Dual Fuel Performance of a Small Diesel Engine for Applications with Less Frequent Load Variations

Md. Ehsan and Shafiquzzaman Bhuiyan

***Abstract*— Small diesel engines are widely used all over Bangladesh. Apart from conventional use in irrigation, power generation and river transportation, they are having many alternative applications. Running such engines in dual fuel mode with indigenous natural gas could have a significant impact on the imported diesel consumption, while retaining the engine warranty and capability of running with diesel-only at any time. In some parts of the country people have already started dual fuel operation of small engines using natural gas line supply. The objective of this work was to quantitatively evaluate dual fuel operation of small diesel engines with the simplest possible change of hardware, which could be suitable for applications where loads are changing less frequently or an engine attendant is already employed. For using natural gas a cross-flow gas mixing chamber was added to the air intake. All the diesel settings including fuel injection timing were kept at the factory defaults to retain instant interchangeability to diesel-only operation, in case natural gas is unavailable. Natural gas could be fed from line supply for urban users or a low pressure CNG package (LPCNG) developed by the author for rural or remote users. The maximum achievable diesel replacement by natural gas was found to vary with engine loads. The engine showed very similar performance compared to diesel-only operation near up to 90% of rated load with up to 88% replacement of diesel by natural gas being possible. The cost analysis showed promising socio-economic feasibility of running such engines in dual fuel mode in remote locations. The arrangement is currently engaged in field trials.**

***Index Term*— Dual Fuel, Small Diesel Engine, Natural Gas.**

I. MOTIVATION AND BACKGROUND

Small diesel engines, typically producing less than 20 hp, are widely used all over Bangladesh. Although there is no accurate survey, the number of small diesel engine in operation is estimated to be about 0.7 million [1]. Introduced in late 70's such engines are now used in a number of non-conventional sectors, as shown in fig.1. The most important conventional use is in irrigation for driving Low Lift pumps (LLP) and shallow tube wells (STW) in rural Bangladesh. Many of such engines are used for standby power generation to cope up with the frequent failure of main electrical power, as a small community solution. Although electricity have reached in about 60% villages, still more that 2/3rd of the irrigation devices are still run on diesel [1]. Diesel engines have got a wide application in about 0.9 million country boat, a large proportion of which run by diesel now-a-days [1]. They have found applications in stone or brick crushing and concrete mixing in construction industry; crushing of rice and sugarcane in food industry. Thousands of locally built 3-wheelers are propelled by such engines, which are mostly used in rural transportation. Most of the engines used now are imported from china, but lots of small industries have developed locally which manufacture many spare parts of these engines. As a whole these engines are playing an important role in the overall economy.

Fig. 1. Various non-conventional use of small single cylinder diesel engines in Bangladesh.

Diesel fuel is the largest imported energy resource for Bangladesh. Presently about 2.4 million metric tons of Diesel is used every year in Bangladesh. Since the requirement of octane/petrol is about 0.4 million metric tons per year, only

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about 0.27 million of the Diesel requirement is met by refining imported crude oil at the only refinery of the country, while the remaining Diesel needs to be imported as a finished product. High fuel price, uncertainty of availability of fuel and the question of energy security – requires Bangladesh to diversify its use of fuels. Although small consumption per unit, the huge number of the engines create a significant share of the total consumption. About 1 million ton of diesel consumption can be related to small diesel engines in the applications mentioned above [1]. Bangladesh has a sizable reserve of natural gas[1] with very high methane content (typically methane 93-96%, ethane 2-4% and negligible sulfur). Using an indigenous fuel source such as natural gas can reduce the import requirement, improve the energy security and reduce environmental pollution. This work has the aim of quantitatively evaluate the performance of a simple, low cost conversion technique of diesel engines to be run with natural gas, which could have wide application in irrigation and power generation in the rural community.

Bangladesh has made significant development in using natural gas in internal combustion engines, especially in the transportation sector. The country has nearly 400 CNG supply stations and about 180,000 natural gas run vehicles (NGV) in operation. Diesel engines could be run with natural gas in two ways – dedicated gas only operation and interchangeable dual fuel operation. The engine can be converted to a spark ignition engine, requiring major engine hardware modification, which typically involves – decreasing the compression ratio by changing piston or combustion chamber geometry, removal of the entire diesel fuel injection system, addition of a gas-air mixing system or gas injection system and addition of a spark ignition system. In this process the modified engine can not be run on diesel any more. Such modifications are more practiced for large buses and trucks. This type of modifications often leads to the termination of the diesel manufacturer's warranty and lags further performance certification. The dual fuel operation does not involve any major change of the engine hardware, only a gas mixing facility is added at the air inlet. In dual fuel operation both diesel and natural gas enters the engine. A small amount of diesel in injected as a pilot fuel, which ignites as usual and initiates the combustion of natural gas which is the main fuel. The injection timing for diesel set by the engine manufacturer (17° BTDC according to the engine specification) would intentionally be kept unchanged. The gas flow can be made using the intake manifold suction (conventional gas fumigation technique) or installing a gas injector in the intake manifold. This process has the advantage of instant inter-changeability to diesel-only operation, in case natural gas is unavailable. The degree of diesel replacement by natural gas depends on - the engine operating conditions and the engine design to some extent, typically varying from 30% to 90%. The dual fuel technology has been much more successfully used in engines with slow variation of load, where the engine speed varies in a small range [2]. The use of the newly developed LPCNG packaging would allow compressed natural gas to be accessible at more remote locations.

II. Literature Review

A number of investigations involving - performance, knock characteristics, control and ignition delay have been carried out on diesel engines run in dual fuel mode with natural gas. Ahmad N. et. al.[3] showed that Dual-fuel engines generally suffer from the problem of lower peak brake power and lower peak engine cylinder pressure due to lower volumetric efficiency; although an improvement in brake specific energy consumption is observed compared to pure diesel mode. A simple dual fuel system was developed indigenously by Balasubramanian V. et. al.[4]. Engine tests with dual fuel gas system have been conducted on a single cylinder diesel engine. These results show that the performance of the engine with dual fuel system can almost match that of standard diesel engine. Karim G. A.[5] specially investigated the dual fuel engines at part loads. More efficient and increased power output relative to the corresponding diesel operation can be achieved with dual fuel engines at relatively high load. The light load performance, especially with high gas to diesel fuel ratios, remains relatively inferior. Poor fuel utilization efficiencies and high unburnt hydrocarbons and carbon monoxide exhaust concentrations are readily encountered at light loads. To improve performance and exhaust emissions of a converted dual-fuel natural-gas engine, the effects of basic parameters were experimentally investigated by Ishiyama et. al.[6]. The results show that a small amount of pilot fuel with a moderate injection rate is effective for suppressing knock at high loads. Adequate control of pilot fuel amount, injection timing gives diesel- equivalent thermal efficiency with very low smoke emission over a wide range of loads. Hountalas D. and Roussos P.[7] showed in dual fuel, combustion rate of natural gas depends on the entrainment rate of surrounding gas into the fuel jet and on the velocity of the flame front, which is formed around the area of the burning zone and spreads inside the combustion chamber. This effect was promoted when increasing the percentage of gaseous fuel.

Wannatong et. al.[8] recorded the average cylinder pressure-time data for a single cylinder diesel engine run in dual mode. Results from cylinder pressure-time data analysis was used to explain the knock characteristics. Moreover, results of abnormal combustion conditions tested in the laboratory were used to explain the possible causes of dual fuel engine damage in the real situation occurred in Thailand. G. A. Karim[9] concluded that acceptable dual fuel operation throughout the power range could be realized only if sufficiently effective measures can be ensured both for the avoidance of knock, usually at high loads, and incomplete gaseous fuel utilization at relatively light loads. Problems associated with the operation of gas fueled dual fuel engines can be reduced via a better control of the relatively complex processes of combustion. An add-on system was developed by Volpato O. et. al.[10] using a production Engine Control Module. Control of pilot diesel injection provides a reliable mode of ignition for lean mixtures of CNG, compared to conventional spark ignition.

In order to improve the engine's emission performance and convert diesel engine to dual fuel engine, an electronically controlled natural gas injection system was developed for a naturally aspirated bus diesel engine by Zhang Y. et. al.[11]. Test results showed advantage in the aspects of emission and economy. Adopting multi-point electronic control injection for dual fuel system could get as high as 92% of CNG substitution at rated power and reduce NOx and PM emissions greatly. These converted engines could provide an effective method for producing power while reducing exhaust emissions, especially exhaust particulates and oxides of nitrogen. The effect of CNG flow rate and Exhaust Gas Re-circulation (EGR) on the performance and emissions of the dual fuel engine was studied by Kapilan et. al.[12]. From the test results, it was observed that the EGR rate of 4.28 % resulted in better brake thermal efficiency and lower CO and NOx emissions, compared to other ERG rates at 25%, 50% and 75% of full loads. At full load, EGR rate of 8.12% resulted in higher brake thermal efficiency and lower NOx emissions. Investigation of Abdalla G. H. et. al.[13] of single cylinder engine reported that operation of dual-fuel engine at lower loads suffers from lower thermal efficiency and higher unburned percentages of fuel. Through the experimental investigations, it was shown that the low thermal efficiency and poor emissions at light loads could be improved significantly by increasing the amount of pilot fuel, while increasing the amount of pilot fuel at high loads led to early knocking. Z. Liu and G. A. Karim[14] showed that the introduction of gaseous fuels and diluents into the diesel engine can substantially affect both the physical and chemical processes within the ignition delay period. The major extension of the delay was due to the chemical factors, which strongly depended on the type of gaseous fuel used and its concentration in the cylinder charge. Neilson O. B. et. al.[15]conducted experiments to investigate the effects of gaseous fuels on the ignition delay in dual fuel engines. From the results of a number of parameter variations, the cylinder charge temperature (determined by intake temperature and compression ratio), the pilot fuel amount, and the flow of combustible gas were found to have the most significant influence on the ignition delay. The effects of changes in the cetane number of diesel liquid pilot fuels on the ignition delay period in dual fuel engines were investigated experimentally by Gunea C. et. al.[16] using different pilot fuels. The ignition delay variation with increased gaseous fuel admission showed a strong dependence on both the quantity and quality of the pilot fuel used. It was found that the use of high cetane number pilot liquid fuels permitted smaller pilot quantities to be used satisfactorily.

III. EXPERIMENTAL SETUP

A single cylinder diesel engine (Model S1100 DONGFENG, China) widely used in Bangladesh was chosen for this study. The engine was designed to operate in a narrow speed range (about 1800 – 2200 rpm), with a rated speed of 2200 rev/min. The major specification of the engine is given in table-I. The engine was tested at constant rated speed through out its power range with diesel-only and dual fuel operations using a standard hydraulic (water-brake) dynamometer (TFL-109, Germany) and the test results were de-rated to standard conditions according to BS5514.

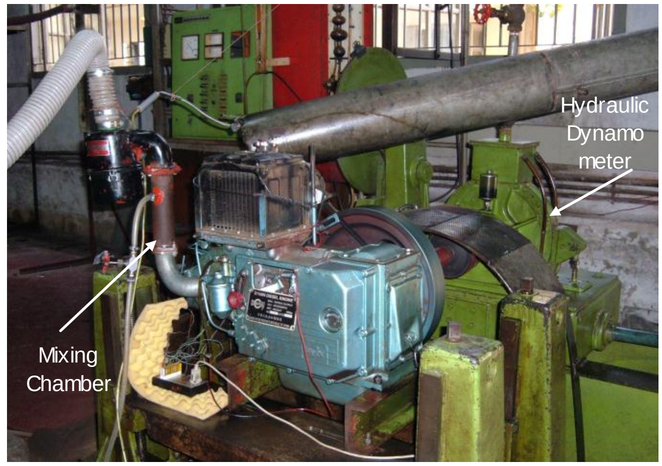


Fig. 2. The test engine coupled with a Dynamometer.

Three separate metering systems were used to measure the flow rates of air, diesel and natural gas. An air drum fitted with a parabolic nozzle and inclined manometer was used for measuring the mass flow of the air entering the engine. Volumetric measurement of diesel consumption was made, which was converted to gravimetric values using the measured diesel density. The conventional gas fumigation technique was used for mixing the natural gas with the intake air through a cross flow mixing chamber added before the intake manifold. Gas could be used from the “Low pressure CNG (LPCNG)” unit developed by the author or from line supply of natural gas. A calibrated flow-meter (rotameter) was used to measure the natural gas consumption rate. Fig.2 shows the photograph of the experimental setup. A cross flow mixing chamber was fabricated and installed between the air cleaner and the intake manifold as shown in fig.2.

Fig.3 shows a photograph of the “Low pressure CNG” unit which is practically a combined package of – a 60 liter type-1 CNG cylinder, a three-stage pressure regulator and control fittings. The whole setting was fitted in a robust steel cage, for ease and safety of transportation. CNG from standard 200 bar filling stations could be refilled into the system, just like filling a Natural Gas Vehicle. However the gas connection to the application is a low pressure hose, eliminating the costly high pressure detachable connector, making it easy and safe to handle by an ordinary user. Details of LPCNG system is described in other papers [17, 18]. Results presented in this paper were collected using line supply of natural gas (to save refilling time), which showed little difference with the LPCNG system [17]. The final performance comparisons were made on mass basis, so they should be independent of the system used. To retain instant interchangeability to diesel-only operation the fuel injection timing was kept unchanged at the engine manufacturer's default (17° BTDC according to engine specification). Type-K calibrated thermocouples and a data-logger were used for temperature measurements of the cooling water, lubricating oil, exhaust gas and exhaust valve. A hand-held Non-dispersive Infrared Emission Analyzers (Crypton 290) was used to measure the percentage volume of CO_2 and CO in the exhaust gas at various operating conditions. Fig.4 shows a schematic presentation of the different systems of the experimental setup.

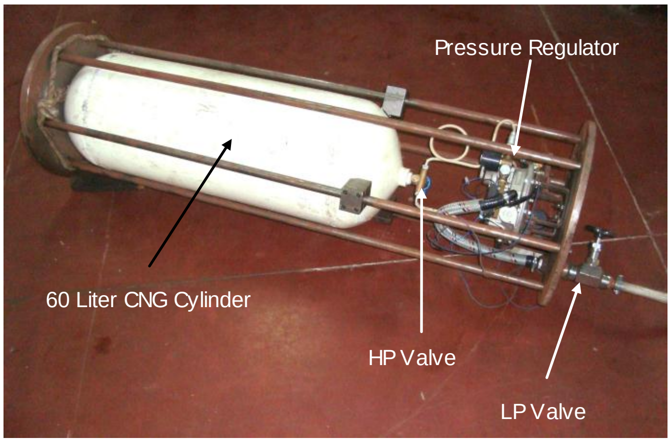


Fig. 3. Low pressure CNG unit – 60 liter CNG Cylinder, 3-stage Pressure Regulator and Controls packaged together.

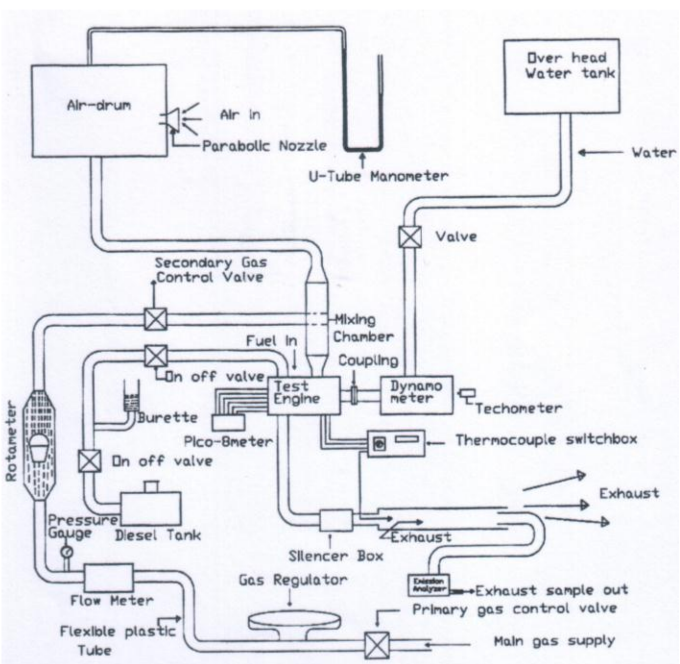


Fig. 4. Schematic diagram of the experimental setup showing different systems.

Although the attached specification of the 903 cc engine supplied by the manufacturer showed a maximum rated power of 15 metric horsepower (PS) at 2200 rpm, in real testing the maximum power was found to be limited to about 13 hp when running with diesel. Later the engine was tested at 10%, 30%, 50%,75%,90% and 100% of the actual rated load, at a constant rated speed of 2200 rpm in dual fuel mode. For each setting, diesel was used as the pilot fuel for starting auto-ignition while, natural gas from line supply was used as the main fuel. For each power level the proportion of natural gas replacing diesel was gradually increased by manually opening a control valve to determine the maximum possible diesel replacement using natural gas with satisfactory engine performance. The overall accuracy of Brake Power and Brake Specific Fuel Consumption rates are expected to be within ±2% error band.

TABLE I
Test Engine Specifications

Brand	DONGFENG
Model	S1100D
No. of cylinders	One, Horizontal
Type	4-Stroke, DI - 17 ° BTDC
Displacement	903 cc
Bore x Stroke	100 x 115 mm
Compression Ratio	20
Rated Power (12 h)	11 kW (15 PS)
Rated Speed	2200 rpm
Cooling	Water, Radiator
Lubrication	Forced, SAE30
Fuel Tank	16 liters
Starting	Manual

IV. ENGINE PERFORMANCE AND DISCUSSION OF RESULTS

It was possible to run the engine in dual fuel mode with different maximum diesel replacement levels by natural gas, at different power levels. Diesel replacement was measured volumetrically, based on the amount of liquid diesel saved by using natural gas. The engine was started with Diesel as usual keeping the gas valve of the mixing chamber closed. Engine was loaded to the desired level and the gas valve was manually operated to control the flow of natural gas, replacing the diesel. The diesel consumption decreases automatically as the flow of natural gas is increased. This resulted from the action of the built-in centrifugal governor system of the engine, which readjusts the high pressure diesel flow from the fuel pump in order to maintain the speed. At each load as soon as the additional gas supplied tries to speed up the engine, the governor cuts down the diesel flow to maintain the speed. During the tests data was recorded for engine operations with gradually increased diesel replacement of natural gas up to the maximum possible limits, at different power levels. This is a simple and low cost way of controlling dual fuel operation of a diesel engine suitable for applications where the engine loads do not vary frequently. This could also be suitable for applications were an engine operator (or the engine owner himself) is already employed to look after the engine, which is not very uncommon in Bangladesh. Examples could be engines working in irrigation fields or standby generators supporting shops in a small market.

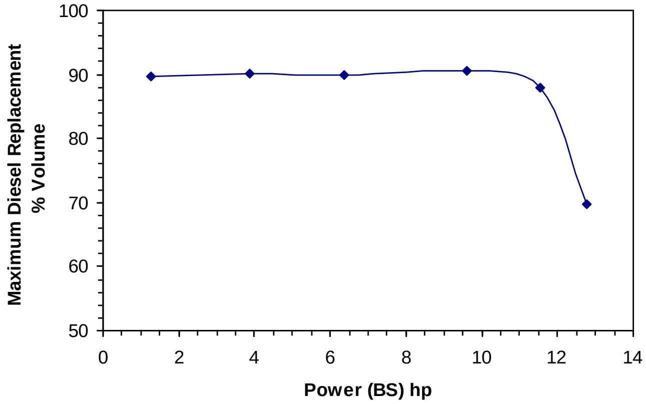


Fig. 5. Variation of maximum possible diesel replacement with load.

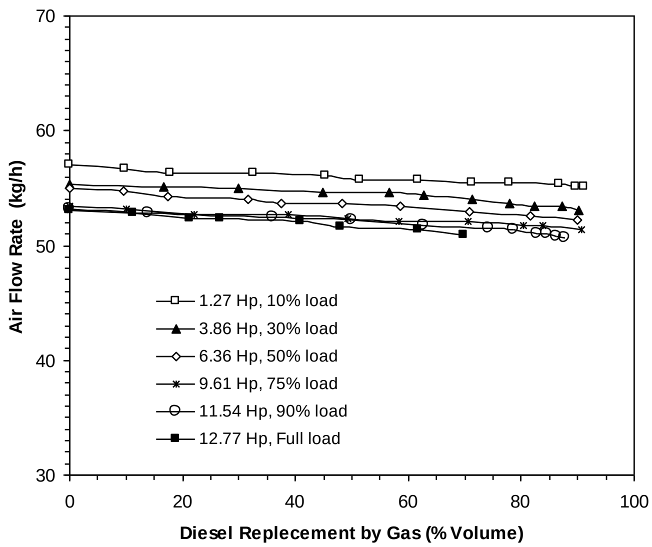


Fig. 6a. Variation of air flow rate with increased diesel replacement by natural gas at different power levels.

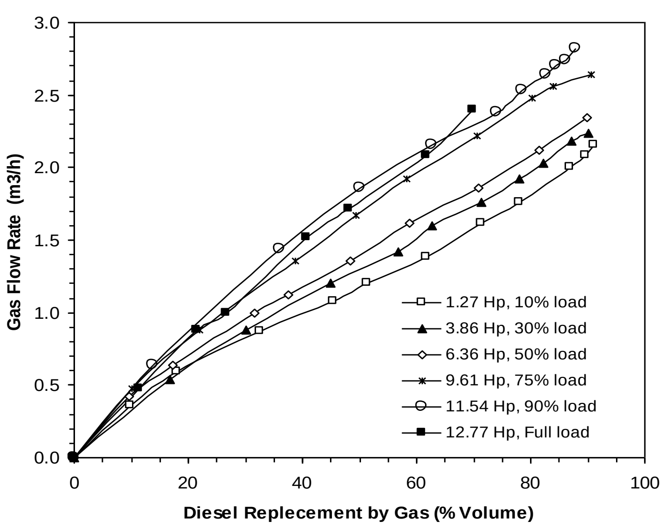


Fig. 6b. Variation of natural gas flow rate with increased diesel replacement by natural gas at different power levels.

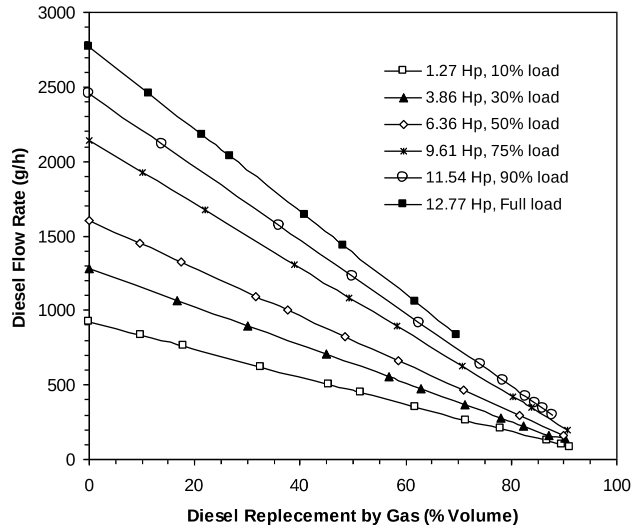


Fig. 6c. Variation of diesel flow rate with increased diesel replacement.

As shown in fig.5 the replacement could be - as high as 90% of the diesel used up to 9.6 hp (about 75% of the actual capacity), this was limited to 88% diesel replacement at 11.5 hp (about 90% of the actual capacity) and only about 69% diesel replacement at 12.8 hp (near the actual full load). As shown in fig.6a, the air flow rate through the engine in diesel-only operation varies by about 7%, from about 57 kg/h to 53 kg/h throughout the entire power range. Fig.6a also shows the relatively small decrease of air flow rate at different loads with variation of diesel replacement by natural gas. Fig.6b shows the increase in gas flows and fig.6c the corresponding decrease in diesel flow, at different power levels as the engine is run in dual fuel mode. Fig.7a shows the drop of diesel equivalent mass basis AFratio as the diesel replacement by natural gas increases at different power levels. Fig.7b compares the mass basis AFratios of diesel only engine operation with maximum possible diesel replacements through out the entire power range.

Since there is no throttle valve, this decrease in air flow is due to the slight decrease of volumetric efficiency, caused by higher residual pressure of exhaust gases at higher loads, typical of diesel engines. This reduces the air handing rate at higher loads with nearly fixed speed and is exhibited in diesel only operation as well. However at each power level the increase in diesel replacement by natural gas results in relatively greater volume occupied by natural gas in the intake flow. This reduces the air flow compared to diesel-only operation, since diesel is injected directly in to the cylinder which has little influence on air intake. However as diesel engines inherently are designed for handling much excess air than the stoichiometric requirement, the introduction of natural gas in intake manifold has less effect on the maximum power development compared to spark ignition engines [2]. This is only exhibited at higher loads with the rated speed, since the relatively higher gas requirements occupies more volume restricting the air handling leading to reduction in the maximum power. So in order to achieve high power the proportion of diesel replacement by natural gas had to be limited in general at higher loads. At each load the diesel replacement is again limited by the knocking tendency in dual fuel mode. The flame propagation is slower with natural gas which improves for richer mixture, but with a richer mixture the delay period is shorter. These two effects counteract each other with the shorter delay being more dominant [2], increasing knocking tendency of a richer mixture. Attempts to increase diesel replacements over a limit resulted in engine knocking, vibration and unreliable engine operation. These two factors stated above are super imposed at higher loads causing the rapid decrease of maximum possible diesel replacement by natural gas at high loads, as shown in fig.5.

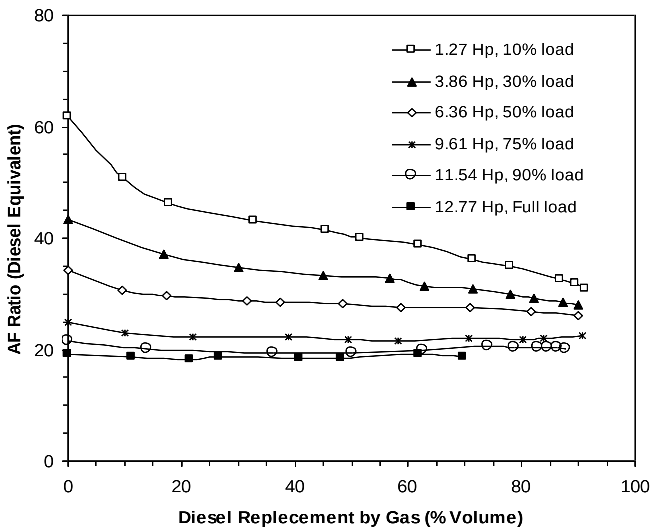


Fig. 7a. Variation of mass basis air-fuel ratio with increased diesel replacement by natural gas at different power levels.

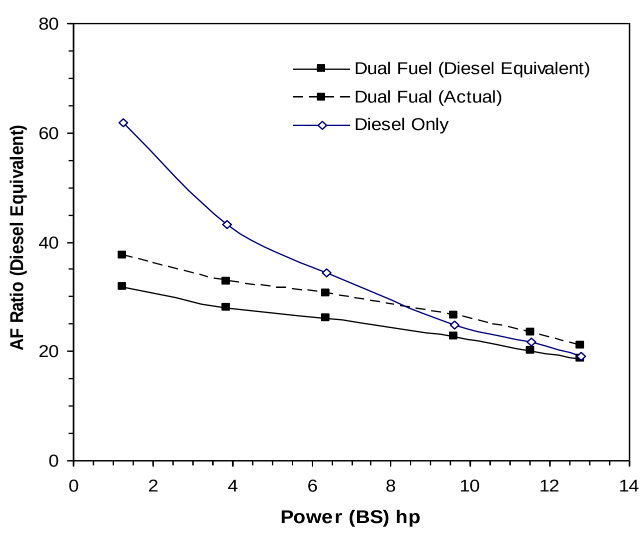


Fig. 7b. Variation of AFratio with load for maximum diesel replacement, at 2200 rpm.

Since natural gas has a different heating value a diesel equivalent AFratio in dual operation was also calculated. AFratio decreases sharply with increased load, as the fuel flow (diesel-only or dual) increases, while the air flow decreases slightly. On the other hand actually natural gas has a higher requirement of air for stoichiometric combustion (17.2 by mass) compared to diesel (14.6 by mass). As a result with high rate of diesel replacement with natural gas the engine is restricted in term of maximum power produced. For loadings of 10%,30%,50% and 75% of the actual rated load the engine could produce the required power with up to 90% diesel replacement. Things started to change at high loads, at 90% load up to 88% replacement was possible, but at full load this was much more restricted to 69% diesel replacement only.

Fig.8a shows the variation of diesel equivalent (ebsfc) for dual fuel and brake specific (bsfc) fuel consumptions for diesel-only. Since the heating value of natural gas (50 MJ/kg) and diesel (42 MJ/kg) are different, a diesel equivalent of natural gas consumption was calculated for comparison. The thermal efficiency of the two can be compared directly. The thermal efficiency of dual-fuel operation was found to be lower compared to diesel-only operation at part loads. However near the rated full load the efficiencies are very much comparable (about 29% for both cases). Fig.8b shows the variation is about 5% up to 50% load and at higher loads the difference is gradually eliminated. The variation of efficiency is partly associated with more heat losses due to late burning of the mixture. In dual fuel combustion the diesel portion of the fuel auto ignites first due to compression heat and remaining gas-air mixture burns in progression. The combustion stages are a bit different from typical compression ignition of diesel. The flame propagation speed of natural gas is relatively slower compared to diesel, especially when the mixture is lean [2]. In order to have instant interchangeability to diesel-only operation at any time, the injection timing had not been changed for dual fuel operation. This effect the combustion, more at part loads. The lower flame speed at part loads causes late combustion and heat release, resulting in higher exhaust temperature and heat losses – reducing the thermal efficiency. The late burning and higher AFratio requirement also causes incomplete combustion of some of the fuel, causing increase on CO formation as shown in fig.10, which is also partly responsible for reduction in thermal efficiency. At higher loads the situation improves as the concentration of gas in the combustible mixture improves the flame propagation speed and increases the thermal efficiency. Advancing the diesel injection timing for dual fuel operation at part loads may improve the part load thermal efficiency. However it was found that for loads varying in the higher range only, the engine could be run almost as efficiently as diesel-only operation, without changing the injection timing.

Using natural gas showed some increase in exhaust gas temperature indicating increased heat losses in dual fuel mode. The difference in exhaust temperature is caused due to the late burning of the mixture with lower flame propagation speed. However rise of exhaust gas temperature was relatively smaller compared to a spark ignition engine running on natural gas [2].

This caused less significant change in heat losses, as relatively higher amount of air is handled through a diesel engine.

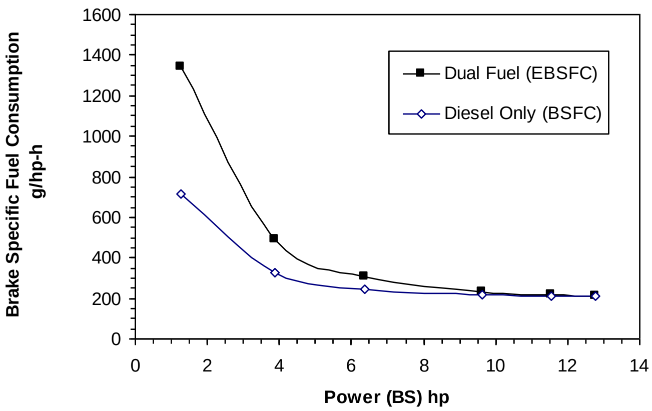


Fig. 8a. Variation of diesel equivalent Bsfc for dual fuel operation and diesel fuel alone.

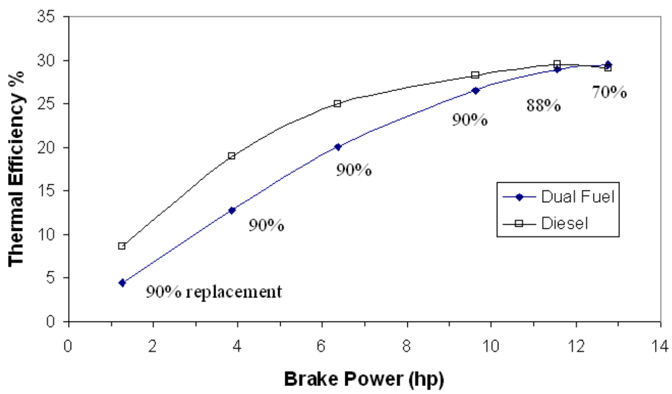


Fig. 8b. Variation of thermal efficiency for dual fuel operations using maximum possible gas replacements.

Fig. 9a shows that the exhaust gas temperature increased by 10-15°C at part loads. At full load diesel replacement was only about 69%, the mixture was more concentrated and presence of larger proportion of diesel fuel mass caused a drop of exhaust temperature compared to diesel-only operation. Fortunately the corresponding rise in exhaust valve temperature was even less significant. As shown in figure 9b the exhaust valve metal temperature rose at higher power levels, similar to diesel only operation. However they increased by less than 5°C as the proportion of diesel replacement by natural gas increased. The variations also exhibited the trend of decrease in valve temperature with limited diesel replacement of gas near full load conditions. The late burning of gas mixture in dual fuel mode caused some rise in temperature in the exhaust line, but coolant and lubricating oil temperatures changed very little compared to diesel-only operation.

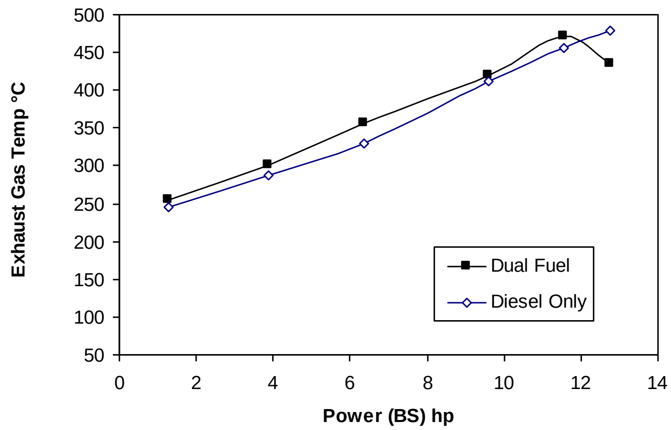


Fig. 9a. Increase in exhaust gas temperature with highest possible diesel replacement by natural gas at different power levels.

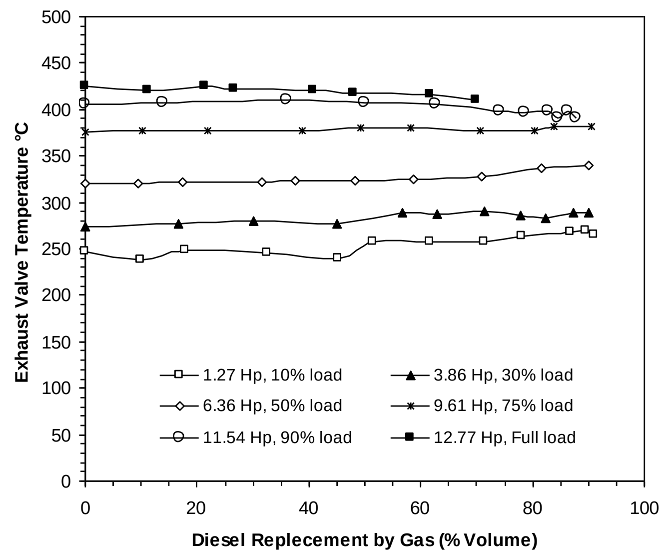
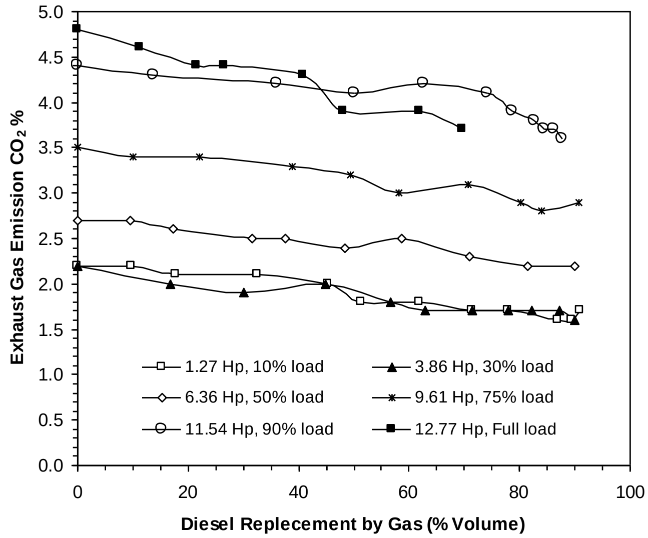


Fig. 9b. Variation in exhaust valve temperature with increased diesel replacement by natural gas at different power levels.

Fig.10 shows the variation of CO_2 and CO emission from the engine with increased diesel replacement of natural gas at different power levels. Exhaust analyzer measurements showed that generally the volume of CO (less than 0.1%) formed and the proportion of CO_2 (2-5%) in the exhaust gas was very low, which is typical of a diesel engine. With higher diesel replacement the level of CO_2 generation decreased and CO emission was found to increase. The late burning of the mixture with higher diesel replacement levels of natural gas, had caused more fuel to remain partially unburned increasing the formation of Carbon monoxide and decreasing the proportion of Carbon-di-oxide. This would contribute to the reduction of efficiency at light loads.



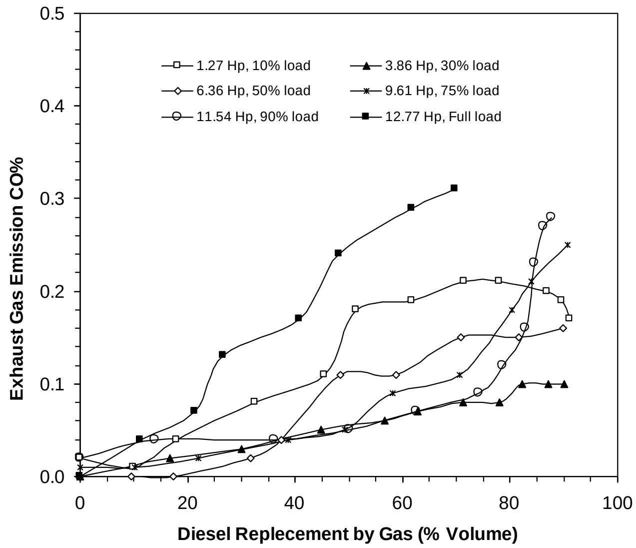


Fig. 10. Variation of CO_2 and CO emissions from diesel engine in Dual fuel mode.

V. ECONOMIC FEASIBILITY OF DUAL FUEL OPERATION

Table-II shows the details of diesel replacements by natural gas possible at different power levels of the engine. Table-III compares the cost saving of dual fuel operation based on a 60 water liter size CNG cylinder attached to the engine using a pressure regulator and manual flow control valve (Low pressure CNG unit). The costs were calculated on the basis of the engine performance described earlier and current price of fuels. The comparison of three power levels near the rated values with maximum possible diesel replacement was considered. The engine had an existing 16 liter fuel tank, which allows to have a continuous run at the rated load with diesel alone for about five hours. The 60 water liter size CNG cylinder was considered as it provides a similar time of operation compared to diesel with a full tank and its commercial availability. The cylinder size would practically dictate the time limit of a single run in dual fuel operation. The fuel cost of indigenous natural gas is much lower compared to imported diesel in Bangladesh. The comparison is made on mass basis of fuel consumption and the costing is based on the present fuel price of Taka 44 per liter for diesel and Taka 16.75 per Nm^3 of natural gas used in transportation sector (70 Taka, Tk. = 1 US$).

TABLE II
CNG replacements of diesel fuel in dual mode operation.

Loading Capacity	30%	50%	75%	90%	100%
Brake Power hp (kW) at 2200 rpm	3.86 (2.84)	6.36 (4.68)	9.61 (7.07)	11.54 (8.49)	12.77 (9.39)
Maximum possible Gas replacement of diesel	Up to 90%	Up to 90%	Up to 90%	Up to 88%	Up to 70%
Diesel consumption rate with max. gas replacement g/h (for diesel only g/h)	139 (1278)	160 (1601)	200 (2141)	298 (2453)	836 (2767)
Max gas replacement rate at STP m^3/h (g/h)	2.24 (1478)	2.34 (1544)	2.64 (1742)	2.82 (1861)	2.4 (1584)
Equivalent Bsfc g/Bhp-h (Diesel only) g/Bhp-h	492 (331)	314 (252)	237 (223)	218 (213)	213 (217)
Thermal Efficiency % Dual Mode (Diesel Only) %	12.8 (19)	20.1 (25)	26.6 (28.3)	28.9 (29.6)	29.6 (29)

TABLE III
Diesel replacement with 60 liter LPCNG

Gas Replacement options near full load	Opt-1 : 90% gas replacement at 75% load 9.61 hp	Opt-2 : 88% gas replacement at 90% load 11.54 hp	Opt-3 : 70% gas replacement at 100% load 12.77 hp
Gas Consumption rate Nm^3/h (g/h)	2.6 (1742)	2.77 (1861)	2.36 (1584)
Diesel consumption rate l/h (g/h)	0.238 (200)	0.354 (298)	0.995 (836)
Run time for each CNG cylinder	5 hrs 41 min	5 hrs 19 min	6 hrs 15 min
Gas cost per run Tk	251.3	251.3	251.3
Diesel cost per run Tk	59.5	82.8	273.6
Dual Cost per run Tk	310.8	334.1	524.9
Equivalent Diesel Only Run cost Tk	637.4	683.5	905.8
Saving per CNG cylinder run Tk	326.6	349.4	380.9
% Saving w.r.t. Diesel	51.2	51.1	42

Option-1 could be running the engine at 75% load (about 9.6 hp) with 90% diesel replacement by gas. In this case the total Dual fuel cost per CNG cylinder run is 311 Tk (251 Tk. NG and 60 Tk. Diesel), compared to Tk. 637 for the same power and for the same time with diesel only. This can reduce the fuel cost by 51%, saving Tk. 326 per run but this option is limited by reduced load capacity. Option-2 could be running the engine at 90% load (about 11.5 hp) with 88% diesel replacement by gas. In this case the total Dual fuel cost per CNG cylinder run is 334 Tk (251 Tk. NG and 83 Tk. Diesel), compared to Tk. 684 for the same power and for the same time with diesel only. This can reduce the fuel cost by 51%, saving Tk. 349 per run. Option-3 could be running the engine at 100% load (about 12.7 hp) but with only 70% diesel replacement by gas. In this case the total Dual fuel cost per CNG cylinder run is 525 Tk (251 Tk. NG and 274 Tk. Diesel), compared to Tk. 905 for the same power and for the same time with diesel only. This can reduce the fuel cost by 42%, saving Tk. 380 per run, but the diesel replacement is limited and running the engine at the rated load continuously for a long time may not be recommended. The comparison showed that running the engine at about 90% (11.5 hp) of the rated load with 88% diesel replacement, with a 60 liter CNG (200 bar) filled cylinder could provide about 5 hrs and 20 minutes of continuous operation and provide the most economic use of the engine in dual fuel mode.

The savings of 51% fuel cost, about Tk 350 per 5 hour run, will require about 72 days of running (considering two runs per day) to recover the cost of the 'Low Pressure CNG System', that can be used for supplying natural gas to engines at remote locations. Hence the feasibility of such operation seems to be promising. Probably a new breed of small rural entrepreneurs will develop who will have few of such units scheduled to supply gas to a number of stationary diesel engines in localities around each CNG supply station or daughter station. The engine owners will require very minimum change to their hardware, retaining instant inter changeability to diesel operation, while sharing the benefit of saving in fuel cost. This could reduce the imported diesel requirement of the country and create some new job opportunities in the process.

VI. Conclusions

The dual fuel operation of a widely used single cylinder diesel engine, with natural gas was investigated. Gas fumigation into intake manifold was used for running the diesel engine in dual fuel mode. This is an easy and low cost way of running a diesel engine with natural gas as dual fuel and the technique could be suitable for applications where the engine load does not vary frequently and widely. This required minimal modification of the engine and all the diesel settings were kept unchanged to retain instant interchangeability to diesel-only operation. Natural gas could be used from line supply or a low pressure CNG system developed. The maximum achievable diesel replacement by natural gas was found to vary with engine loads, while the speed was kept constant at the rated rpm.

The engine showed very similar performance compared to diesel only operation near 90% of rated load with up to 88% replacement of diesel by natural gas being possible. At the rated load the diesel replacement by natural gas needed to be limited to 70% in order to avoid knocking of the richer mixture. At part loads, as high as 90% diesel replacements were attainable, but the thermal efficiency was less compared to diesel only operation. Since the injection timing was not changed, the slower flame propagation speed of natural gas mixture caused late burning of fuel. This increased - exhaust gas temperature, exhaust heat loss and produced less complete combustion of fuel, effecting the part load efficiency of dual fuel operation to some extent. However exhaust valve, coolant and lubricant temperatures were not increased significantly.

Running the engine near rated load was found to be almost equally efficient with much less fuel cost. Analysis of three probable high-load dual fuel operations reveled that running the engine at nearly 90% of the load capacity with 88% diesel replacement by natural gas would give the highest overall economic benefit. For such operations a 60 liter CNG cylinder could support the engine for more than 5 hours, comparable with its existing fuel tank. Each run would save 51% fuel cost worth taka 350, ensuring a short payback period of the additional hardware required. The socio-economic feasibility of running such engines in dual fuel mode in remote locations appears to be promising.

Acknowledgment

The authors acknowledge the Department of Mechanical Engineering BUET for technically supporting and funding the work through M.Sc and CASR Research projects.

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