Perfomance and Emission Characteristics of a Compressed Natural Gas Fuelled Spark Ignition Engine

M.S.A. Molla, M.A. Hossain.Mollah, S.M. Sapuan and M.M.H.M. Ahmad

Department of Mechanical and Manufacturing Engineering
University Putra Malaysia
43400 Serdang, Selangor
MALAYSIA

ABSTRACT

Among alternative fuels for internal combustion engine, natural gas can be considered as the single largest alternative fuel. Natural gas can substitute totally or partially the liquid fossil fuels (gasoline and diesel). This research work was intended to study the performance characteristics of a two cylinder diesel engine converted to spark ignition (SI) engine to run on 100 percent compressed natural gas (CNG). In this study the test emissions were measured with the advancement in ignition timing which is very uncommon with other available test reports and this gives new relation of emissions level with ignition timing change. From the experimental result, it is seen that a converted natural gas fuelled SI engine can deliver approximately equal output to its diesel counterpart. The combustion of natural gas in CNG fuelled SI engine is found to be more efficient at the equivalence ratio of 0.9. The exhaust gas temperature of natural gas fuelled SI engine is found to be 120°C to 180°C above that of diesel and petrol engines of similar type. The exhaust gas emissions (CO and HC) of natural gas fuelled SI engine are found to be much lower than their respective admissible limits. Natural gas fuelled engine is friendly to environments for its lower level of air pollution and lower level of green house gas emission.

1. INTRODUCTION

The demand of world annual oil consumption is approximately 60 EsJ (Exa Joules) (10^{12} Joules) with annual growth of 2.9%. The proven reserve [1] of natural gas is 3000 EsJ and it can meet the world energy demand for more than 50 years.

The sudden rise of oil price in 1970s has increased the concern and research interest in alternative fuels for IC engine and transportation. The research interest on natural gas fuelled engine further increased when some investigators reported that natural gas fuelled vehicles were less polluting and friendly to environment. In order to accomplish Clean Air Act Amendments of 1970 and 1977 and Energy Policy and Conservation Act of 1975 (Corporate Average Fuel Economy (CAFÉ)), the law makers [2] imposed the industries to comply with more stringent requirements for the decade of the nineties and beyond. Over the last 15 years environmental legislation required the reduction of engine exhaust emissions of IC engines. Forthcoming legislation seems to follow this trend. Vehicle manufacturers, on the other hand, have successfully fulfilled these stringent emission controls by significantly reducing emissions from new gasoline and diesel-powered vehicles. Natural gas is cheaper than diesel and gasoline fuels but its cost rises when it is processed for storage and delivery. In most of the areas in the world, the processing cost of natural gas is substantially cheaper than diesel and gasoline fuels. It is easily available and the price is stable. Stationary engines like those of generators, pumps, and compressors can be connected to domestic gas supply line where the gas cost is cheaper many folds or usually 1/5 to 1/7 times lower than that of gasoline or diesel fuel.

Doughty, et al. [3] conducted a research investigation in a natural gas fuelling of a Caterpillar 3406 turbo charged diesel engine. It was operated by a natural gas with a diesel pilot injection mode and was evaluated for performance and emission characteristics. The full load power was achieved with natural gas fuelling without knocking. Good efficiency was obtained at high load but efficiency was lower at low load. CNG premixing was effective in improving brake thermal efficiency and also in reducing smoke density. NO_x emission was found to be lower at low load and higher at high speed and high load. CO emission increased for natural gas fuelling while CO_2 concentration in the exhaust was reduced.

Hara, et al. [4] studied CNG engine in a hybrid combustion engine premixed with CNG homogeneous charge ignited by a small amount of injected diesel fuel. It was achieved by modifying a four-stroke diesel engine. The result showed that CNG premixing was effective not only in improving the brake thermal efficiency but also in reducing the smoke density both in heavy and over-load regions.

Bittner and Aboujaoude [5] studied selective catalytic reduction (SCR) and oxidation catalyst technology and applied to a stationary diesel and dual fuel engines for catalytic control of nitrogen oxides (NOx), carbon monoxide (CO) and non-methane hydrocarbon. At rated conditions, NOx emissions have been effectively reduced up to 90% with little loss of SCR catalyst performance after 850 hours of operation. Using adequate control of ammonia (NH_3) feed, the SCR system was capable of maintaining NH_3 slip to 10 ppm or less. Emissions like CO and non-methane hydrocarbon (NMHC) were reduced by 93% and 85%, respectively. Little soot was observed on the surface of the catalyst due to the use of a catalyst system that minimized the build-up of heavy hydrocarbons on the catalyst surface. In addition, the catalyst structure effectively resisted the build-up of sulphur compounds that could cause premature deactivation of catalyst.

US Environmental Protecting Agency (EPA) and California Air Resources Board (CARB) have introduced their own standards [6] allowing transitional low emission vehicle (TLEV) and low emission vehicle (LEV) until 2003 with final aim to obtain ultra low emission vehicle (ULEV) and zero emission vehicle (ZEV) engines without sacrificing engine power and efficiency. European countries also set targets to further low emission engine by updating new emission standard Euro-III from the existing Euro-II standard. Japanese car manufacturers are found to set targets to further lower limits of emissions than Euro III or ULEV by controlling injection rate, injection period and using catalytic converters. Meanwhile natural gas fuelled engines have also been developed to fulfil the emission limits of Euro II and Euro III .

Sato and Daisho [7] investigated the combustion and exhaust gas emissions characteristics of a diesel engine fuelled with natural gas. Natural gas premixed with air was introduced into the cylinder and ignition was assisted by injection of diesel fuel sprays. The effects of gas energy fraction on performance, combustion, and exhaust gas emissions were investigated. In the experimental investigation it was found that without sacrificing thermal efficiency it was possible to obtain 80% of energy fraction by eliminating smoke. Emissions levels (CO, HC, and CO_2) reduced remarkably when the load of the engine increased from quarter load to full load. The engine efficiency increased from 15% to 37% as the load increased from 25% to 100%. The level of NOx showed decreasing trend with increase of fuel fraction and load up to 75% of full load operation. But the trends (the level of NOx) slightly increase with full load operation and with the increase of gaseous fuel fraction. The peak pressure inside the cylinder increased from approximately 7.5 MPa to 8.5 MPa when engine changed from diesel fuel operation to natural gas fuel operation. The rate of heat release per degree crank angle (J/CA) increased during the active combustion stroke of the full load operation with natural gas than that of diesel cycle operation. Heat of combustion released quite late, i.e. from 5° before top dead centers (BTDC) to approximately 0° BTDC when operated with 54% and 75% natural gas fuel fraction instead of 7° BTDC for diesel fuel mode. When the engine was operated in half load condition the peak pressure inside the cylinder lower than that of diesel fuel operation. But the heat release rate followed a decreasing trend which initiated and ended with similar degree of crank angle (i.e., 5° BTDC to approximately 1° after top dead centers (ATDC) when gas fraction further increased from 46% to 84%. The unburned fuel emission increased in low load operation of the engine. The effects of advancing and retarding of ignition timing or the effects of addition of ignition enhancer to the gaseous fuel were not investigated. The aim of this study is to investigate the performance and exhaust gas emissions of the compressed natural gas fuelled SI engine.

2. METHODOLOGY FOR CONVERSION OF GASOLINE FUELLED ENGINE INTO NATURAL GAS FUELLED ENGINE

In this research work [8], a two cylinder diesel engine (Duetz, 14 kW) was converted to 100% compressed natural gas fuelled SI engine with the following modifications:

(a) The engine compression ratio was reduced from 17:1 to 12:1 by removing metal from piston head.
(b) Compression ignition system of the diesel engine was replaced by electronic SI system with the installation of spark plugs, electronic control unit, high energy induction coils, etc.
(c) Diesel fuel injection system was replaced by natural gas fuelled system consisting of pressure regulator, gas-air mixer (gas carburetor), CNG cylinders, etc.
(d) A Crypton 270 Emission Analyzer was installed with the exhaust line of the converted CNG fuelled SI engine to measure its exhaust gas emissions. The working principle of the analyser, Crypton 270 is based on Infra Red Analysis in emission. Moreover the accuracy of infrared emission is sufficient to meet up the requirement of detecting international emission level Euro-II to Euro-III and other scale of USA.
(e) The converted CNG fuelled SI engine was coupled with a hydraulic dynamometer. The engine was tested at a constant speed of 1500 rpm as it was designed to run pump with the same engine speed.

3. TEST CONDITION AND PROCEDURE

The engine was installed on an engine test bench and was coupled to a hydraulic dynamometer. The details of the engine specifications are given in Table 1. A high energy electronic ignition system was installed with the facility to change the ignition timings from 6°BTDC to 15°BTDC. During the test period, the engine was set to a constant speed of 1500 rpm and its load was gradually increased from half load to full load by increasing the dynamometer load at every one and half degree interval from 6°BTDC to 15° BTDC. The performance parameters and exhaust gas emissions were recorded for each set of reading. The variations of ambient temperature, pressure and humidity of air were also recorded for calculating the engine de-ratings and standardization of engine power. It may be mentioned in this study that an engine can give more hydrocarbon when it is tested in cold (cooling) condition than when is properly warmed up. The test engine was properly setup and emission were properly measured with high degree of accuracy of measuring instrument.

Table 1 Specifications of Diesel Engine Converted to CNG Fuelled SI Engine

Engine	Duetz
Model	F2L912
No. of cylinder	2 cylinders
Compression ratio (before modification)	17:1
Compression ratio (after modification)	12:1
Bore/Stroke	100/120 mm
Rotational speed (rated rpm)	2500
Tested speed (rpm)	1500
Specific fuel consumption	223 gm/kW-hr
Starting system	Electric motor (12V)
Cooling system	Air cooled
Battery	12 V
Cylinder order	Inline vertical
Power Continuous rating ("A" to DIN 6270), at 10% overload capacity.	(i)14 kW (ii) 15.5 kW

SI engine or gasoline engine can be operated with 100% natural gas in parallel mode with gasoline fuel operation with the installation of natural gas fuel system without much more modifications. Similarly compression ignition engine or diesel engine can also be operated by natural gas in dual fuel mode without much more modification where the natural gas is supplied to the intake air of the engine and a small quantity of diesel fuel is injected inside the cylinder to initiate firing.

Generally it required a lot of modifications for converting a diesel engine to 100% natural gas fuelled SI engine. In this research work, a two-cylinder Duetz diesel engine was converted to 100% CNG fuelled SI engine.

4. RESULTS AND DISCUSSION

The following are the observations from the experiment.

4.1 Effects of Ignition Timing on the Brake Thermal Efficiency and on the Maximum Brake Output

The ignition timing of the engine was advanced from 6°BTDC to 15°BTDC and it was found that the brake thermal efficiency and maximum brake output of CNG fuelled SI engine increased with the advance of ignition timing as depicted in Fig. 1 and Fig. 2. Generally the brake thermal efficiency of gasoline fuelled SI engine is maximum at the ignition timing of approximately 12°BTDC to 14°BTDC and

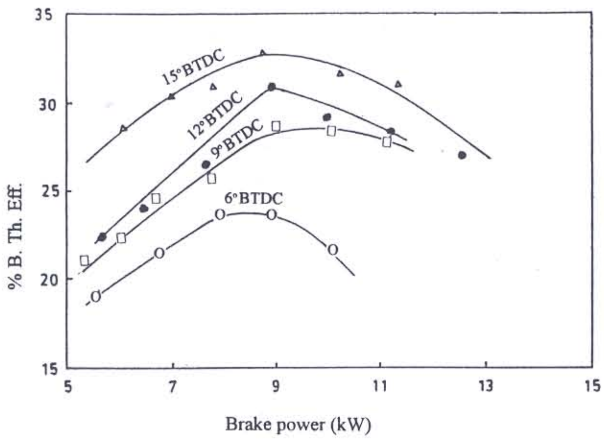

Fig. 1. Variation of brake thermal efficiency (B. Th. Eff.) with respect to brake power (kW) at different ignition timing from 6°BTDC to 15°BTDC at a constant speed of 1500 rpm.

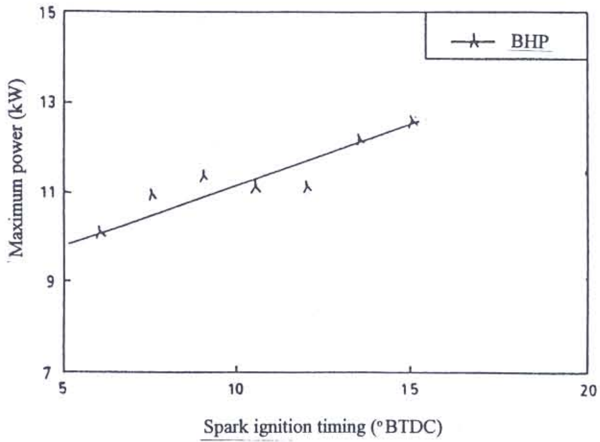

Fig. 2. Variation of maximum load (kW) carrying capacity of the engine at different ignition timing from 6°BTDC to 15°BTDC at a constant speed of 1500 rpm.

it is approximately 20°BTDC to 22° BTDC for diesel engine but in the natural gas fuelled SI engine, it is found to bemore efficient at 15° BTDC and beyond. As such whenever any engine is converted to natural gas fuelled SI engine it needs proper setting of ignition timings for getting better output.

4.2 Brake Specific Energy Consumption

Brake specific fuel consumption of the converted natural gas fuelled CNG engine was found to increase with the advance of ignition timing from 6° BTDC to 15° BTDC as shown in Fig. 3. The minimum brake specific energy consumption was approximately 11 MJ/ kW-hr at 15° BTDC at two-thirds of the full load but the same was found to be 15 MJ/kW-hr at 6° BTDC at the corresponding load position. Thus setting of proper ignition timing can reduce the fuel consumption significantly.

4.3 Exhaust Gas Temperature

The variation of exhaust gas temperature is shown in Fig. 4. The exhaust gas temperature is observed to decrease with the advance of ignition timing from 6° BTDC to 15° BTDC. Generally the exhaust gas temperature of SI engine is 310° C to 350° C and that of a diesel engine is 350° C to 410° C. However, in the natural gas fuelled SI engine, the exhaust gas temperature is found to be 563° C to 584° C as shown in Table 2. Thus the exhaust temperature of CNG fuelled SI engine is about 120° C to 180° C higher than that of its gasoline and diesel engine counterpart.

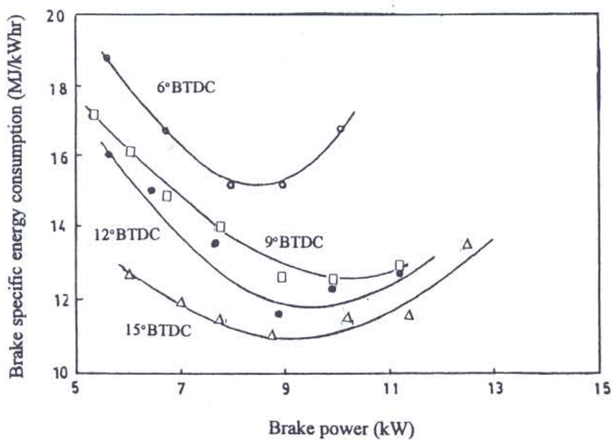

Fig. 3. Variation of brake specific energy consumption (BSEC) with respect to brake power (kW) at different ignition timing from 6° BTDC to 15° BTDC at a constant speed of 1500 rpm.

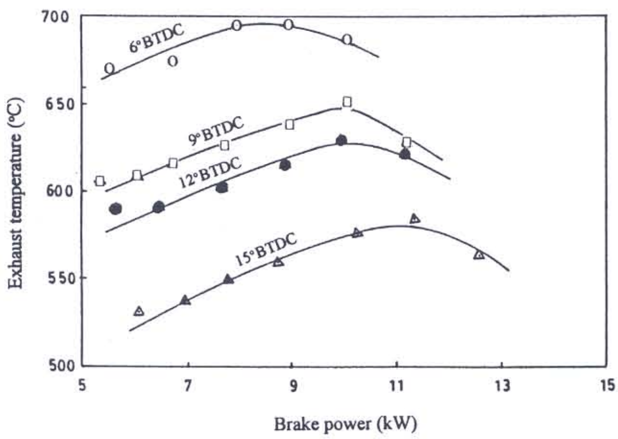

Fig. 4. Variation of exhaust gas temperature with respect to brake power (kW) at different ignition timing from 6° BTDC to 15° BTDC at a constant speed of 1500 rpm.

Table 2 Exhaust Gas Temperature of CNG Fuelled, Gasoline Fuelled, and Diesel Fuelled Engine

Item	Tested engine (2-cylinder CNG fuelled spark ignition engine)	General range of exhaust gas at full load operation [8]	Test report [9]
i) Maximum exhaust temp. at full load operation	563°C-584°C 1500 rpm.	370°C-410°C 1500 rpm.	550°C at 1500 rpm & 700° C 3000 rpm.

4.4 The Effects Equivalence Ratio or Air Fuel Ratio on the Brake Thermal Efficiency of the CNG Fuelled SI engine

The combustion in natural gas fuelled engine was found to be most efficient at about 10% excess air, i.e. at equivalence ratio of 0.9 as shown in Fig. 5. But combustion efficiency of gasoline SI engine is generally found maximum at the equivalence ratio of 0.8 or at about 17% to 20% excess air than its theoretical requirement. So proper control of air fuel ratio of the natural gas fuelled engine can improve the combustion efficiency and thereby can improve the engine efficiency.

4.5 Comparison of the Load Carrying Capacity of Natural Gas Fuelled SI Engine with Diesel Fuelled CI Engine

The unconverted or original diesel engine had a load carrying capacity of 14 kW but the load carrying capacity of the converted natural gas fuelled engine reduced to 12 kW. So at the sacrifice of some load carrying capacity of approximately 14%, both and CI engine and SI engine can be converted to natural gas fuelled SI engine. The brake thermal efficiency and specific fuel consumption in CNG fuelled SI engine was found competitive and satisfactory.

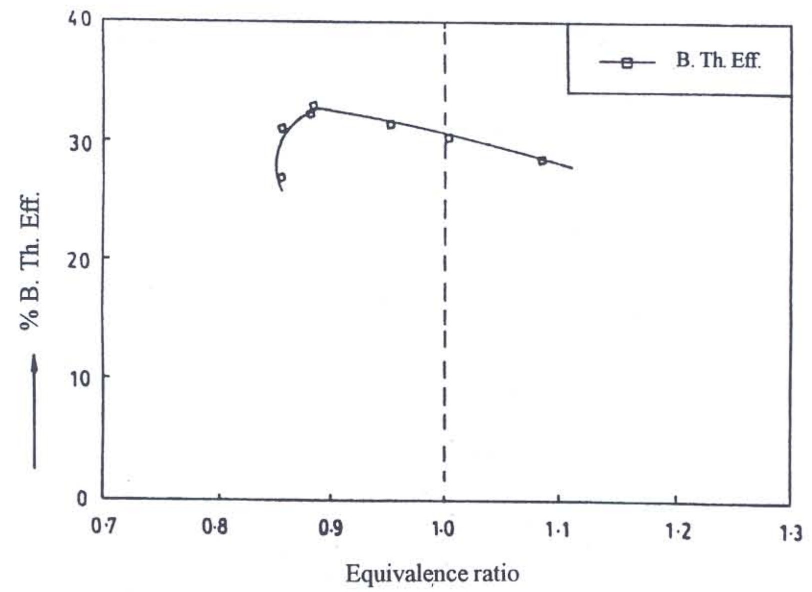

Fig. 5. Variation of break thermal efficiency with respect to equivalent ratio at the ignition timing of 15° BTDC at a constant speed of 1500 rpm.

4.6 The Emission Levels in Natural Gas Fuelled SI Engine

The harmful exhaust gas emissions like CO, HC and CO_2 were measured and found less in natural gas fuelled SI engine as shown in Table 3. The harmful pollutant (CO) was found to be zero in natural gas fuelled spark ignition engine at air fuel ratio above 17.6:1. Carbon monoxide (CO) increased with load. Hydrocarbon (HC) pollutant in CNG fuelled SI engine was found and within the acceptable limits as shown in Table 3. Carbon dioxide is the equilibrium product of combustion. The CO_2 emission level was found lower by 20% in CNG fuelled engine in comparison to other gasoline or diesel fuelled engine because of its hydrogen enriched fuel composition as shown in Table 4. Hydrogen fuel produces no green house gas. It is an increasing concern that the rise of CO_2 in the atmosphere is responsible for its greenhouse effect but none can think of zero emission of carbon dioxide during combustion process of hydrocarbon fuel.

Table 3 Emission Levels and Emission Limits

Emission	CNÇ fuelled Engine (at Constant Speed and Variable load test)	Accepted limit of TUS legislative 1978 [10]	Accepted limit of Toyota vehicle in Japan [11]	Accepted limit in England and European countries [12]
%CO	1.9% v/v	3.4 g/veh.-mile	2.5 % v/v	-
HC- level	160 ppm	-	-	400 ppm
NOx	-	0.39 * g/veh.-mile	-	-
(Note * g/veh.-mile, 275 ppm = 2.2 g/vehicle mile)				

Table 4 Approximate H/C Energy Specific CO_2 Rate

Fuel	H/C ratio	Energy specific CO_2 Rate (grams of CO_2 per million Joules energy)
Methane	4	55
Methanol	2	69
Gasoline	1.85	73
Diesel	1.8	74

4.7 Uncertainty of Discharge and Flow Coefficients

The discharge coefficient for airflow measurement was taken to be 0.59 following the table of discharge and flow coefficients in BS 1042, Section 1.1.1981 where the uncertainty of discharge coefficient is 0.6%.

5. CONCLUSIONS

Based from the test result, it can be concluded that the CNG fuelled engine is more efficient at the ignition timing of 15°BTDC, as shown in Fig. 1 and also most efficient at the equivalence ratio of 0.9, i.e., at about 10% excess air, than the theoretical air requirement as shown in Fig. 5.

Engine load carrying capacity increases with the advance of ignition timing from 6°BTDC to 15°BTDC as shown in Fig. 2.

Exhaust gas temperature of natural gas fuelled spark ignition is approximately 120°C to 180°C above that of diesel and gasoline engine as shown in Table 2.

The natural gas fuelled SI engine can deliver approximately equal output of its diesel fuel and petrol fuel operation.

The formation of pollutants (CO/HC) in CNG fuelled SI engine is very low in comparison to gasoline engine (SI) and diesel engine (CI). Since the sulfur content in natural gas is zero in many countrie , so there is less possibility of formation of SO_2 pollutant.

The disadvantage in CNG fuelled SI engine is that its exhaust gas temperature is high and flame velocity is low. This high exhaust temperature is for slow flame velocity of natural gas than gasoline flame inside the cylinder. But this high exhaust gas temperature can also be reduced by increasing stroke length and reducing engine speed.

The CNG fuel can be utilized in SI engine with appropriate modifications. Similarly natural gas can also be used as a fuel source in stationary SI engine like irrigation and standby power generation converted from any diesel engine.

6. REFERENCES

1. Bossanyi, B. E; Bowers, S.J.; Crouch, E.A.C.; Eden, R.J.; Hope, C.W.; Humphery, W.S.; Mitchell, J.V.; Pullin, D.J.; and Stanish, J.A. 1978. World energy demand to 2020. In *Proceedings of World Energy Conference*., Guildford, U.K, pp. 445-458.
2. Springer, K.J. 1992. Energy efficiency and environments: The Es of Transportation *Journal of Engineering for Gas Turbines and Powers, Transactions of ASME*, Vol. 114.
3. Doughty, G.E.; Bell, S.R.; and Midkiff, K.C. 1992. Natural gas fuelling of a Caterpillar 3406 diesel engine. *Journal of Engineering for Gas Turbine and Power, Transactions of the ASME*, 114 : 459-465.
4. Hara, K.; Yonetani, H.; and Fukutani, I, 1994. A study of gas engine - a hybrid combustion engine- premixed CNG homogeneous charge ignition by injected diesel fuel, *SAE Paper 943916*.
5. Bittner, R.W.; and Aboujaoude, F.W. 1992. Catalytic control of NOx, CO and NMHC emissions from stationary diesel dual fuels engines. *Journal of Engineering for Gas Turbine and Power, Transactions of the ASME*, 114: 497-601.
6. State of California Air Resources, 1990. *Resolution 90-58, State of California Air Resources. Board Agenda Item 90-14-1 1990: Low Emission Vehicle/Clean Fuels Amending*, California Code of Resolution.
7. Sato, T; and Daisho, Y. 1995. Combustion and exhaust gas emissions characteristics of a diesel engine fueled with natural gas, *Transactions of JSAE 953809*, 26(3): 21-26.
8. Molla, M.S.A. 1990. A Study of Performance Parameters and Exhaust Gas Pollution Of Natural Gas Fuelled Spark Ignition Engine, MSc. Engineering Thesis, Department of Mechanical Engineering, Bangladesh University of Engineering Technology, Dhaka, Bangladesh.
9. Cambell, A. 1989. *Engine Test Data and Result for a Single Cylinder Diesel Engine (Duetz, 210D, 6.7 kW) Converted to CNG Fueled SI Engine LFMG Ltd. of New Zealand,* Sponsored by COMSEC under CNG Conversion Programme in BUET, Dhaka, Bangladesh. March-April.
10. FKI Crypton Ltd., 1988. *Operating and Maintenance Instruction* 270 Crypton ($CO/HC/CO_2/O_2$) Analyzer, TES 903/2.
11. Newton, K.; Steeds, W.; and Garrets, T.K. 1972. The Motor Vehicle, 9th edition, the Press Ltd. London.
12. Toyota Motor Corporation. 1986. Overseas Service Department. *Service Information*, Publication No. SDS097E.