Design Modification of High Speed Diesel Engine to Accommodate Compressed Natural Gas

Talal F. Yusaf *, Abdul Halim Shamsuddin **, Yusoff Ali **, and Ahmad Faris Ismail *

* Faculty of Engineering, International Islamic University, Lembah Pantai, Jalan Bantai Baru, 59200 Kuala Lumpur,

** Mechanical & Materials Department, Faculty of Engineering, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor D.E.,

MALAYSIA.

ABSTRACT

Compressed natural gas CNG was inducted through various experimental mixers mounted between the air manifold and air filter of a high speed four stroke diesel engine. Pilot diesel was used for the initial ignition. An experimental plate was inserted between the cylinder face and the engine block to reduce the compression ratio from 22.9:1 to 16:1. The power, torque, lubricant oil temperatures, coolant water temperatures, and exhaust gas temperatures of the modified engine are evaluated. The result were compared with the data of diesel fuel. An eddy current dynamometer and group of temperature sensors have been used to evaluate the performance of the engine.

1. INTRODUCTION

Various researchers in Malaysia have been examining ways of substituting diesel fuels with alternative fuels [1]. It is estimated that Malaysia's known reserves of crude petroleum oil will last approximately 15 years compared with its NG reserves which are estimated to last about 50 years or more. Researchers are examining alternative fuels, which could be more cost-efficient than diesel. If such an alternative fuel is successful, Malaysia will have a great potential to use its natural gas reserves. Researches into this area has been motivated by the low cost of fuel and the cleanliness of the exhaust when using CNG. As of January 1995, there were about 1,000 vehicles converted to use CNG as fuel [3].

It is imperative to note that CNG is a colorless, odorless, non-toxic, asphyxiate, flammable fuel. It is much lighter than air, and as its name suggests, NG is a gas at normal temperature and pressure. The composition of NG depends primarily upon its source. Essentially NG is a mixture of carbon and hydrogen, the main component being methane with lesser amounts of ethane, propane, n-butane, isobutane, isopentane, n-pentane as shown in Table 1 [4].

2. THE ENGINE MODIFICATIONS

The engine used in the test has the following specifications:

1. Diesel 2.2 L, four stroke. four cylinders
2. Displacement (cm^3) : 2184
3. Bore, stroke (cm) : 8.6, 9.4
4. Maximum power (kW/rpm): 48/4250
5. Maximum torque (Nm/rpm): 136/2000
6. Compression ratio: 22.9:1

An eddy current dynamometer was used to test the engine. This dynamometer was supplied with a drive shaft coupling flange and drive shaft guard to connect to the engine. A control system and instrumentation system were used to control the speed and the torque. The temperature and pressure measurements were provided by six temperature sensors and four pressure sensors. Test bed also has a thermocouple, a pressure transducer, as well as display unit. The cooling tower, complete with cooling fan and integral sump, provides cooling for the dynamometer and engine water/oil circuits. The cooling tower also contains a cooling water recirculation pump. A diesel fuel flowmeter is used for measuring the quantity of diesel that is discharged to the engine from the fuel tank. The air flowmeter is used for measuring the air flow discharged to the engine.

Table 1. Typical composition of natural gas in Malaysia.

Components	Mole %
Methane	83.44
Ethane	10.55
Propane	1.13
Iso butane	0.13
Normal butane	0.07
Iso pentane	0.01
Normal pentane	-
Hexane	0.01
Carbon dioxide	4.17
Nitrogen	0.31
Real density (kg/m^3)	0.81
Gross calorific value (MJ/m^3)	40.03
Molecular weight	19.19
Real specific gravity	0.66

2.1 Fuel System Conversions

There are two common techniques for fuel system conversions using CNG in an internal combustion engine: the first method is the diesel-CNG system, in which CNG is introduced into the engine, while the quantity of diesel is reduced. The second method is a CNG-spark ignition or mono gas system [5].

The advantage of diesel-CNG operation is that it is easy to switch to the diesel fuel system and does not require a spark ignition system. The cost of conversion is also lower. However, there are disadvantages; firstly the fuel mixing system is more complex than the spark ignition, and secondly, the gas and liquid fuel require separate tanks, which will increase the weight of the vehicle. The CNG injection system used for metering CNG into the engine (currently used for gasoline vehicles in Malaysia [3]) was modified for the new CNG-diesel fuel operation. The CNG injection systems consist of the following major equipment:

1. The gas cylinders are made of strong high - strength steel and have a capacity of about 55 liters, The natural gas is compressed at high pressure (18 MPa - 20 MPa).
2. A gas regulator assembly is installed into the mixing system to reduce the pressure of the gas from the cylinder and regulate the gas flow to the mixer.
3. A mixer system mixes the air and CNG at a set ratio and injects then into the engine.
4. Hot water circulates to prevent freezing of CNG when the pressure is reduced, and a fuel selector switch is used to switch the CNG flow on-off. Several valves are used to control the CNG flow.

2.2 Reducing the Compression Ratio

The octane rating is an important combustion characteristic that affects the proper compression ratio. The typical range of the compression ratio of Compression Ignition (CI) engines is from 14:1 to 23:1. Although theoretically increasing the compression ratio should increase the thermal efficiency, it is not a linear relationship [7]. The original diesel engine that has been converted to diesel-CNG operation has a high compression ratio (22.9:1). This high compression ratio is required to achieve a high compression temperature which is essential for fuel ignition.

There is no specific formula that can be used to calculate the proper compression ratio for diesel-CNG engines, the only solution is to use sound judgment, depending on experience and the practical applications for which the converted engine is to be used [8].

Generally a fuel with a cetane number of 50-60 shows the best performance in a high speed engine. Fuel tests have shown that a lower cetane number will perform better in medium and lower speed engines. The octane number of CNG is approximately 130, and the ignition temperature is 360°C. The expected compression ratio with CNG operation in CI engines would be lower than 17:1. Due to these reasons the compression ratio needs to be reduced from 22.9:1 to 16:19.

The compression ratio can be reduced by redesigning the pistons. In order to redesign the piston, the following points must be taken into account:

1. The operation temperature and maximum pressure.
2. The size and the weight of the piston after modification should not change very much from the original piston to reduce vibration and inertia loading on the bearings.
3. The effects of the friction force of piston and cylinder.

Increasing the deep recessed bowl combustion chamber by milling the piston crown will reduce the compression ratio. This method depends on the structure and size of the piston and is suitable for a large piston. Another possible method is to reduce the length of the connecting rod. However this method is very complicated and costly. It needs accurate design and calculations, because the dynamics and thermal stresses could damage the modified connecting rod [5].

The third method is the addition of a plate between the engine block and cylinder head. The shape of the plate will correspond with the top of the cylinder head.

Compression ratio can be obtained from Eq. 1. This method is much simpler and does not require difficult calculations. The cost is also much lower compared to the other methods. The compression ratio can be decreased or increased by changing the thickness of the plate. The material of the plate should resist the high pressure and temperature of the combustion, while forming a seal between the head and the cylinder.

$$\textit{Compression ratio} = \textit{clearance volume } (V_c) + \textit{swept volume } (V_s) \,/\, \textit{clearance volume} \qquad (1)$$

When the plate thickness t = 0.2 cm, the new added volume per cylinder is obtained as follows:

$$\text{Added Volume } (V_{add}) = \pi d^2 t / 4$$

$$= \pi (8.6)^2\, 0.2 / 4 = 11.62 \text{ cm}^3$$

Given the value of V_c and V_s, the new compression ratio is

$$\text{New compression ratio} = (V_{add} + V_c + V_s) / (V_{add} + V_c)$$

$$= (546 + 11.62 + 24.932) \,/\, (11.62 + 24.932)$$

$$= 16 : 1$$

2.3 Fuel Injector Pump

The fuel injector pump is used to select fuel, whether diesel or CNG, without stopping the engine. During CNG-diesel operation, the diesel injection duration is stopped just above the off - idle position and held there throughout the continuing rise in engine speed, while the remaining increase in fuel is with CNG only. Table 2 shows the CNG ratio under different speed values (under maximum operating conditions).

Any increase in the mass flow rate of the CNG should correspond with a decrease in the flow rate of the diesel. From the test data the CNG ratio can be estimated for different operational conditions (no load, part load, maximum load).

Table 2. CNG ratio as a function of engine speed under maximum operating conditions.

Speed (rpm)	Pilot Diesel (%)	CNG Ration (%)
2000	11.75	88.25
2200	10.50	89.50
2400	9.50	90.50
2600	9.00	91.00
2800	8.40	91.60
3000	7.80	92.20

2.4 Measurement of Air and CNG Flow Rate

The main function of the mixer is to measure out the correct proportions of CNG and air for combustion. During the induction stroke, the displacement of the piston will reduce the pressure in the engine cylinder allowing the mixture to enter the engine. The amount of the mixture is affected by the volumetric efficiency, throttle opening, and speed of the engine.

The typical Malaysian natural gas composition (Table 1) is 83.44% CH_4, 10.5% C_2H_6, 1.13% C_3H_8, [6] with some minor elements [10]:

$$aCH_4+bC_2H_6+cC_3H_8+Y\,(O_2+3.76N_2) \rightarrow dCO_2 + eH_2O + Energy$$

where:

a, b, c	=	natural gas components as given in Table 1.
e, d	=	production components.

The standard air to CNG ratio is 17.2 :1. The mixer design depends on CNG-air ratio and the venturi tube. The venturi tube consists of three sections as shown in the Fig. 1 [11]:

1. The function of the main pipe (section 1) is to withdraw the air from the air filter and transfer it to section 2.
2. Air flows from the main pipe (section 1) through a narrow pipe or throat (section 2). The velocity increases due to the pressure drop in this section.
3. The flow in section 3 is expanded to the same diameter or little bit smaller than section 1.

$$Q = V_1 A_1 = V_2 A_2 \tag{2}$$

$$P_1/\sigma + V_1^2/2g = P_2^2/\sigma + V_2^2/2g \tag{3}$$

$$Q = C\,A_2\sqrt{\left(2g(P_1 - P_2)/\sigma\right)/\left(1 - (A_2/A_1)^2\right)} \tag{4}$$

where:

ρ_1, V_1, A_1	=	density, velocity and area at section 1
ρ_2, V_2, A_2	=	density, velocity and area at section 1
σ	=	specific weight
P_1	=	pressure at section 1
P_2	=	pressure at section 2
Q	=	volumetric flow rate
ρ	=	density
C	=	constant

The constant C value depends on the Reynolds number of the flow. The flow rate of air was calculated from the above equations (Eq. 4).

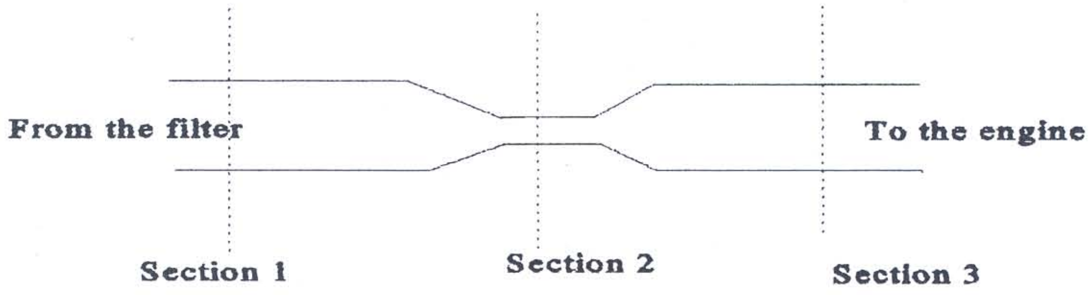

Fig. 1. Venturi mixer diagram

$$D_h = \pi d_0^2 n / 4 \tag{5}$$

where:

D_h	=	hose diameter.
d_0	=	orifice diameter.
n	=	number of orifices.

3. EXPERIMENTAL RESULTS

Tests were carried out to examine the effectiveness of this modification. The plate was dismounted from the engine after about 2000 operating hours, it was in a very good condition with no deformations.

The engine performance was calculated and found to be very close to the performance before conversion, and sometimes better than the original. After 2000 operating hours, there was no lubricant oil leaking from the cylinder face, even though the tests were done at maximum operation conditions (maximum speed and torque). The exhaust gas temperatures, lubricant oil temperatures, and cooling water temperatures were carefully monitored during that test. Table 3 shows the engine power and torque against speed under maximum operating conditions before and after engine modifications.

After about 1000 operating hours, the mixer unit was modified to take the NG flow through two main holes not one. The NG enters the mixer unit through two main holes to be more homogeneous (as a mixture of air and NG).

4. CONCLUSION

Research in diesel-CNG fuels has been motivated by the cost of CNG, the cleanliness of the exhaust, and the performance of CNG, which makes it potential fuel for diesel engine. This study is the first phase of a project designed to convert a commercial high speed diesel engine to enable it to use natural gas as a fuel. The CNG regular conversion kits available in Malaysia have been used for diesel-CNG conversion. The conversion process started with reducing the compression ratio from

22.9:1 to 16:1. A thin plate was used for that purpose. The mixer unit was designed based on a venturi meter, whose function was to measure out the correct air to CNG ratio in the engine during the induction stroke.

Table 3. Power, torque before and after conversion under maximum operating conditions.

Speed (rpm)	Torque (Diesel) (Nm)	Torque (Dual) (Nm)	Power (Diesel) (kW)	Power (Dual) (kW)
2000	114.90	116.20	24.05	24.32
2200	112.80	130.00	25.97	27.21
2400	111.30	127.00	27.96	26.59
2600	111.80	125.00	30.42	26.17
2800	106.10	106.08	31.09	22.21
3000	99.30	94.00	31.18	19.68

Table 4. Exhaust gas, lubricant oil temperatures before and after conversion under maximum operating conditions.

Speed (rpm)	Exhaust Gas Temp.(Diesel) °C	Exhaust Gas Temp. (Dual) °C	Lubricant Oil Temp. (Diesel) °C	Lubricant Oil Temp. (Dual) °C
2000	660	520	100	99.9
2200	670	534	101	101.3
2400	740	550	107	102.0
2600	770	584	110	104.2
2800	775	620	112	105.0
3000	780	640	115	107.0

4. ACKNOWLEDGMENT

The authors would like to thank theUniversiti Kebangsaan Malaysia for providing the facilities and funding for this research, UKM Research Grant No 38/93.

5. REFERENCES

1. Sumner, B.D. 1985. *Natural Gas for Vehicles in Canada: A Study of Market Penetration Problems*. Alberta, Canada: Canadian Energy Research Institute.
2. Abdulaziz, M. K., and Ani, F. N. 1987. The future of methanol in Malaysia. Conversion of diesel vehicles for CNG operation. In *UNESCO Regional Seminar on Alternative Vehicle Fuels Seminar*. Christ.: University of Canterbury.

3. Faridon Bin Hj. Idris. 1993. Study on the performance of CNG fueled vehicles with various types of engines. Report No. : PRSS - RP3 - 93-02. Kuala Lumpur, Malaysia.
4. Heath, M. 199?. *Alternative Transportation Fuel: Natural Gas, Propane, Methanol, Ethanol Compared with Gasoline and Diesel*. Canada: Canadian Energy Research Institute.
5. Raine, R.R.; Stephenson, J. ; and Elder, S. T. 1987. CNG conversion of automotive diesel engines technical and economic aspects. In *UNESCO Regional Seminar on Alternative Vehicle Fuels Seminar*. Christ: University of Canterbury.
6. Mazharullah, A. 1987. Conversion of diesel vehicles for CNG operation. In *UNESCO Regional Seminar on Alternative Vehicle Fuels Seminar*. Christ: University of Canterbury.
7. Sorensen, H.A. 1987. *Energy Conversion System*. Canada: John Wiley & Son Inc.
8. Newton, K.; Steeds, W.; and Garrett, T. K. 1985. *The Motor Vehicle*. Tenth Edition.London: Butterworth Scientific.
9. Karim, G.A. 1983. The dual fuel engine of the compression ignition type - prospects, problems and solutions - A review. In *Conference Proceedings (P-129) of Compressed Natural Gas*. Warrendale, PA: Society of Automotive Engineers, Inc (831073).
10. Medici, M. 1974. *The Natural Gas Industry, A Review of World Resources and Industrial Applications*. England: Newnes-Butterworths.
11. Rose, J.W., and Cooper, J. R. 1977. *Technical Data on Fuel*. 7th Edition. London: The British National Committee, World Energy Conference.
12. Waugh, D.; Harris, G. S. ; Ernst and Young. 1990. Review of New Zealand NGV industry. In *Proceeding of Conference of NGV- New Life in Transportation, Naturally*. Buenos Aires, Argentina. October 21-24.