

## Effect of Air Intake Pressure Drop on Performance and Emissions of a Diesel Engine Operating with Biodiesel and Ultra Low Sulphur Diesel (ULSD)

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**Abstract.** The main objective of this research is to study the effect of the pressure drop in the inlet manifold, on the engine performance and exhaust emission system, the fuel used in this v6 diesel engine is Rapeseed Methy Ester (RME) and a comparison between (RME) fuel and ultra low sulphure diesel (ULSD) was conducted and a steady state test for both fuels were carried at BMEP 3.1 and 4.7 bar. At combustion process in terms of cylinder pressure and heat release, engine performance and exhaust emission were analysed, an experimental evidence showed that, pressure drop increasing in the intake manifold will increase the fuel consumption and reduces the engine efficiency by using both, RME and ULSD. Engine efficiency with RME is 1.2%- 2% lower than ULSD, having exhaust emission level of NO<sub>x</sub> and CO slightly higher for RME comparing to ULSD. Emissions of unburned hydrocarbon for RME is much smaller than ULSD.

### Key words

Air intake, pressure drop, biodiesel

## 1. Introduction

Engine performance is sensitive to induction depression especially for Internal Combustion (IC) engines running without turbocharger or supercharger. Most of engine intake systems consist of dirty duct, air box, air cleaner, clean duct, intake manifold plenum, and intake manifold runner. The typical length of the air intake system (AIS) can be up to 1 meter. The air path through this manifold presents a pressure drop challenge to the designer of air induction system. The pressure drop across the air intake system is known to have a significant influence on the indicated power of the IC engine. The pressure drop is created due to the suction generated by the descending

piston in the case of natural aspirated engine. The pressure drop along the intake system is very dependant on engine speed and load, the flow resistance of different elements in the system, the cross sectional area through which the fresh charge moves, and the charge density[1].

Measurements of pressure drop along the air intake system could be performed by the use of standard steady flow test bed. These measurements are carried out on complete air intake system together with cylinder head and ports. This is particularly important for direct injection engines where the port is shaped to generate the required degree of swirl within the cylinder [2]. Therefore, it is very imperative to study the effect of air intake pressure drop on a standard multi-cylinder diesel engine operating with different fuels. This paper intends to comprehend this phenomenon and their effect on the combustion quality as well as emissions on conventional V6 diesel engine by means of all modern technologies such as common-rail injection system and variable geometry turbine (VGT) which equipped to the engine.

## 2. Biodiesel as an Alternative Fuels

The European Parliament and the Council of the European Union have taken serious action to promote the use of biodiesel as an alternative to fossil fuels for transport sector [3]. The transportation sector accounted for 21% of all CO<sub>2</sub> emissions worldwide in 2002. Currently, 95% of all energy for transportation comes from fossil fuel oil [4]. The step taken is not just to reduce the emission but also to reduce the dependence on imported energy and influence the fuel market for transport and hence to secure the energy supply in the medium and long term basis. The ordinance sets a European aim of 5.75 % replacement of conventional transport fossil fuels with biofuels by December 2010

[5]. In United Kingdom (UK), 30% of energy consumption was recorded from transport sector in 2004 and it is the sector where the emission growth rate is the fastest among other sectors [6].

Studies conducted by different researches around the world also revealed a positive benefits of biodiesel towards reducing emissions level [7-10]. However, it was reported that the emission level varies depending on the type of the sources where the biodiesel produced (rape seed, palm oil, animal fat etc.) [11]. In addition, the NO<sub>x</sub> is slightly increase and proportional to with the mass percentage of oxygen in the biodiesel and engine speed [12]. RME mixing with diesel fuel reduces the calorific value of the fuel blend, thus resulted on the engine power drop and increased in brake specific fuel consumption (bsfc) [13, 14]. The lubrication properties of RME also give a great benefit to the cylinder wall. A series of experiment with RME showed that after 33 hours of operation, no excess carbon built-up was found in the engine [14]. Biodiesel is biodegradable, non-toxic and most importantly it is based on renewable resources. Biodiesel feed stocks also do not contain sulfur compound where it is part of the causes of emissions produce from the combustions of fossil fuels in internal combustion engines.

Biodiesel is methyl or ethyl ester of fatty acid made by transesterification process of vegetable oils or animal fats. Biodiesel has been defined in the European Union in the technical regulation EN14214 or in the United State in ASTM 6751-02 [15]. The standard ensure that the biodiesel meet the regulation in fuel production process of removing glycerin, catalyst and alcohol. Not as the pure vegetable oil, the transesterification process ensures that the unnecessary element removed from the oil. It has been prove that for the engines running on 100% vegetable oil in long term may show serious problems in injector coking, ring sticking, gumming and thickening of lubricating oil due to higher viscosity and non-volatility [4, 16]. In the European Union biodiesel is the biggest biofuel used and represents 82% of the biofuel production. Biodiesel production for 2003 only in EU-25 was 1,504,000 tons [17]. In 2003, the world total biodiesel production was around 1.8 billion liters [17].

Most of the modern car in EU are currently has capability to operate on biodiesel with low percentage of biodiesel blend without having any problems. The biodiesel could be used as it own or blended with conventional fossil fuel without having to change or made any modification on the standard diesel engines because biodiesel has similar properties as mineral diesel [18, 19].

### 3. Experimental Setup

The experimental work was performed on a V6 diesel engine. The engine was water-cooled, fitted with a high pressure direct fuel injection system from common rail and equipped with twin variable-geometry turbine (VGT)

turbochargers and a cooled exhaust gas recirculation (EGR) system. However, the EGR is isolated from this experiment to avoid the effect of exhaust gas to the characteristics of fluid flow in intake manifold such as pressure, temperature and specific heat value. The engine was operated at equal brake torque for both ULSD and RME. Details of the engine are described in Table 1. Figure 1 shows the photograph of the test engine used in this study.

Table 1. Specification of test engine

Engine Specification	Details
Type	V6 Twin Turbo
Injection System	Common Rail
Bore x Stroke	81.0mm x 88.0mm
Displacement	2721 cm <sup>3</sup>
Compression ratio	17.3
Injector type	Piezo actuator injector
Injection cone angle	156°
No. of Injection nozzle holes	6

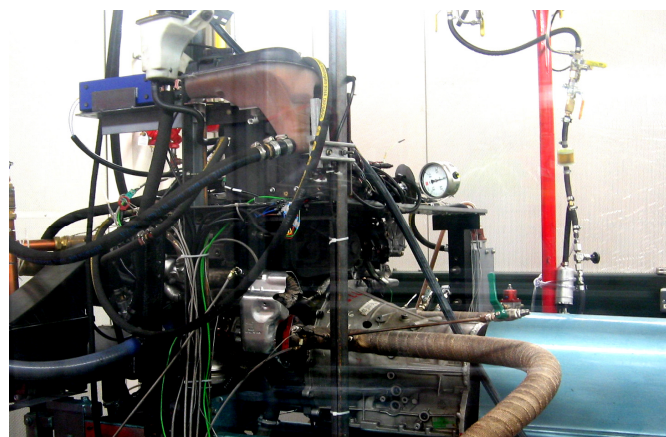


Figure 1. Photograph of test engine

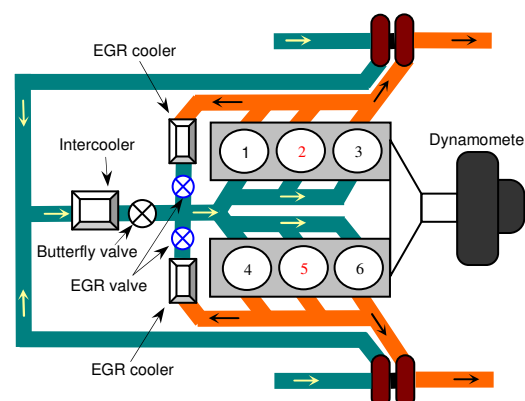


Figure 2. Schematic diagram of a V6 engine system

An eddy-current water-cooled Schenck dynamometer model W230 with a series S2000 control system was used to load the engine. The in-cylinder pressure was measured by piezometric glow-plug high pressure transducers supplied by AVL, with model number AVL GU13G wired to AVL Piezo Amplifiers model 3066A03 where pressure was read at crankshaft positions recorded by a shaft encoder. The piezo sensor used has a sensitivity of 15pC/bar. Both data series (pressure and crank angle degrees) were recorded through a National Instrument data acquisition system NI PCI-6023E installed in a Windows XP - based PC. Pressure was measured in cylinders 2 and 5 as depicted in Figure 2. Temperature was measured in all exhaust manifolds by *k*-type thermocouples with data recorded by a second National Instrument data acquisition system NI PCI-6224 and monitored through a LabVIEW-coded graphic user interface.

An off-line steady state analysis based on in-cylinder pressure was carried out using an in-house LabVIEW code and the analysis included peak pressure, indicated power, indicated mean effective pressure (IMEP) and coefficient of variation of IMEP. Furthermore, the analysis of mass fraction burn, rate of heat release, brake specific fuel consumption (bsfc), thermal efficiency and ignition delay were performed to evaluate the overall parameters of combustion.

The analysis of emissions data was carried out using an AVL CEB200 analyser and recorded in Excel file. The exhaust gas was sampled at 30cm downstream of the turbine exit. The measurement methods included non-dispersive infrared method (NDIR) for CO and CO<sub>2</sub>, heated flame ionization detector (HFID) for total unburned hydrocarbon and heated chemiluminescence detector (HCLD) for nitrogen oxides.

The engine was controlled by an ETAS unit. It was operated with the boost air temperature and fuel temperature kept constant at 35°C. The specific engine operating conditions was controlled by the Engine Management System (EMS) and the engine data was recorded by INCA software in a portable computer. The experiments were conducted at two different engine loads as shown by the test conditions in Table 2.

Table 2. Test condition

Engine Parameter	Low Load	Part Load
Engine speed, n	1550 rpm	1550 rpm
Brake Torque, Tb	67 Nm	102 Nm
Fuel temperature, Tf	35 °C	35
Boost air temperature, Tba	35 °C	35

Table 3 shows the combinations of experimental modes used throughout the test. The pressure drop in intake manifold was varying by the use of butterfly valve which is installed between the intercooler and plenum chamber as shown in Figure 2. The pressure drop is defined as the

different between local static pressure in intake manifold and initial boost pressure divided by initial boost pressure. The engine was fuelled with biodiesel (RME) and ULSD. Both fuels were supplied by Shell Global Solutions UK, details of the properties of the test fuels are summarized in Table 4.

The main differences in comparing RME with ULSD are (i) an increase in cetane number by 1.5%, (ii) an increase in density by 6.8%, (iii) an increase in viscosity by nearly 81%, (iv) a decrease in lower calorific value (LCV) by 8.7% and (v) a large decrease in sulfur content by 89.1%. (vi) The RME contain oxygen bonded in the fuels.

Table 3. Pressure drop in air intake systems

Mode	Engine Load	Pressure drop [%]
LP1	Low load	0
LP2	Low load	20
LP3	Low load	40
LP4	Low load	60
PP1	Part load	0
PP2	Part load	20
PP3	Part load	40
PP4	Part load	60

Table 4. Fuel properties

Property	ULSD	RME
Cetane number	53.9	54.7
Density at 15°C [kg/m <sup>3</sup> ]	827.1	883.7
Viscosity at 40°C [cSt]	2.467	4.478
50% distillation point (°C)	264	335
90% distillation point (°C)	329	342
LCV [MJ/kg]	42.7	39.0
Sulfur [mg/kg]	46	5
Molecular mass (equivalent)	209	296
C (% wt.)	86.5	77.2
H (% wt.)	13.5	12.0
O (% wt.)	-	10.8

The engine operating conditions are based on the NEDC (New European Driving Cycle). The experiment was conducted under controlled environment. Air temperature was controlled between 23°C and 27°C and the relative humidity was measured by RH sensor and recorded by Window based PC. Air inlet temperature and atmospheric pressure were measured and calculated to comply with the test validity as explained in Directive 1999/96/EC, 2000 [20].

## 4. Engine Feedback

The engine clearly is responding to the pressure drop in the intake manifold, while other parameters are consequences of engine feedback by the EMS.

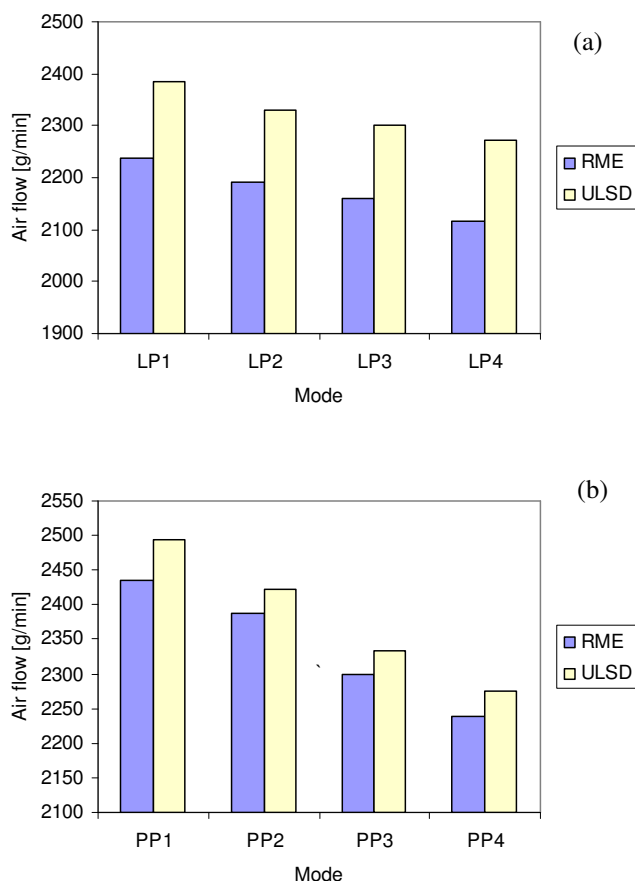


Figure 3 Air flow rate (a) low load, (b) part load

Figure 3 shows the air flow rate of the intake manifold as consequence of pressure drop of RME and ULSD. When air flow is decreasing the pressure drop increased, It is very well predicted as a direct effect from the flow restriction in AIS. We can also see that, the engine operating with RME induced less air as compared to ULSD in both low load and part load. Low load induced less air as compared to high load. Note that the engine was running at the same brake torque for both ULSD and RME. The stoichiometric air-fuel ratio (AFR) for RME is 15.6% lower than ULSD. Therefore, the engine operating with RME is induced less air as compared to ULSD to gain equal brake torque.

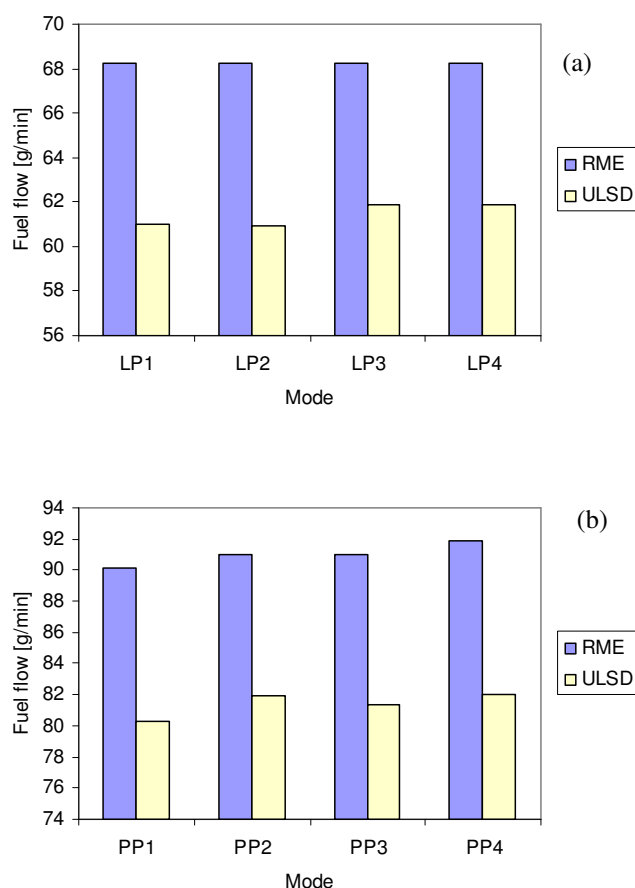


Figure 4. Fuel flow rate (a) low load, (b) part load

Figure 4 shows that the fuel flow rate is higher at part load as compared to low load, and the fuel flow is slightly increasing as pressure drop increases. At part load, the increase of fuel flow is clearly responding to pressure drop, while the fuel flow rate is rapidly increased as pressure drop increases. At low load, RME is injected 11.5% more than ULSD. Figure 4 also revealed that at part load, RME is injected 12.5% more than ULSD. This is the consequence of low calorific value of RME which is slightly lower resulted to consume more fuel to gain similar brake torque with ULSD.

## 5. Engine Performance and Emissions

Figure 5 present the in-cylinder pressure from the combustion of ULSD and RME at increase of pressure drop. The dotted lines represent the in-cylinder pressure for RME while the straight lines for ULSD. The in-cylinder pressure data was retracted from cylinder number 5 of the engine operating at 4.7 Bar BMEP and 1550 rpm. It is found that the in-cylinder pressure for the case of RME is higher at all pressure drops. The pressure difference is clearly seen on RME and ULSD at main fuel injections.

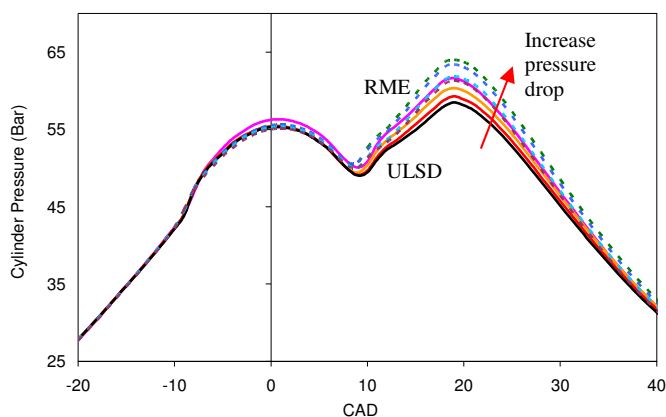


Figure 5. Cylinder pressure for ULSD and RME at different pressure drops (a) low load, (b) part load

It is very interesting to see that even when the pressure drop decline, the peak pressure decrease. A research conducted by Spaddacini as quote by reference [1] on autoignition characteristics under controlled conditions revealed that when the boost pressure increase (or pressure drop decrease), the ignition delay decrease, resulted to the higher peak pressure in engine cylinder. The ignition delays reduced associated with reduction in premixing time when the boost pressure increase due to the increase of volumetric efficiency at constant intake  $O_2$  concentration.

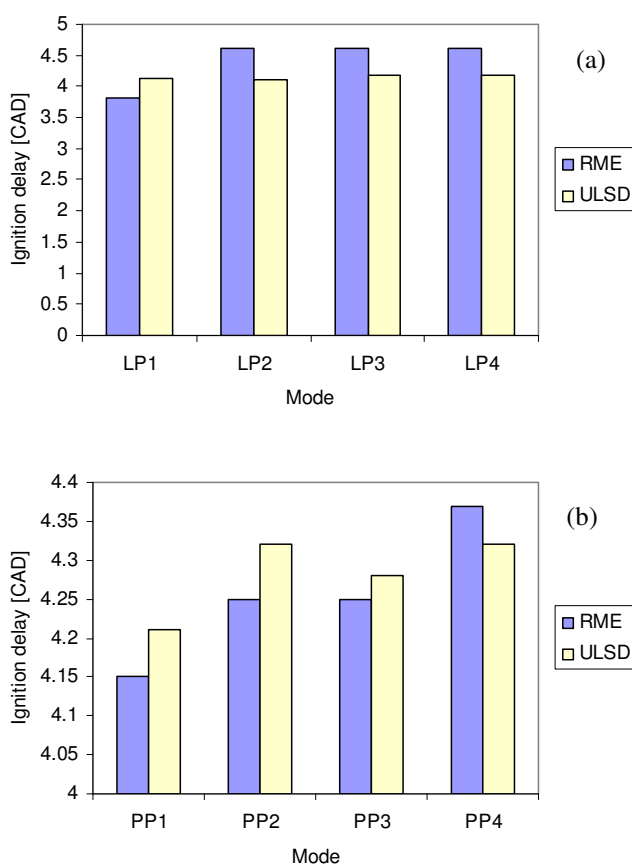


Figure 6. Ignition delay as consequences of pressure drop and engine load (a) low load, (b) part load

Figure 6 shows the ignition delay as a function of pressure drop and fuel type. The ignition delay is clearly higher at part load as compared to lower load. Figure 6 also shows that at low load, the ignition delay is slightly increasing as pressure drop increased. While, at part load, ignition delay is quickly increased as pressure drop increases. The intake air pressure is one of the parameter that has been proved to affect the ignition delay. The change of pressure in air intake systems will varies the charge conditions during the delay period, thus resulted to decrease the ignition delay as intake pressure increases [1]. Figure 6 is clearly shows that the ignition delay for RME is shorter as compared to ULSD. The best reason to explains this phenomena is perhaps due to higher bulk modulus of RME which caused an early injection event [9, 19]. The results are also agree with other study when a diesel engine operating with RME.

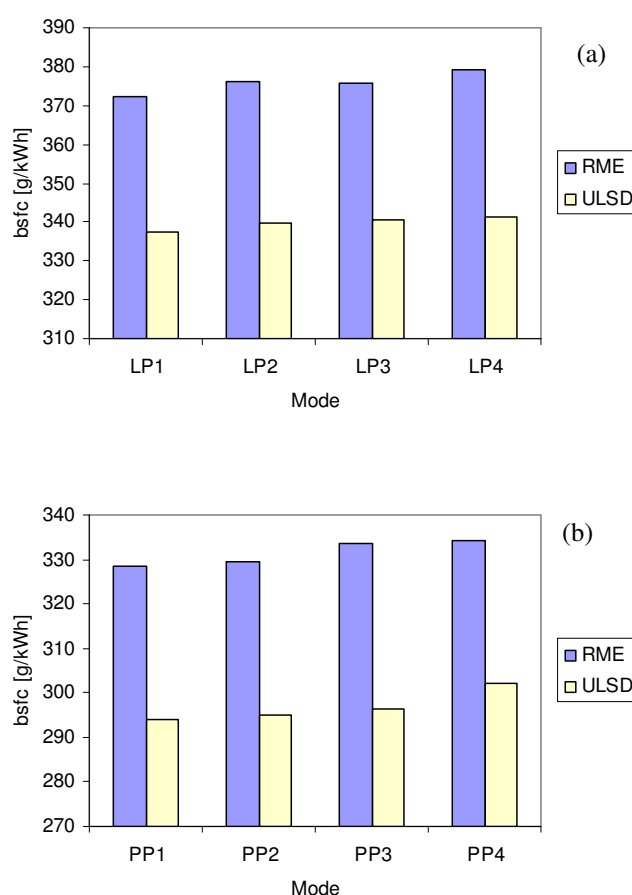


Figure 7. Brake specific fuel consumption (a) low load, (b) part load

Figure 7 shows the bsfc of the engine operating with RME and ULSD at low load and part load. It is found that the bsfc is higher at low load as compared to high load. It clearly shows that bsfc for RME is higher as compared to ULSD. The higher bsfc value in the case of RME is due to lower energy content as depicted in Table 4. This result cause the engine to inject more fuel to gain equal brake torque. Figure 7 also revealed that the bsfc is slightly increased as pressure drop increases for

all fuel and engine loads. The bsfc is clearly a function of AFR as discussed in details by Heywood [1]. The discharge air decrease when the pressure drop increases in intake manifold, as depicted in Figure 3. This brings a lower AFR and increasing engine bsfc.

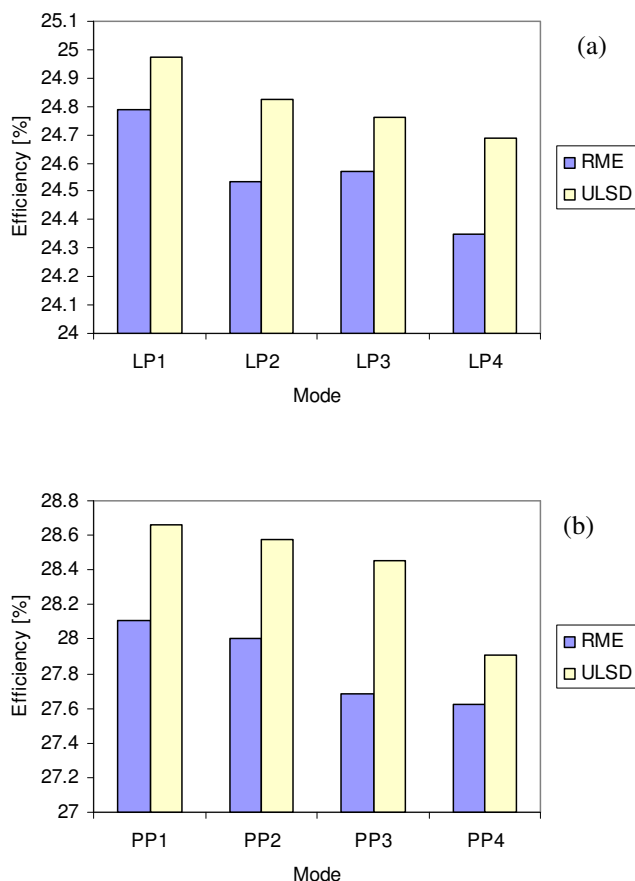


Figure 8 Efficiency of the Enghien (a) low load, (b) part load

Figure 8 shows the efficiency of the engine as consequence of fuel and pressure drops. It clearly shows that the engine efficiency is lower for RME as compared to ULSD. The engine efficiency is higher at part load as compared to low load. Figure 8 also revealed that the efficiency is slightly decreased as pressure drop decreases for all of the fuels.

NO<sub>x</sub> formed by the combustion of fuel in internal combustion engine typically consists of nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) where the nitric oxide is dominant with a small amount of NO<sub>2</sub> [1]. The formation of NO<sub>x</sub> is mostly from nitrogen in the air but some liquid fuels contain nitrogen such as NH<sub>3</sub>, NC and HCN thus contribute to higher potential on producing more NO<sub>x</sub> [21]. It is acknowledged that this emission was highly dependent on post-combustion gas temperature, duration of gas exposure to this high temperature combustion and the species in post-combustion gases which are highly related to equivalent ratio,  $\phi$  [22].

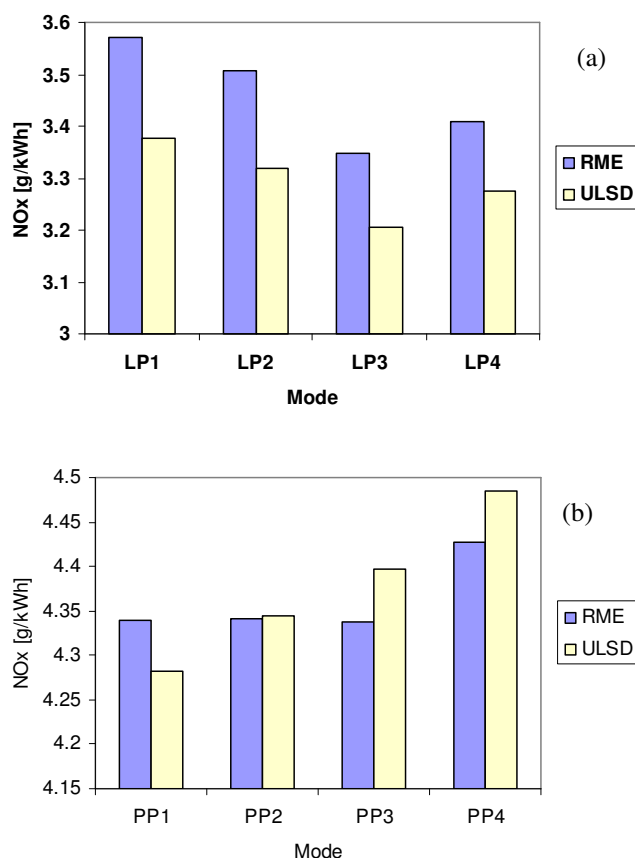


Figure 9. Exhaust emissions of NO<sub>x</sub> (a) low load, (b) part load

Figure 9 shows the NO<sub>x</sub> emission as a consequence of fuel and pressure drop. All NO<sub>x</sub> levels depicted in Figure 9 are relatively higher due to no EGR used. It is found that RME produces higher NO<sub>x</sub> as compared to ULSD at all load and pressure drop. The results are generally established with the reports by other studies on RME [12, 14]. The researches suggested that the premixed combustion is promoted when RME is injected by the common rail fuel injection system. This resulted to the advanced of injection timing thus, increased the peak in-cylinder pressure and temperature [9]. The combustion of RME promotes very low unburned hydrocarbon as compared to ULSD due to high burning rate estimated by heat release as reported by many researchers on biodiesel [23].

The trend of NO<sub>x</sub> formation in Figure 9 is almost comparable to in-cylinder maximum pressure (P<sub>max</sub>) suggested that NO<sub>x</sub> formation is strongly dependent on maximum pressure and temperature as explained in details by Zeldovich mechanism. It is found that at low load, the formation of NO<sub>x</sub> is slightly decreased as pressure drop increases while at part load; NO<sub>x</sub> is slightly increased as pressure drop increases. The formation of NO<sub>x</sub> is clearly related to the combustion behavior in the combustion chamber. Figure 6 shows that the ignition delay varies when the pressure drop increases. At low load, the ignition delay is slightly increased promoted to increase the premixed combustion thus reduces the exhaust NO<sub>x</sub>.

The combustion of fuel occurred at low pressure in combustion chamber as compared to part load. This condition has lead to lower peak flame temperatures as well as post combustion mixing with cooler excess air [24]. At part load, the function of AFR is significant to the formations of NO<sub>x</sub> rather than ignition delay. The formation of exhaust emissions is strongly dependent on fuel distribution and the rate of change for fuel distributions due to mixing process [1]. The NO<sub>x</sub> is increased when the AFR decreases as discussed by many authors [1, 24]. Many researchers agree that the increase of boost pressure promoted to the lean combustions of diesel engine and the rate of heat release is resemble to the injection rate and becomes sharper and the quality of combustion improves [24, 25]. Therefore, the increase of pressure drop is proved to gives opposite results as the boost pressure on engine emissions.

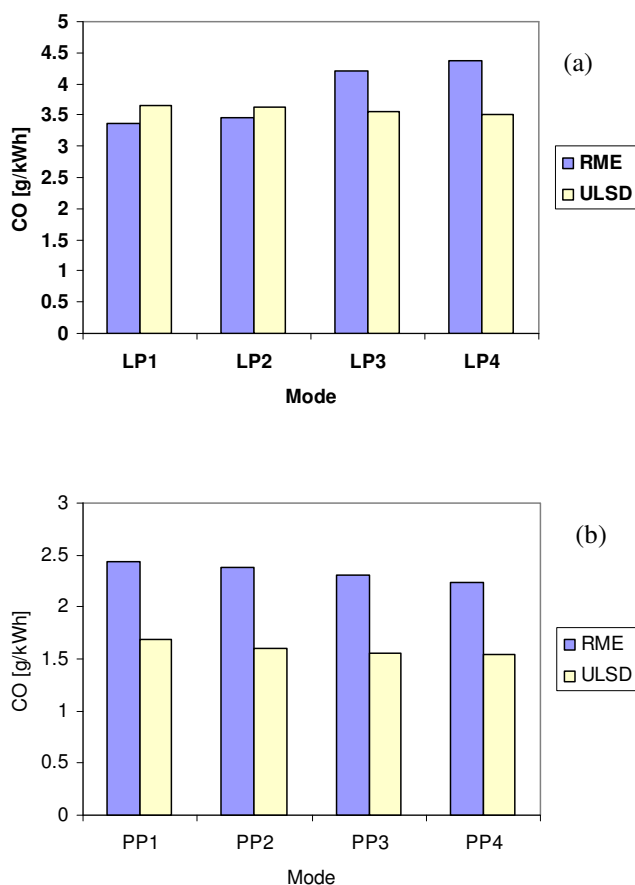


Figure 10 Emissions of carbon monoxide (a) low load, (b) part load

Figure 10 shows the emissions of carbon monoxide from the combustion of RME and ULSD at low load and part load. It is found that the combustion of RME in a diesel engine produces more CO as compared to B50 and ULSD. Figure 10 also revealed that at low load, the formation of CO is higher as compared to part load.

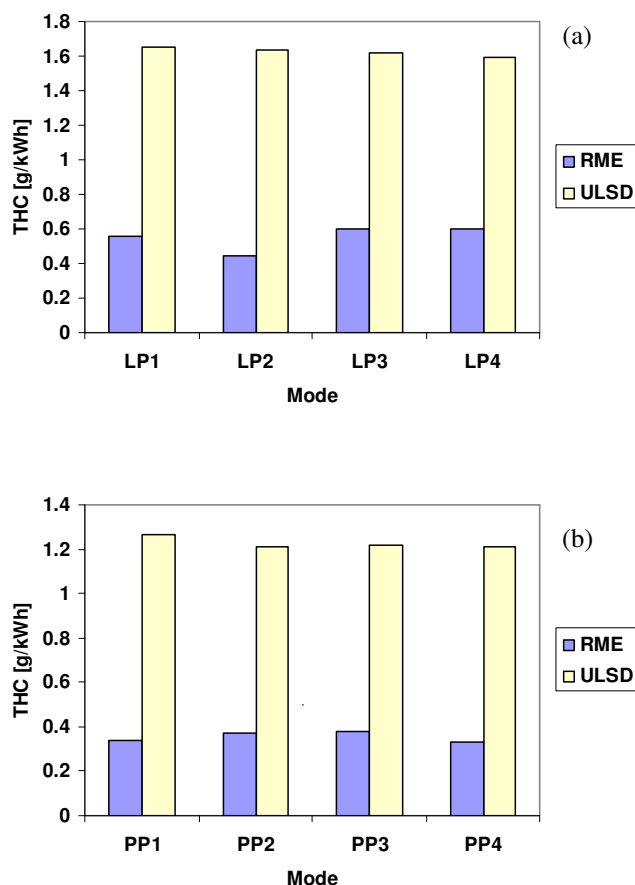


Figure 11 Emissions of total hydrocarbon (a) low load, (b) part load

Figure 11 shows the emissions of total hydrocarbon. It is found that the combustions of ULSD produces higher THC as compared to RME at all pressure drop and engine loads. At low load, the formation of THC is not affected by the pressure drop. It is found that at high load, the formation of THC for RME is level as pressure drop increase. Meanwhile at part load, the HC is reduced as pressure drop increases.

## 6. Conclusion

The results show that the pressure drop in intake manifold gives negative impact not only to the engine efficiency and power density, but also in terms of engine-out emissions. The effect of air intake pressure drop on the engine performance and emissions of a V6 diesel engine has been investigated and the conclusions can be summarized as follows.

1. The increase of pressure drop resulted to increase bsfc and reduces the engine efficiency at low load and part load.
2. The exhaust emission of NO<sub>x</sub> is slightly decreased at low load due to longer of ignition delay. While at part load, the function of AFR is significant to the formations of NO<sub>x</sub> rather than

ignition delay thus promoted to increase NO<sub>x</sub> as pressure drop increase.

3. The emission of CO and THC is slightly reduced at part load but these emissions are slightly level at low load.
4. The effect of pressure drop is significantly affected the combustion and emissions of the engine on both ULSD and RME. The trend of change is almost similar for RME as compared to ULSD. However the rate of change is slightly different due to different fuel properties.

## 7. Acknowledgement

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