (2 ms to 18 ms). The integrated circuits were triggered by the raising and falling edge of the pulse. This output of the second IC is given to the injector. The injection duration and delay are measured by a cathode ray oscilloscope (CRO) (Fig.5)

Error analysis and uncertainty

All measurements of physical quantities are subject to uncertainties (Table 3). Uncertainty analysis is needed to prove the accuracy of the experiments. In order to have reasonable limits of uncertainty for a computed value an expression is derived. Hence to get

Fig. 3. Location of premixed fuel injector on the cylinder head (a) Front View (All dimensions are in mm)

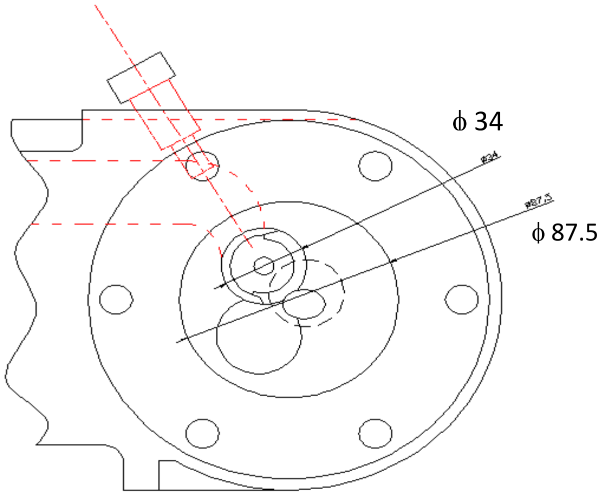


Fig. 3. Location of premixed fuel injector on the cylinder head (b) Top View (All dimensions are in mm)

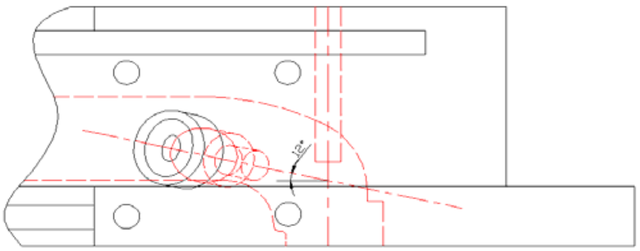


Fig.5 Injection timing diagram

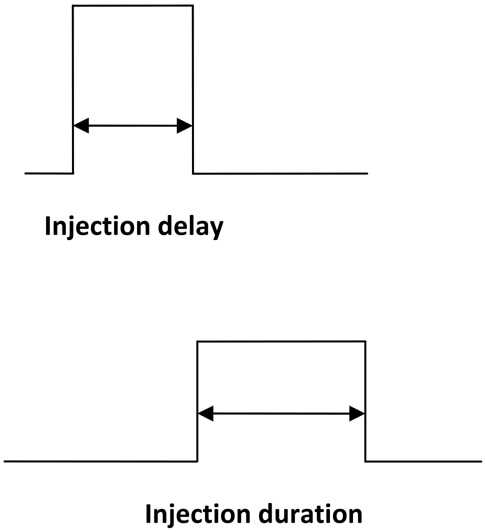


Fig.4. Circuit diagram of injection controller

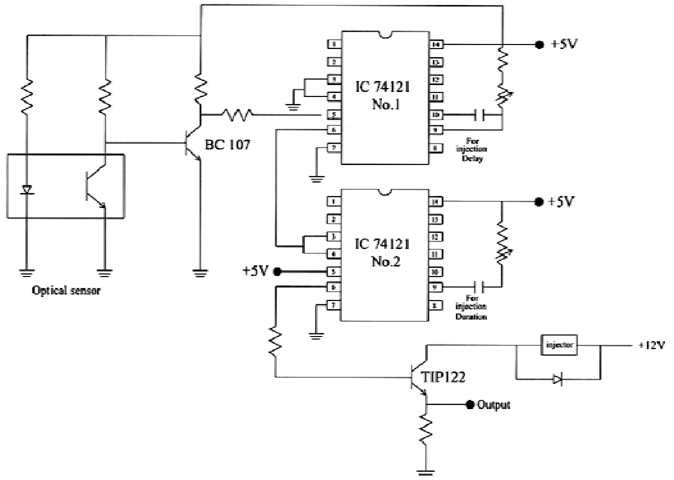


Fig.6. Variation of oxides of nitrogen with percentage of rated power with pure sarasol (175/360) and diesel for various premixed charge percentages

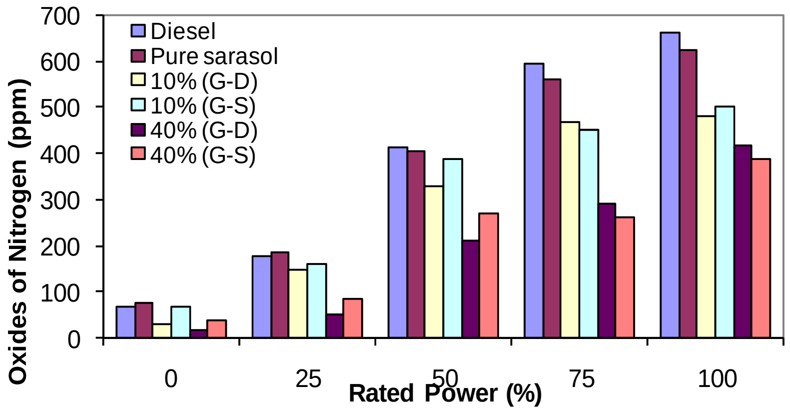


Table.3 Average uncertainties of some measured and calculated parameters

Parameter	Uncertainty (%)
Total fuel consumption	0.75
Speed	1.5
NOx	2
HC	2.8
CO	0.08
Smoke	2.2
Exhaust gas temperature	1.2

Fig.7. Variation of smoke with percentage of rated power with pure sarasol (175/360) and diesel for various premixed charge percentages

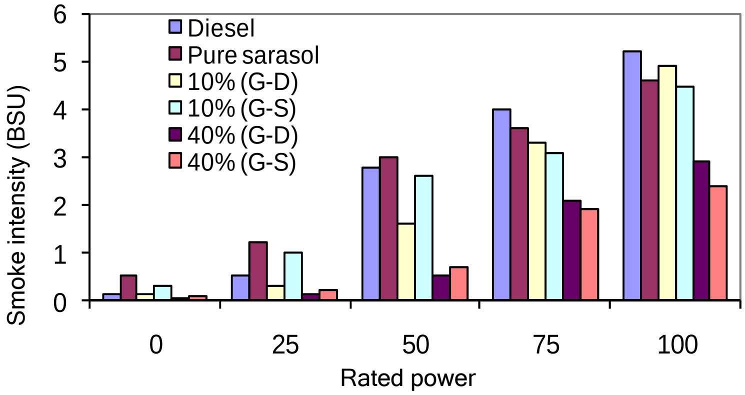


Fig.8. Variation of unburnt hydrocarbons with percentage of rated power with pure sarasol (175/360) and diesel for various premixed charge percentages

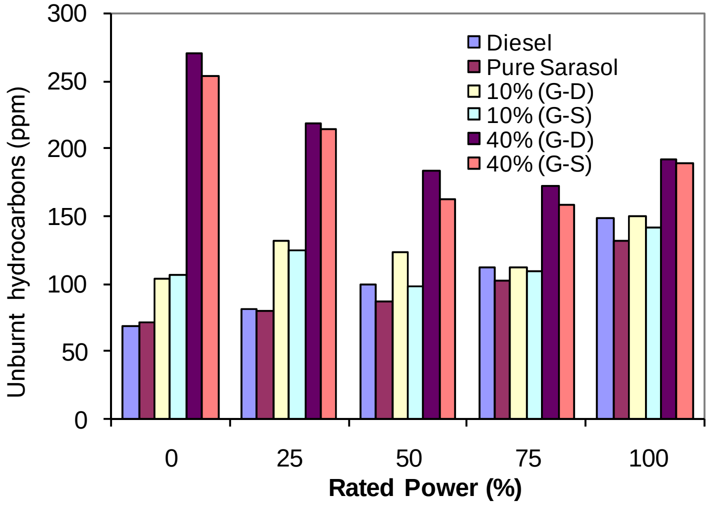
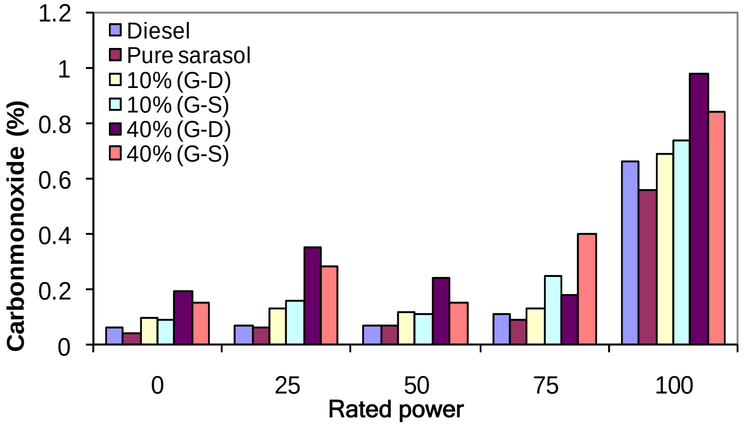


Fig.9 Variation of Carbon monoxide with percentage of rated power with pure sarasol (175/360) and diesel for various premixed charge percentages



the realistic error limits for the computed result the principle of root-mean square method is used to get the magnitude of error given (Kline & McClintiff,1953) as

$$\Delta R = \left[\left(\frac{\partial R}{\partial x_1} \Delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \Delta x_2 \right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial R}{\partial x_n} \Delta x_n \right)^2 \right]^{1/2}$$

(2.2)

Results and discussion

The lower and higher limits of premixed charge percentages namely 10% and 40% (optimum percentage) are considered here to investigate the possibility of substituting commercial diesel with sarasol (175/360) as a secondary fuel in HCDC system. The results of mixtures of gasoline-diesel (G-D), gasoline-sarasol (G-S), base diesel, and base sarasol are discussed in the following sections.

NOx emission

The variation of NOx emissions with percentage of rated power is shown in Fig.6 with 10% and 40% premixed charge of G-D and G-S in HCDC mode along with base sarasol and base diesel. It is observed that 40% G-S show less NOx emissions to a greater extent especially at 75% load when compared to other cases. In the case of 10% premixed charge of G-D, the NOx level remains lower until 50% load when compared to G-S. At 75% load, it is slightly more than G-S. In the case of 40% premixed charge of G-S, the NOx level is higher when compared with G-D upto 50% load, from when on G-S show slightly lower NOx upto full load. With 40% of G-S, at 75% load the NOx reduces by 56.15%, whereas with G-D the reduction is 51.09% when compared to base diesel. The impact of fuel properties of sarasol (cetane number, density, viscosity and latent heat of vaporization) offers particular benefits as far as NOx emissions are concerned in gasoline-sarasol mixture than gasoline-diesel in HCDC mode.

Smoke intensity

The variation of smoke intensity with percentage of rated power is shown in Fig.7. In all the cases, the smoke intensity was very minimal at no loads. With 40% premixed charge of G-D, it shows comparable values of smoke intensity until 50% loads with G-S, after which smoke intensity is high while G-S shows a significantly low level. This may be due to lower C/H ratio as well as the virtual absence of sulphur in synthetic fuel. In addition, since most of the combustion takes place under premixed conditions, there is limited rich mixture available for the soot to form. The premixed charge of 10% of G-D, it shows lower smoke intensity than 10% G-S until 75% load after which G-S show lower smoke intensity when compared to G-D similar to NOx formation. With 40% premixed charge of G-S and G-D, the reductions in smoke intensities are 2.1 BSU and 1.9 BSU respectively when compared to base diesel.

Unburnt hydrocarbons emission

Fig.8 illustrates the variation of UBHC emissions with percentage of rated power for 10% and 40%

Fig.10. Variation of brake thermal efficiency with percentage of rated power with pure sarasol (175/360) and diesel for various premixed charge percentages

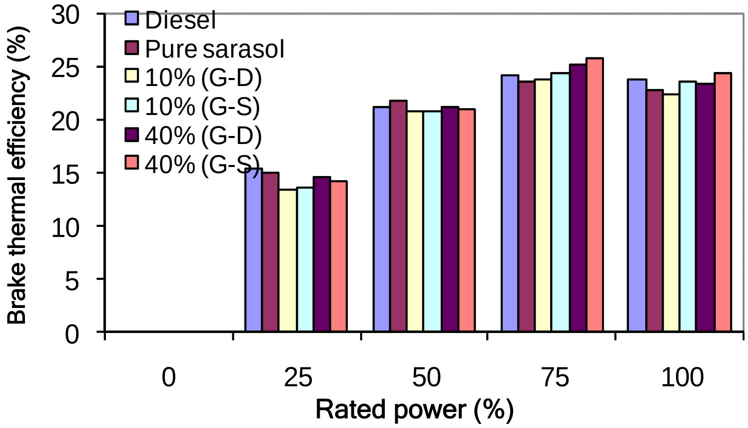
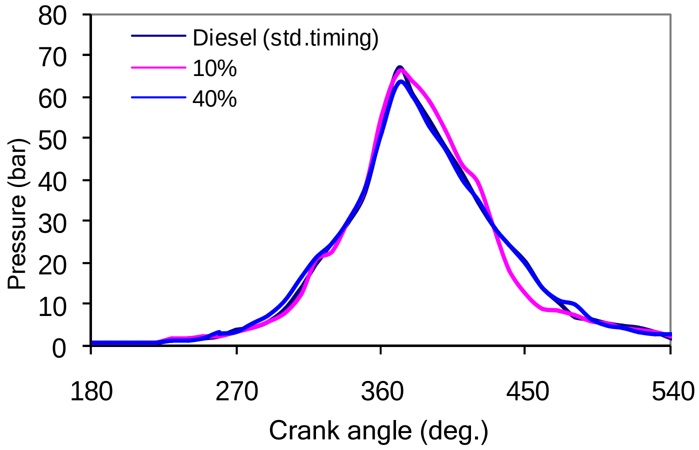


Fig.11. Variation of pressure with crank angle for diesel in HCDC mode and for base diesel, during standard timing at 75% load



premixed charge of G-Dand G-S. The UBHC emission with both G-S and G-D is high with 10% and 40% premixed charge percentages. With 40% premixed charge, G-S shows slightly lower UBHC levels than G-D. This may be due to high cetane number, which directly relates to ignition delay and better vaporization (density) characteristics of sarasol helps to lower the UBHC. Further, since diesel is the conventional base fuel with saturated hydrocarbons and Sarasol G-D and G-S are fuels with unsaturated hydrocarbons, it may lead to differential combustion rate. This may be the reason for the variation of UBHC.It is also believed that lower aromatics also contribute to the reductions of UBHC emissions. UBHC level varies from 270 ppm at no load to 192 at full load in case of G-D, whereas it varies from 254 ppm at no load to 189 ppm at full load in case of G-S with 40% premixed charge.

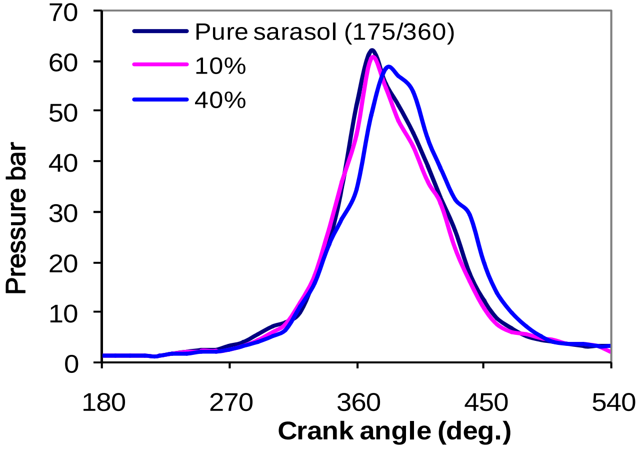
Carbon monoxide emission

The variation of carbon monoxide with percentage of rated power is shown in Fig.9 CO emissions with pure sarasol are comparable at lower loads with pure diesel, whereas at higher loads there is distinct reduction in CO when compared to pure diesel. Both the premixed charge percentages with G-S and G-D show higher CO emissions when compared to base fuels. They follow a very close trend up to 50% loads, which is more at higher loads. However, in the case of 40%, G-S shows comparatively lower CO levels than G-D. Similar to UBHC, the reduction of CO emissions for sarasol may be attributed to its high cetane number and low density when compared to diesel. With 40% premixed charge of G-S, the CO level ranges from 0.15% at no load to 0.84% at full load whereas with G-D it varies from 0.19% at no load to 0.98% at full load.

Brake thermal efficiency

The variation of brake thermal efficiency with percentage rated power is shown in Fig.10. For all the cases the brake thermal efficiency almost remains the same. In the case of 40%, G-S indicates a positive performance over G-D at higher loads with negligible improvement at 75% load. With 40% of premixed charge of G-S in HCDC mode an improvement of 1.77% at 75% load is obtained. G-S is a fuel with unsaturated hydrocarbons and a higher chemical structure. This could have led to a better combustion rate and better thermal efficiency.

Fig.12. Variation of pressure with crank angle for sarasol in HCDC mode and for base sarasol at 75% load

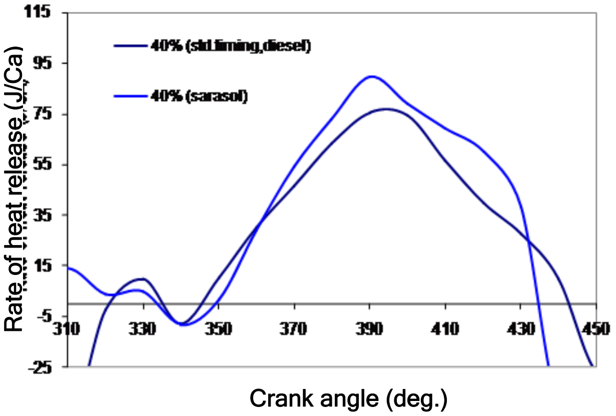


Pressure crank angle analysis

The measured pressure crank angle diagrams are presented in Fig.11 and Fig.12 for base diesel and pure sarasol as well as for the premixed charge percentages (10% and 40%) in HCDC operation at 75% load. The peak pressure decreases with increase in premixed charge percentages. The cylinder pressure initially increases at low rate and then rises steadily for a few degree of crank angle, then to a peak value of about 9-12° ATDC. In the case of 10% premixed charge, the peak combustion pressure with DI diesel during standard timing is 66 bar. However, in case of 40% premixed charge the peak pressure with DI diesel during standard timing is 63.6 bar. Similar observation is made with sarasol and premixed charge percentages (10% and

40%) at 75% load, which is depicted in Fig.12. With pure sarasol the maximum pressure is 62 bar, which occurs at 10° ATDC. In HCDC operation with 10% premixed charge the peak pressure is of 60.5 bar whereas with 40% premixed charge the peak pressure is of 58.5 bar. Combustion pressure rises more slowly with sarasol due to higher cetane number, which reduces the ignition delay.

Fig.13. Variation of rate of heat release with crank angle for 40% premixed charge in HCDC operation at 75% load



Heat release rate

Fig.13 shows the variation of heat release rate with crank angle for the optimised premixed charge percentage of 40% in HCDC operation with DI fuels namely diesel (standard fuel injection timing) and sarasol. The general shape of the heat release curve for 40% premixed charge shows a single stage profile with a small initial heat release during the 310-330 CAD called the cool flame (pre-reactions), subsequently proceeding vigorously called the hot flame which occurs 10° ATDC. This is unlike the typical 2-stage profile observed for the standard DI process, which is divided between an initial stage of premixed combustion and the main stage of diffusion combustion. This type of profile characterizes the heat release rate of HCDC mode. All the three premixed charge percentages trace a close trend however the maximum heat release rate occurs in the case of sarasol. This is due to high energy content (heating value) of sarasol and lower density.

Conclusion

Based on the experimental studies with premixed charge of gasoline and DI injection of diesel and also sarasol (175/360) nearer to TDC for various percentages (optimized 10% and 40%), the following conclusions are drawn. At low premixed percentage of gasoline, the engine behaves almost similar with diesel or sarasol as secondary fuel. As the percentage of premixed gasoline increases, the behavior of the engine is better optimized in terms of efficiency and emissions. The best result was achieved at 40% of premixed charge of gasoline-sarasol rather than gasoline-diesel. At higher percentages (above 50%), knock plays a limiting factor. At 40% of premixed charge of G-S and 75% of operating load, the following results were obtained when compared to base diesel: NOx is reduced to 56.15%; HC increases to 46 ppm; CO increases to 0.29%; Smoke intensity is reduced by 2.1 BSU; BTHE increases to 1.77%. Overall, 40% premixed charge of gasoline sarasol at 75% operating load gives the best results than gasoline to diesel. This is due to influence of the physical and chemical properties sarasol (175/360), as secondary fuel and better homogenous mixing that has enough potential to reduce both NOx and smoke simultaneously and significantly with slight improvement in efficiency.

Acknowledgment

The author sincerely thanks the Shell MDS (Malaysia) Sdn.Bhd. Bintulu Malaysia for providing the sample for research purpose.

References

1. Thring RH (1989) Homogeneous-Charge Compression-Ignition (HCCI) Engines. *SAE* 89. pp:58-66.
2. Allen W (Bill) Gray III and Thomas W. Ryan III (1997) Homogenous charge compression ignition of diesel fuel. *SAE* 97. pp: 1927-1935.
3. Chang Sik Lee, Ki Hyung Lee and Dae Sik Kim (2003) Experimental and numerical study on the combustion characteristics of partially premixed charge compression ignition engine with dual fuel. *Fuel*. 82. 553-560.
4. Charles J. Mueller, Glen C. Martin, Thomas E. Briggs and Kevin P. Duffy (2004) An experimental investigation of in-cylinder processes under dual-injection conditions in a DI diesel engine. *SAE Trans*. 2004-01-1843. pp: 1146-1163.
5. Fuquan [Frank] Zhao, Thomas W. Asmus, Dennis N. Assanis, John E. Dec, James A. Eng and Paul M. Najt (1994) Homogenous Charge Compression Ignition (HCCI) Engines *SAE*. PT-94 Key Research & Devpt. Issues.
6. Kline SJ and McClintock FA (1953) Describing uncertainties in single-sample experiments. *Mech. Engg*, 75 (1), 3-8.
7. Magnus Christensen, Anders Hultquist and Bengt Johansson (1999) Demonstrating the multi fuel capability of a homogeneous charge compression ignition engine with variable compression ratio. *SAE Trans*. 1999-01-3679. pp: 261-275.
8. Odaka Matsuo, Hisakazu Suzuki, Noriyuki Koike and Hajime Ishii (1999) Search for optimizing control method of homogeneous charge diesel combustion. *SAE Trans.* 1999-01-0184. pp: 133-141.
9. Yokota Haruyuki, Yugo Kudo, Hiroshi Nakajima, Toshiaki Kakegawa and Takashi Suzuki (1997) 'A new concept for low emission diesel combustion. *SAE Trans.* 970891. pp: 1479-490.

Nomenclature

° : Degrees; °C: Degrees Centigrade;η: Efficiency; %: Percentage; ATDC: After Top Dead Centre; BP: Brake Power; BSN: Bosch Smoke Number; BSU: Bosch Smoke Unit; BTDC: Before Top Dead Centre; BTE: Brake Thermal Efficiency; CAD: Crank angle degrees; CI: Compression Ignition; CO: Carbon monoxide; CRO: Cathode Ray Oscilloscope; DI: Direct Injection; ECU: Electronic Control Unit; EFI: Electronic Fuel Injection; HCCI: Homogeneous Charge Compression Ignition; HCDC: Homogeneous Charge Diesel Combustion; IC: Integrated Circuit; KW: Kilo Watts; ms: Milliseconds; NDIR: Non Dispersive Infrared; NOx: Oxides of Nitrogen; PFI: Port fuel injector; PM: Particulate matter; ppm: Parts Per Million.