Small Scale Power Generation using a Dual Fuel System

Talal F. Yusaf [*], Mushtak Talib Ali Al-Atabi [**], and D. R. Buttsworth [*]

[*] Department of Mechanical Engineering,
University of Southern Queensland, 4350 Queensland,
AUSTRALIA

[**] School of Engineering, Taylor's College,
47500 Subang Jaya, Selangor DE,
MALAYSIA

ABSTRACT

Single-cylinder diesel engines are widely utilized in Malaysia to generate electricity on small scales in open markets and rural areas. This paper presents a brief study carried out to: (i) understand the nature of exhaust emissions (NO_x, CO and CO_2) when adopting a dual fuel system using Compressed Natural Gas (CNG) in a single-cylinder, stationary diesel engine, and (ii) compare the dual fuel emission and engine performance results to those of diesel. The use of CNG is considered a possible solution for reducing the toxic emissions from these engines. This work shows that by using the dual fuel system, NO_x, CO and CO_2 concentrations in the exhaust gases were, on average, reduced by 54%, 59% and 31%, respectively when the engine runs at maximum-load operating conditions. The average power output from the engine operating on dual fuel was 10% higher than that operating on diesel over the tested range of engine speeds.

1. INTRODUCTION

Over the past six decades, researchers have demonstrated that natural gas (NG) can be successfully used as a fuel for motor vehicles as well as power generation [1]. These researches were mainly motivated by the introduction of stringent air quality regulations in urban areas in different parts of the world.

The major hazardous components of the exhaust gases of a diesel engine are oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and unburned total hydrocarbon (UTH). NO_x emissions are produced almost entirely by combustion processes. During combustion, oxygen (O_2) reacts with nitrogen to form nitric oxide (NO), nitrogen dioxide (NO_2), and relatively small amounts of other compounds of oxygen and nitrogen.

Both molecular nitrogen (N_2) in the atmosphere and the chemically bound nitrogen in materials being burned (called "fuel nitrogen") can react with oxygen to form oxides of nitrogen (NO_x). When ultraviolet light from the sun reacts with a mixture of NO_x and hydrocarbons, ozone is formed. Ozone is the major constituent of what is commonly referred to as smog. In addition, NO_2 is considered a major pollutant by itself [2]. High levels of nitrogen oxides can lead to smog and acid rain, it can cause respiratory infections, lung irritation, bronchitis, or pneumonia. Excessive levels of nitrogen oxides can decrease the strength of textiles, discolor fabrics and corrode metal surfaces.

CO is the most widely spread gaseous health hazard to which man is exposed. The toxicity of CO is a result of its reaction with the hemoglobin of blood. CO combines with hemoglobin of the blood to form bright red carboxy-hemoglobin (COHb), which is chemically stable, and thus the hemoglobin is no longer available to carry oxygen.

High concentration of free CO_2 in water may adversely affect respiration and gas exchange of aquatic animals. It may even cause death and should not exceed levels of 25 mg/L in water [3].

Single-cylinder diesel engine-run generators are heavily utilized in Malaysia to generate electricity at low scales in non-permanent locations. A typical example is the night market (or "pasar malam" in local language), which is a huge open market that convenes once or twice a week in a certain location in every neighborhood. Hundreds of sellers use these generators to provide electricity to run and illuminate their booths. These night markets are visited by a large number of customers during the time of their convention. A view of a typical night market is shown in Fig. 1.

The deterioration of the quality of air due to generators' exhaust emission, and the high density of people at the market place during its convention are among the reasons why the use of dual fuel instead of diesel should be seriously considered.

2. ENGINE MODIFICATION AND EXPERIMENTAL WORK

This work included modifying an existing four-stroke single-cylinder diesel engine to operate using a dual fuel system. The most practical way of converting a diesel engine to accept CNG was by installing CNG-air mixer at the air inlet before the combustion chamber. In this arrangement, the CNG would be admitted into the combustion chamber along with the air intake charge, while the diesel was used as a pilot in maintaining the flame inside the combustion chamber [4]. Some modifications needed to be done in dual fuel system. The design of the venturi-mixer used in this study was based on the CFD study [5]. The mixer was fabricated based on the best simulation results which showed that the best mixing was attained at L/D = 4, and number of holes = 8. A sketch of the mixer is shown in Fig. 2.

Fig. 1 A view of a typical night market in Malaysia

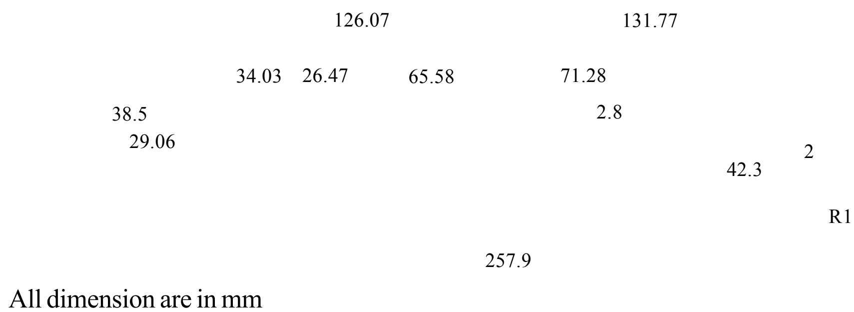


Fig. 2 A sketch of the mixer used in this study

In order to perform the required tests, the experimental engine test bed was utilized, as shown in Fig. 3. This engine test bed allowed to measure exhaust temperature, lubricant oil temperature, fuel consumption rate, and engine speed.

An eddy-current dynamometer was used to apply variable torques to test the ability of the engine to produce power. Exhaust gas detector units were employed to study the concentration of exhaust gases components. The Exhaust Gas Detector Unit is a portable automotive exhaust gas analyzer that uses single beam Non-Disperse Infrared (NDIR) measurement technology to characterize NO_x, CO, CO_2, and O_2 concentrations. Emission elements were measured using electrochemical sensors.

Various experiments were performed using a stationary engine, with the specifications shown in Fig. 4. The engine tests included varying the torques and the engine speeds under different operating conditions.

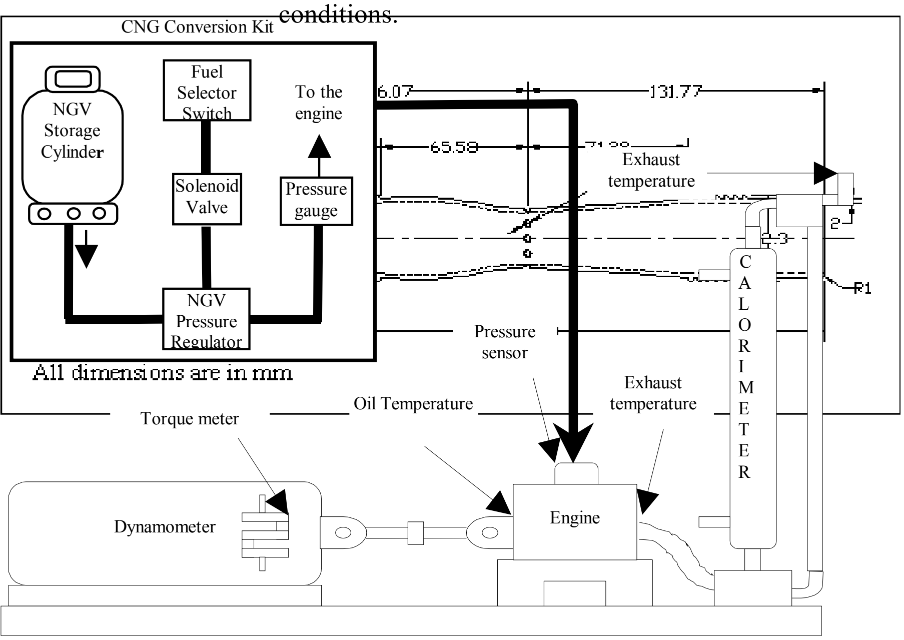
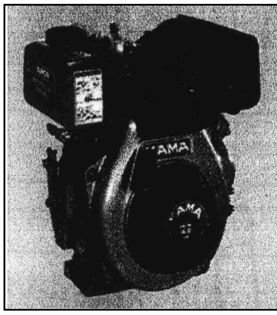


Fig. 3 A schematic diagram of the experimental rig used in this study



Model: Y170F Vertical Strike Diesel Engine

- Air cooled single cylinder type
- Combustion system direct injection
- Bore and stroke (mm): 75 x 55
- Displacement: 211 cc
- Engine speed: 1800/3600 rpm
- Maximum output: 4.7 hp
- Compression ratio: 16:1
- Net weight: 27 kg
- Dimension (mm): 324 x 410 x 416

Fig. 4 The engine used in the current study

3. RESULTS AND ANALYSIS

3.1 Oxides of Nitrogen

Figure 5 compares the relationship between NO_x emission and engine speed for diesel and dual fuel during the maximum operating conditions. It is clear that the dual fuel establishes an overall superiority over the diesel, and the NO_x concentration in the exhaust gases for dual fuel, on average, is lower by 54% compared to diesel.

However during the no-load operating condition this trend was generally inverted. For the no-load operating conditions, as shown in Fig. 6, the NO_x emission was higher with the dual fuel operation during high-speed compared to diesel operation. This was due to the higher air utilization and faster combustion, which resulted in a much higher peak cycle temperature and greater production of NO_x [6]. As the speed increased the diesel fuel engine was running at a lower air to fuel ratio compared to dual fuel, which means the reduction of oxygen intake. Therefore, to reduce the NO_x emissions for dual fuel, the CNG injection should be increased. Another method was to reduce the air flow to make the mixture richer than that under normal dual fuel operation. This could be done by throttling the intake air at light loads using high sophisticated equipment such as electrical control unit (ECU). Another solution was to mix CNG with only part of the incoming air flow [7]. Nevertheless, in the application of power generation, the no-load conditions did not prevail for long periods, as it was the case of idling vehicles, hence their role is mostly downplayed. For the engine speed of 2000 rpm, which yielded maximum torque, dual fuel has a clear cut superiority (less NO_x), at all the applied torques, over the diesel. This is clearly shown in Fig. 7.

Dual fuel Diesel

NO_x (ppm)

Engine Speed (rpm)

Fig. 5 Variation of NO_x with engine speed under maximum operating conditions

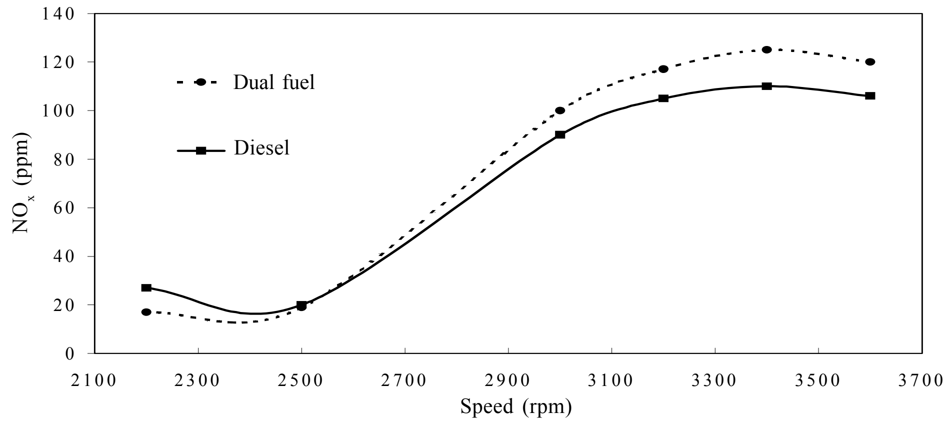


Fig. 6 Variation of NO_x with engine speed under no-load operating conditions

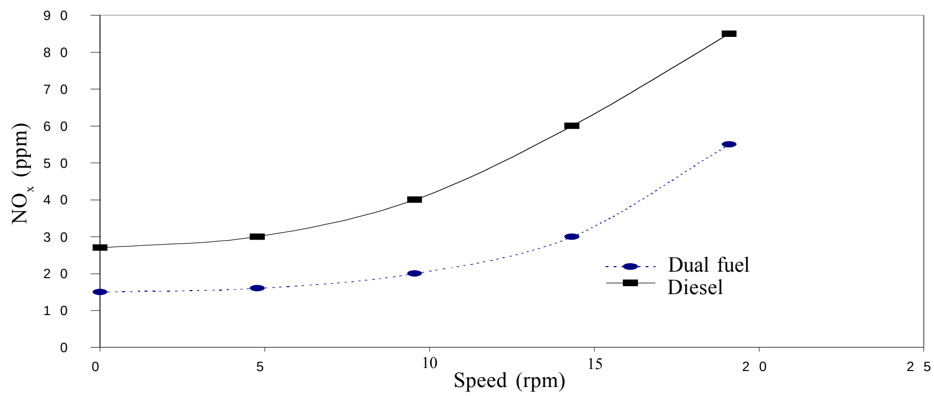


Fig. 7 Oxides of nitrogen emission versus torque, for dual fuel and diesel at constant speed of 2000 rpm

3.2 Carbon Monoxide

For the maximum-load operating conditions, the CO for dual fuel was 59% lower compared to diesel. This is shown in Fig. 8. Generally, the dual fuel operated better than diesel at maximum-load operating conditions. This shows that the dual fuel could achieve better combustion at higher loads compared to diesel.

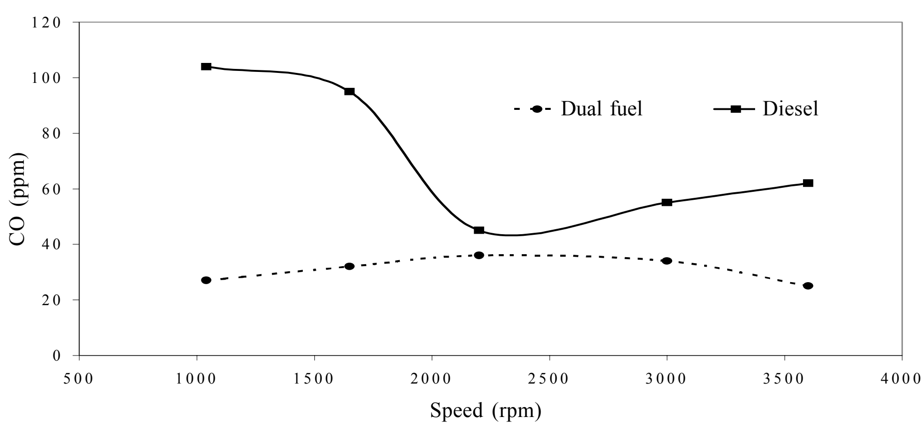


Fig. 8 Variation of CO with engine speed under maximum-load operating conditions

The most important engine parameter influencing CO emissions was the equivalence fuel-air ratio. All other variables caused secondary effects. The CO emission from dual fuel under light operating conditions tended to be higher than that of diesel as shown in Fig. 9. Figure 10 confirms this conclusion; at constant engine speed of 2000 rpm, the dual fuel started to show an improvement only at torques higher than 16 Nm. This was attributed to incomplete combustion, due to the fact that the flow of CNG to the combustion chamber was uncontrolled (un-throttled). In contrary to the CNG, the diesel fuel system used nozzles to supply fuel; therefore diesel delivery was proportional to the pressure difference. When pressure was increased, more diesel fuel would be injected to the combustion chamber. As a result, the dual fuel became very rich and CO emission increased as the engine speed increased. This problem could be overcome by injecting less CNG into the combustion chamber or increasing the air intake using an air controller [8].

3.3 Carbon Dioxide

CO_2 concentration in the exhaust gases is mainly a function of the chemical composition of the fuel and the availability of oxygen during the combustion process. Tests showed that the dual fuel gave lower CO_2 emission during all operating conditions. During the maximum operating conditions the dual

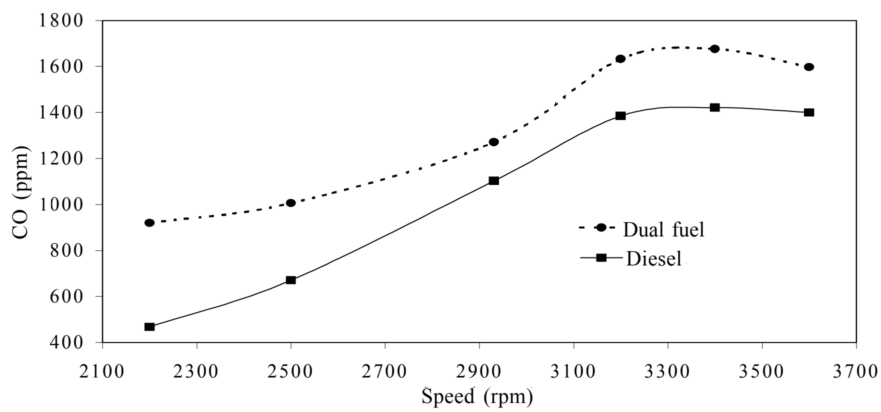


Figure 9 Variation of CO with engine speed under no-load operating conditions

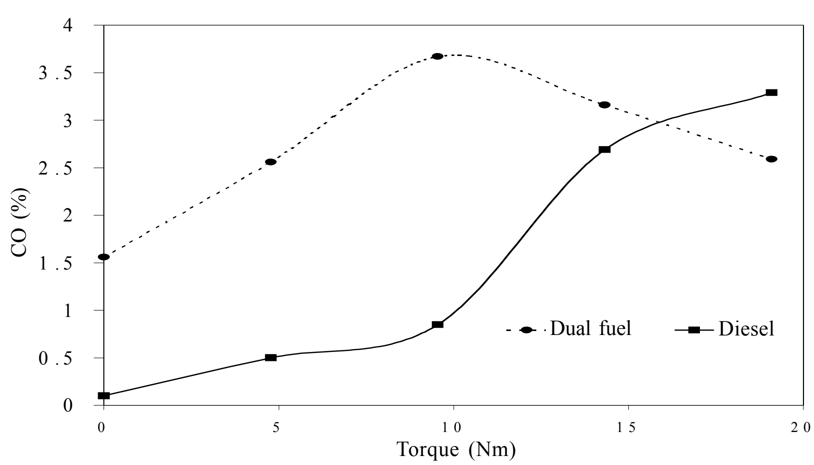


Figure 10 Carbon monoxide emission versus torque, for dual-fuel and diesel at constant engine speed of 2000 rpm

fuel gave an average of 31% less CO_2 emission compared to diesel as shown in Fig. 11. The no-load operating conditions resulted in 5% reduction in CO_2 emission when using the dual fuel compared to the diesel, as shown in Fig. 12. At constant engine speed of 2000 rpm, dual fuel gave lower CO_2 emission at all the tested torques. Figure 13 shows that there was an average reduction in CO_2 emission of 18% compared to diesel.

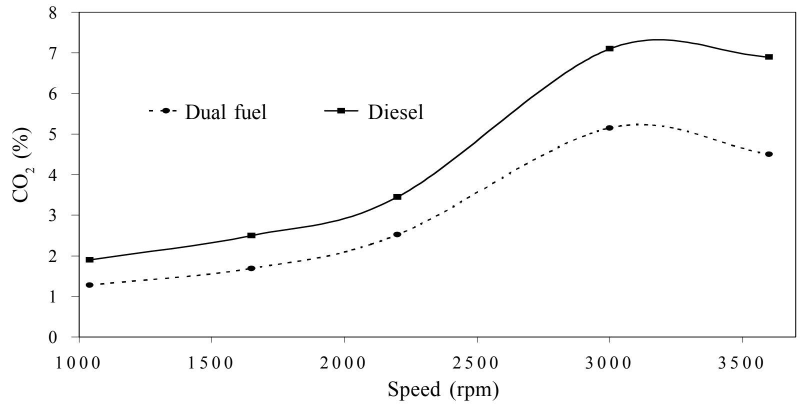


Fig. 11 CO_2 emission versus engine speed for dual fuel and diesel at maximum-load operating conditions

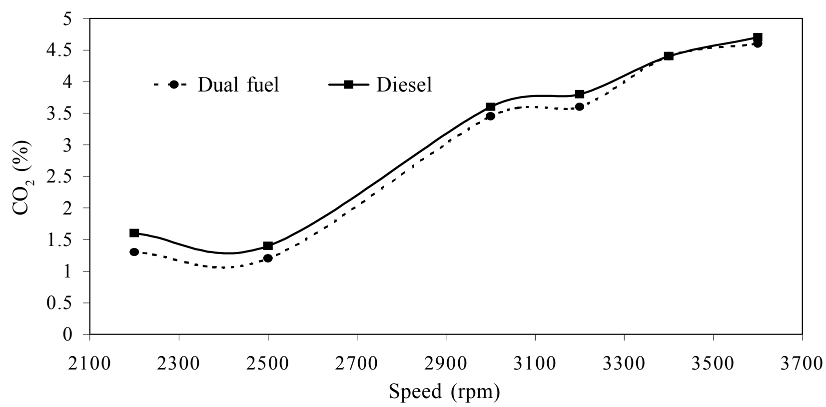


Fig. 12 CO_2 emission versus engine speed for dual fuel and diesel at no-load operating conditions

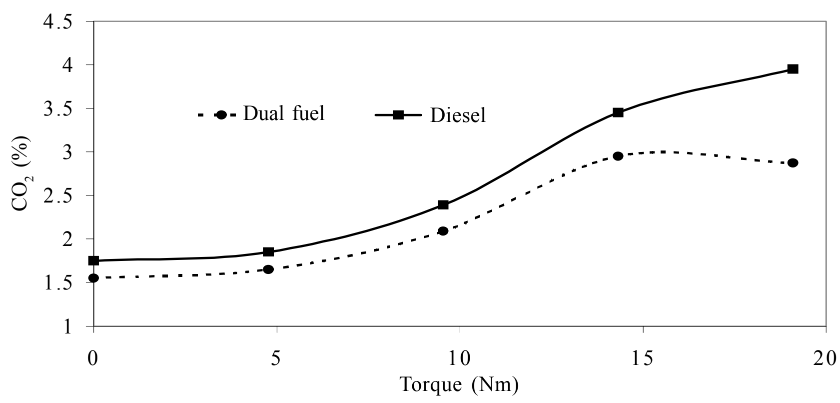


Fig. 13 CO_2 emission versus torque for dual fuel and diesel at constant engine speed of 2000 rpm

The results can be explained in the light of the fact that CNG consists mostly of methane, which is CH_4 whereby diesel fuel is $C_nH_{1.8n}$, which means that for a molecule of carbon there is 1.8 molecules of hydrogen that exist in the diesel, whereas for methane one molecule of carbon is accompanied by four molecules of hydrogen. This indicates that the percentage of carbon in the methane or CNG is low compared to that in diesel. Thus the emission of CO_2 for dual fuel is lower than diesel fuel.

3.4 Power Characteristics

From the results of the study, it was found that dual fuel system produced higher power than the diesel system, at engine speeds up to 3000 rpm. The maximum power achieved increased with the increase in speed to a maximum and then dropped as speed increased to above 3000 rpm. This trend was observed for both dual fuel and diesel as shown in Fig. 14. At engine speeds beyond 3000 rpm, the power output from the diesel became higher than the power of the dual fuel; this was due to knocking, which resulted from rapid combustion.

The energy inputs from CNG for different torques at constant speed (2000 rpm) are shown in Table 1. The emission factors of CO and NO_x in g/kWh of electricity output at different loads for 2000 rpm are shown in Table 2.

Table 1 Energy Input from CNG for Different Torque Values at 2000 rpm

Torque (Nm)	Energy input from CNG (kW)
5	2.616
10	5.233
15	9.560
20	7.850

Table 2 Emission Factor of CO and NO_x in g/kWh of Electricity Output at Different Loads for 2000 rpm

Torque (Nm)	CO (g/kWh)	NO_x (g/kWh)
5	2.50	2.98
10	2.68	3.10
15	3.15	3.25
20	4.12	5.36

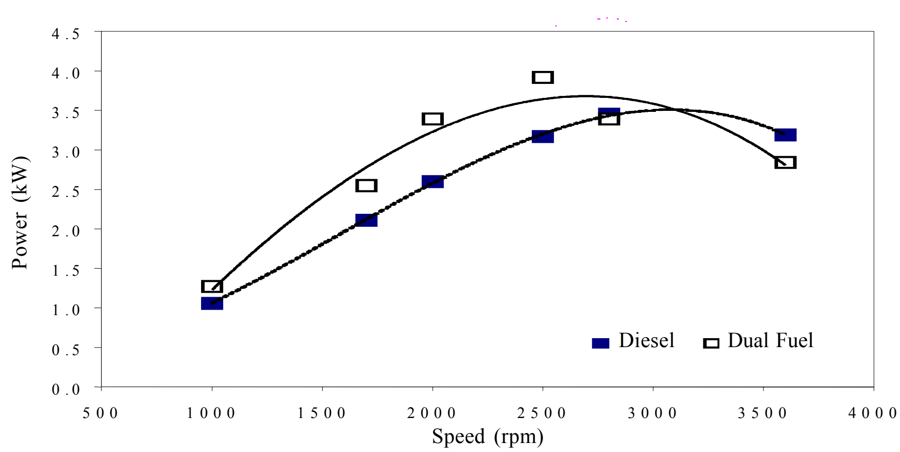


Fig. 14 Power characteristics of the engine at maximum operation conditions

3.5 Comparison with Previous Results

Akihiro showed that there was a reduction in exhaust emission such as NO_x, CO, and CO_2 [9]. The reduction of the NO_x was about 40% compared to the standard diesel engine. In comparison to results obtained in this study, the NO_x reduction was about the same percentage as the work of Akihiro. The average reduction of NO_x components in this study was about 53% under the maximum operating conditions. The large reduction of the NO_x emission is due to the reduction in the use of pilot diesel fuel. Akihiro replaced 80% of diesel by NG (in terms of total fuel energy content), while in this study the CNG percentage metered to the engine was about 85%. Akihiro has reduced the CO by about 90%. The reduction of CO emission, in this study, was observed to be reduced in the similar trend. This is due to high percentages of CNG used during rich combustion. The reduction percentages of CO_2 were about 30% from results obtained in this study under the maximum operating conditions and comparable to Akihiro's study.

Nissan Motor Co., Ltd. in Japan has developed a new advanced medium-duty CNG dual truck [10], using four-stroke six-cylinder engine with brake power and torque of 132 kW/2800 rpm and 539 Nm/1600 rpm, respectively. From Yukihiro study, it was found that the maximum brake power obtained from the dual system on this engine was about 14% more than the standard diesel engine. This has similar trend to the maximum break power from this study. The maximum brake power from results in this study was about 6% for smaller engine. It should be noted that it is not desirable to increase the power and the torque much higher than the manufacturer designed limits. This will cause high thermal stresses and lead to serious damages to the engine [10].

4. CONCLUSIONS

This study shows that the conversion of an existing small single-cylinder stationary diesel engine to a dual fuel system can be done with minimum modification. The attractive feature of such an engine is that it operates on relatively low compression ratio (16:1), which is suitable for dual fuel systems using CNG. This will save the cost and burden of reducing the compression ratio, an unavoidable task when working with bigger engines. Tests showed that the emission of CO_2 was less for dual fuel compared to diesel at all operating conditions. Maximum-load operating conditions yielded higher reduction, 31%, compared to only 5% at no-load operating conditions. At maximum operating conditions both NO_x and CO emissions were less for dual fuel compared to diesel (by 54% and 59%, respectively). However, at no-load operating conditions tests showed, generally, that diesel has an advantage over the dual fuel. From power generation point of view, the no-load conditions are not significant since they do not prevail for long periods of time, as it is the case of idling vehicles.

It was also shown that the use of dual fuel will give higher power compared to the diesel over considerable range of engine speeds of up to 3000 rpm.

It has been demonstrated, beyond doubts, that the use of dual fuel system for power generation, in the "pasar malam" for instance, will have a positive impact on the health of the dwellers of these places, whether sellers or customers. It is to be noted that the sellers are already using CNG cylinders for cooking, therefore this will add no burden on them.

The authors are planning to forward the recommendations of this work, together with a feasibility study, to the Ministry of Health and Environment Authority of Malaysia for further actions.

5. ACKNOWLEDGEMENTS

The authors wish to thank the University Tenaga Nasional - Malaysia for the support extended during this work.

6. NOMENCLATURE

CO	=	carbon monoxide
CO_2	=	carbon dioxide
CNG	=	compressed natural gas
NO_x	=	oxides of nitrogen
ppm	=	particle per million
rpm	=	revolution per minute
UTH	=	unburned total hydrocarbon

7. REFERENCES

[1] International Association for Natural Gas Vehicles, Inc. (IANGV). 1991. *NGV Survey Newsletter* No. 20, V 240, Auckland, New Zealand.

[2] Guthrie, J.; De Vita, J.; Nguyen, K.; and Ferreira, T. 1997. Sources and Control of Oxides of Nitrogen Emissions. A Report. State of California, California Environmental Protection Agency, Air Resources.

[3] Yusaf, T.F. 1995. The Use of Natural Gas in Small High Speed Diesel Engine. A Thesis Submitted to University Kebangsaan Malaysia.

[4] Yusaf, T.F.; Shamsuddin, A.H.; Ali, Y.; and Ismail, A.F. 1996. Design modification of high speed diesel engine to accommodate compressed natural gas. *RERIC International Energy Journal* 18(1): 19-26.

[5] Yusaf, T.F.; Shamsuddin, A.H.; and Ali, Yusoff. 2000. CNG mixer for a commercial diesel engine. In *Proceedings of the Seventh International Conference and Exhibiti on on Natural Gas Vehicles.* Paper No. PP53: 567-574. Yokohama, Japan, 17-19 October 2000.

[6] David, M.C.; Newman, P.E.; Vander Lee, B.H.; and Pollak, I. 1993. Performance and emission of a converted RABA 2356 bus engine in diesel and dual fuel diesel / natural gas operation. In *Proceedings of SAE Future Transportation Technology Conference* (931823). San Antonio, Texas, U.S.A.

[7] Weaver, C.S. and Turner, S.H. 1994. Dual fuel natural gas / diesel engines, technology, performance, and emission. In *International Congress and Exposition,* SAE Technical Paper Series 940548. Detroit, Michigan, 28 February - 3 March 1994.

[8] Dong, S.J.; Sung, W.S.; Seung, M.O.; and Kyo, N.C. 1993. Development of a mechanical CNG-diesel dual fuel system. *SAE Technical Paper Series* (931947).

[9] Akihiro, N.; Ryouichi, K; Akio, I.; and Masao, U. 2000. Low emission and fuel efficient dual fuel diesel engines. In *International Association of Natural Gas Vehicle (IANGV).* Yokohama, Japan, 2-6 November 2000.

[10] Yukihiro, F.; Nobuo, H.; Hiroshi, M.; Satoshi, Y.; and Kiyoshi, M. 2000. Development of medium-duty CNG truck. In *International Association of Natural Gas Vehicle (IANGV)*, Yokohama, Japan, 2-6 November 2000.