DUAL-FUELLING OF A DIRECT-INJECTION AUTOMOTIVE DIESEL ENGINE BY DIESEL-GAS METHOD

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Abstract Use of liquified petroleum gas (LPG) in compression-ignition (C-I) engines has always been considered important in the diesel engineering field. This is due to its easy accessibility and good combustion characteristics. In this paper the application of LPG fuel along with diesel oil in a direct-injection automotive diesel engine is experimentally investigated. In order to convert the pure diesel engine into a diesel-gas one, a carburetted LPG fuel system has been designed and fitted into the engine. Then by means of a system of rods, the LPG system is linked to the diesel fuel injection system. The dual-fuel system is adjusted so that, at full load conditions, the quantity of diesel oil is reduced to 70%, and 30% of its equivalent energy is substituted by LPG fuel. Performance tests conducted under various loads and speeds on both diesel and diesel-gas engines, show that with equal power the diesel-gas engine has the potential to improve overall engine performance. For example, within useful speed range, its fuel economy increases by 2-5% and the amount of smoke and mean exhaust gas temperature are reduced by 25-48% and 3.5-7.2% respectively. Also various proportions of LPG and diesel oil are investigated. It is found that the ratio of 30% LPG/70% diesel oil is the most suitable one. The experimental results verify the predicted results, obtained from a diesel-gas engine cycle model.

چکیده استفاده از گاز نفتی مایع (LPG) در موتورهای اشتعال تراکمی بعلت در دسترس بودن و نیز ویژگیهای احتراقی خوب آن همواره مورد نظر مهندسین موتور دیزلی بوده است. دراین مقاله استفاده از گاز LPG همزمان با سوخت دیزلی دریک موتوردیزلی خودرو با پاشش مستقیم از جنبهٔ تجربی مورد بررسی قرار گرفته است. برای این منظور موتور دیزلی پردو ری انتخاب و سیستم سوخت رسانی گاز LPG طراحی و برروی موتور نصب و سپس بوسیله یک مکانیسم اهرم بندی به سیستم سوخت رسانی دیزلی ارتباط داده شد. با توجه به ویژگیهای احتراقی گاز LPG ، دراین بررسی، سیستم سوخت رسانی دوگانه طوری تنظیم شده که دربار کامل، ظرفیت سیستم سوخت رسانی دیزلی به ۷۰ درصد اسمی آن تقلیل یافته و ۳۰ درصد معادل انرژی تقلیل یافته با گاز LPG جایگزین گردیده بنحوی که سقف قدرت موتور ثابت بماند. پس از انجام تست های عملکردی برروی موتور دیزل خالص و موتور دیزل - گاز تحت بارها و سرعت های مختلف و مقایسه، نتایج حاصل، مشاهده شد که به ازای سقف قدرت یکسان در هردو موتور، عملکرد موتور دیزل-گاز بطور کلی بهتر از عملکرد موتور دیزل خالص بوده چنانکه در دورهای مختلف موتور اقتصاد سوخت بمقدار ۲ الی ۵ درصد افزایش و مقدار دود به اندازه ۲۵ الی ۴۸ درصد و دمای گازهای خروجی به اندازه ۳/۵ الی ۷/۲ درصد کاهش یافته است. ضمناً نتیجه گرفته شد که نسبت ۳۰ به ۷۰ گاز به گازوئیل نسبت متناسبی در موتور دیزل-گاز است. بعلاوه نتایج تجربی فوق با نتایج پیش بینی شده از یک مدل سیکل موتور دیزل-گاز نیز مطابقت داشته و آنرا تأئید مینماید.

INTRODUCTION

Since the invention of intermittent internal-combustion engines (I-I-C-E), application of gaseous fuels to these engines has always been considered important by inventors, researchers, and engine manufacturers. This is because gaseous fuels, such as liquified petroleum gas (LPG) and compressed natural gas (CNG), in comparison to conventional liquid fuels, from the point of view of combustion and emission are of a better quality. Also in certain countries, like Iran, they can be considered as reliable energy sources.

During this period, interest in using gaseous fuels in I-I-C-E has both increased and decreased depending upon the availability and cost of gaseous fuels compared to conventional liquid fuels. However, in recent years, stringent emission legislation has focused attention on the clean burning gaseous fuels, especially in the automotive engines.

Due to the homogeneity of the fuel-air mixture in S-I engines, using gaseous fuels in this type of engine is easy. But in C-I engines, due to the heterogeneous nature of the charge-mixing and combustion characteristics, application of gaseous fuels in so-called diesel engines is not an easy task, and it requires sound research and development work.

The main purpose of this investigation is the application of LPG fuel parallel to diesel fuel in a D.I. automotive diesel engine. To this end, LPG has advantages of higher density, less complex storage and ease of handling compared to CNG. In order to use LPG in diesel engines, the following approaches are suggested:

- Converting diesel engine to S-I engine (100% LPG)

-Diesel-gas engine, in which diesel fuel and LPG are used simultaneously (partial substitution of LPG for diesel fuel).

For this purpose the diesel-gas concept was chosen. In this method, engine design was not altered and the working cycle remained as efficient as a limited-pressure diesel cycle.

In the diesel-gas engine (D-LPG) during the intake stroke, a lean mixture of dry LPG and air was drawn through an LPG fuel system into the engine. During the compression stroke, the mixture was compressed (compression ratio unaltered). At injection, a predetermined quantity of liquid diesel fuel was injected into the hot gas air mixture, through the conventional fuel injection system. The homogeneous mixture of hot dry LPG, air, and diesel spray was ignited with local flame nuclei created by the spray or true flame propagation. It seems that due to a greater proportion of diesel (in this study about 70%) the former type of combustion occurred in the engine. However, in this case, the percentage of substitution of LPG to diesel oil was limited to 30-35%, due to onset of knock which occurred with higher percentages of LPG substitution.

For many years, the dual-fuel engine was used in the slow and medium-speed stationary diesel market. High-speed automotive diesel engines do not lend themselves well to diesel-gas operation.

Their richer mixture strength (near stochiometric) and rapid variation of load and speed during the engine operation, can be a problem for dual-fuel combustion. In 1980 at TNO, Holland, a number of automotive diesel engines were converted to diesel-gas engines using LPG fuel and diesel fuel. Their performance was compared with corresponding diesel engines [1,2,3].

Some engine models were developed at this research centre, to predict diesel-gas engine performance for dual-fuel system optimization [4,5].

Due to the variation of the combustion-chamber design characteristics and in cylinder flow patterns, it was necessary to conduct a seperate conversion and test for each engine. In this research project an automotive D. I. diesel engine was converted to a diesel-gas engine with a specially designed dual-fuel system. A test program was carried out to obtain performance and emission chracteristics of the engine.

Along with engine testing, extensive theoretical work was undertaken, and an engine cycle model was constructed for diesel-gas engines [6]. The engine cycle models saved time and cost in diesel-gas engine design, development, and test-bed. Finally, results obtained from the test program were compared with the predicted results, from the model.

ENGINE DATA AND DESIGN OF THE DUAL-FUEL SYSTEM

Table 1 shows the technical data of the diesel engine used in this investigation.

In this project the fuel injection system of the engine was adjusted so that, at full load conditions, the amount of diesel fuel per cycle was reduced to 70% and this reduction was made up by the aspiration of LPG into intake manifold. Figure 1 shows schematically the layout of the dual-fuel used in this investigation. LPG fuel at a pressure of 6-7 bar

TABLE 1. Specification of Diesel-Gas Engine

Engine type	4-stroke, naturally aspirated, D.I. diesel engine
Cylinder number	6
Bore	0.115 m
Stroke	0.140 m
Displacement volume	8.72 lit
Compression ratio	16.8
Rated power	130 Kw at 2500 rpm
Fuel injection system	Bosch in-line pump with mechanical governor.
Air-fuel ratio	25

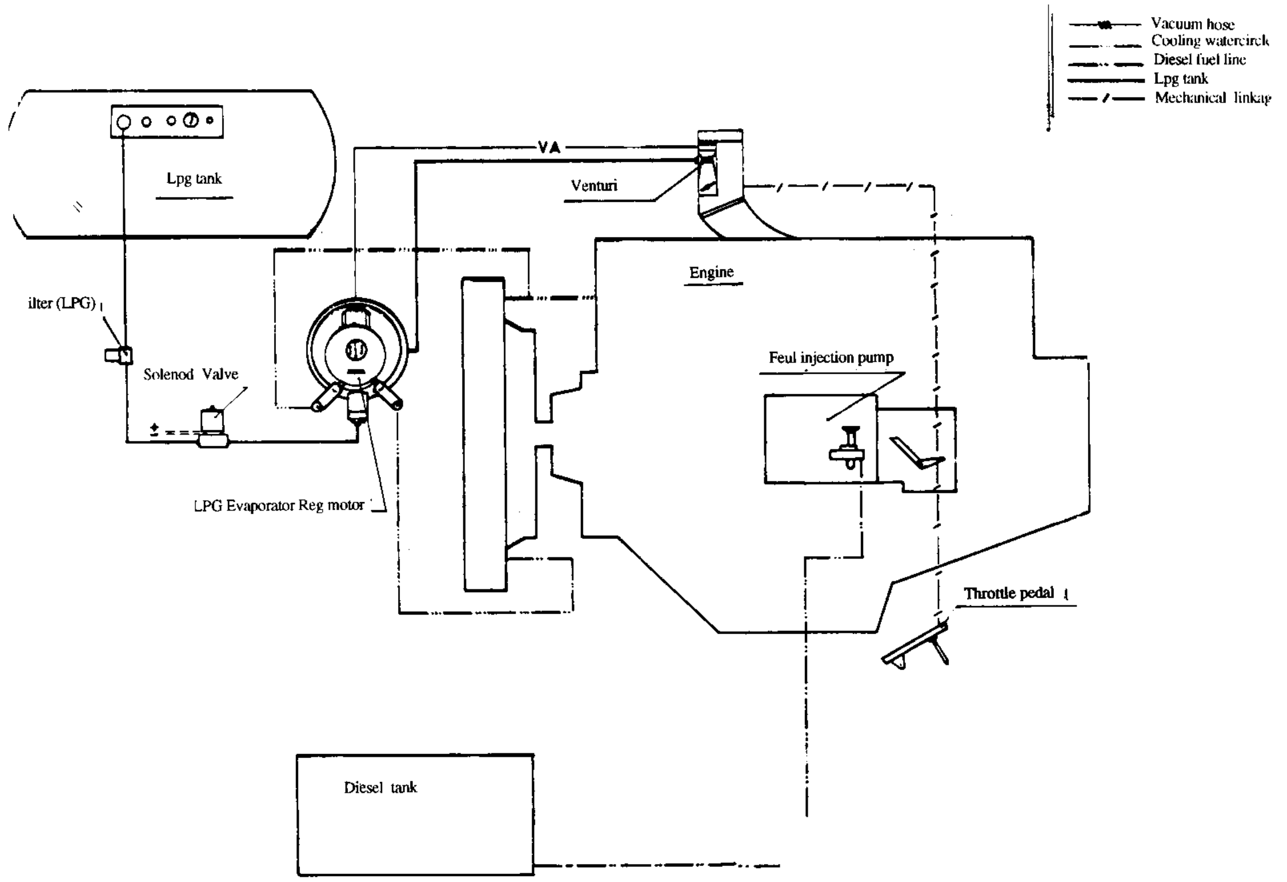

Figure 1. Schematic layout of the dual-fuel·

is delivered from the LPG tank, through an LPG filter and a solenoid actuated LPG valve to a combined evaporator and pressure regulating unit (Miyari, Japan). Here the pressure of the LPG is reduced to atmospheric pressure and by receiving heat from the cooling system of the engine, it becomes as dry vapour. It enters into the venturi tube of the LPG carburettor, where it mixes with air, then the mixture passes through the throttling valve. Here the mixture of LPG and air is diluted by the air flowing from the unthrottled part of the carburettor. Finally, a very lean mixture enters the inlet manifold of the engine.

Under the various speeds and loads the amount of LPG is controlled by air flow passing through the venturi and by the throttling valve operated by the governor of the fuel injection system.

PERFORMANCE AND EMISSION TEST

Before testing the diesel-gas engine on an Eddy-Current dynamometer (Schenk type W 400), it was ensured that all systems were functioning properly and that there were no gas, air or water leaks in the system. Performance tests of the diesel-gas engine showed that the engine performed best with a diesel/LPG ratio of approximately 70% diesel fuel and 30% LPG under various speeds at full load. Other proportions of diesel fuel and LPG were also tried (i.e. 20, 40% LPG). It was found that the proportion of 30% LPG and 70% diesel fuel was the optimum. Under these operating conditions, the diesel-gas engine showed good performance and smooth running.

The results obtained from the performance tests can be considered typical. During extensive testing programs the results remained almost the same and repeatable. The observed results such as engine torque, power output, smoke, and CO_2 were corrected to standard atmospheric conditions (pressure 760 mmHg, temperature 20 C) and plotted versus engine speed. For comparision purposes, performance and emission test results of the diesel engine are also plotted.

PERFORMANCE AND EMISSION TEST RESULTS AND DISCUSSION

The performance and emission results of a diesel-gas engine and a diesel engine are shown in Figures 2-5. In comparing these results, it must be noted that the maximum load versus speed remained the same for both engines. Power curves in Figure 2 coincide except for points 1200 and 2500 RPM, which show small differences.

It can be seen from Figure 2 that the torque curves of both engines coincide except at 1200 RPM. Under the 1200 RPM condition the amount of diesel fuel in the injection pump past the pumping elements is quite high resulting in a decrease of diesel fuel from 70% to 66% with an increase of the LPG fuel from 30% to 34%. This amount of LPG leads to detonation. At this particular speed power for diesel-gas, operation is lower than that for the diesel engine (about 3%).

Figure 3 shows brake specific fuel consumption (b.s.f.c.) curves versus speed for both engines. It is observed that the b.s.f.c. curve for diesel-gas operation is always less than the diesel operation. The b.s.f.c. of the diesel-gas engine is 3%-6.6% (depending on speed) less than that of the diesel engine. Reduction of b.s.f.c. is primarily due to substitution of LPG fuel, which has higher heating value, compared to diesel oil; and secondly it is due to cleaner and complete combustion of LPG in the diesel-gas engine. Of course, it is obvious that reduction of b.s.f.c. means increasing the thermal efficiency of the diesel-gas engine (2%-5%) relative to the efficiency of the diesel engine.

Figure 4(a) shows the curves of smoke versus speed for both engines. By comparing these curves, the amount of smoke of the diesel-gas engine is shown to be considerably lower than the diesel engine at all speeds at 30% fuel substitution. The difference between them is 24.2%-48.1% depending on speed. In a diesel engine, there is not enough time for complete mixing of liquid fuel and air. In the diesel-gas engine, about 30% of the total fuel is vapor mixed with inlet air. Thirty percent of the mixture is premixed leading to cleaner combustion in the diesel-gas engine.

Smoke characteristics of the diesel-gas engine are more desirable, and a reduction of smoke will have positive effects on engine oil life. Therefore engine service intervals

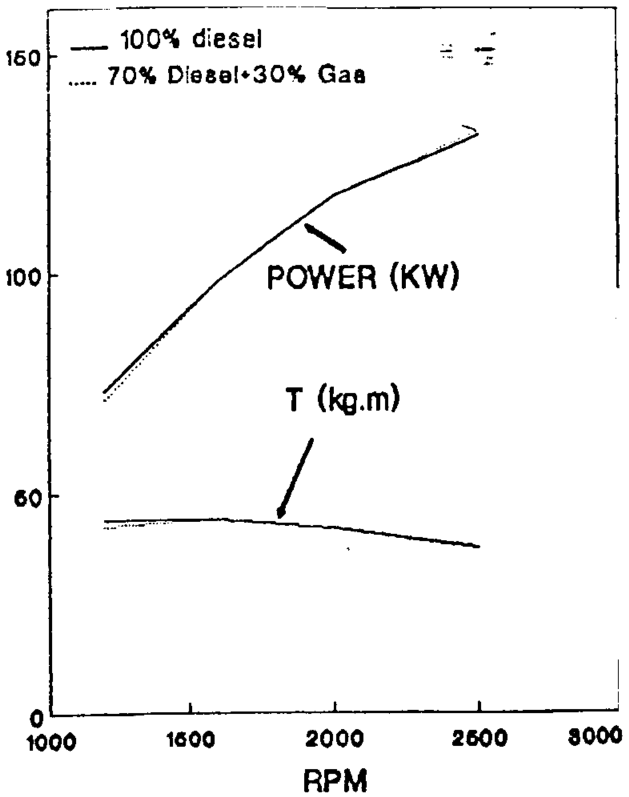

Figure 2. Comparison of power and torque curves for pure diesel and diesel-gas engines at full load.

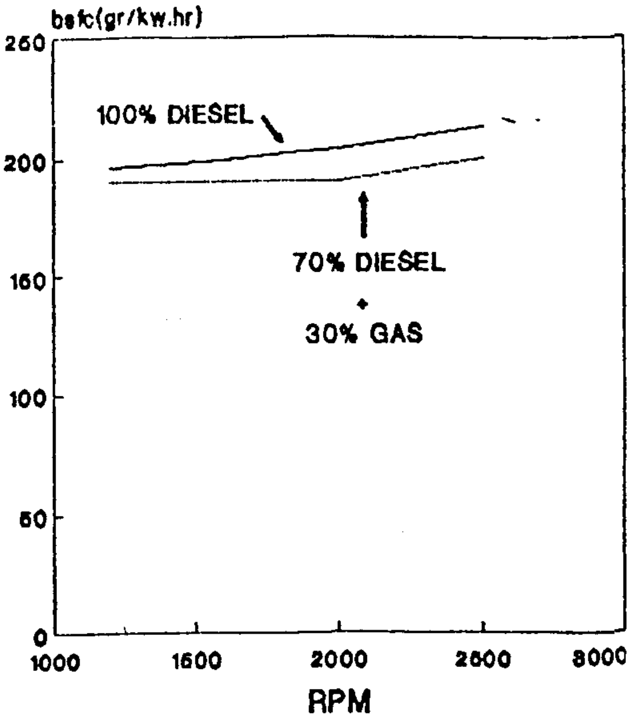

Figure 3. Comparison of specific fuel consumption curves for pure diesel and diesel-gas engines at full load.

may be extended.

Figures 4-6 show the curves of total unburnt hydro carbon (UHC) in the exhaust gas versus engine speed for both engines. It can be seen that in the diesel-gas engine, the amount of UHC is higher than that in the diesel engine and decreases with an increase in the engine speed. This is mainly due to an increase in ignition delay time of the dual-fuel (reduction of cetane number). By increasing the ignition delay period gaseous fuel will not burn completely and some of it appears as UHC in the exhaust gas of the diesel-gas engine. At higher engine speeds, the time period of the ignition delay becomes shorter and cylinder charge motion increases. These two lead to relatively complete combustion and hence a lower amount of UHC.

Fig 4(c) shows the volume percentages of carbon monoxide (CO) gas in the exhaust gas of both engines versus engine speed. As shown, in the diesel-gas engine the amount of CO gas is higher than the diesel engine and decreases slightly with engine speed and then increases again at higher engine speeds. This is mainly due to the heterogeneous nature of the cylinder charge and the incomplete combustion process which occurs particularly in the rich core of the liquid fuel spray and also perhaps in the very lean part of the cylinder charge. In these parts of the clyinder charge, recombination reactions, i.e. $CO + {}^1/_2 O_2 \rightarrow CO_2$, are incomplete because of lack of oxygen, low gas temperature, or short residence time, hence CO will be higher (7). The increase of CO at higher engine speeds maybe due to the incomplete combustion because of short residence time (time available for combustions is

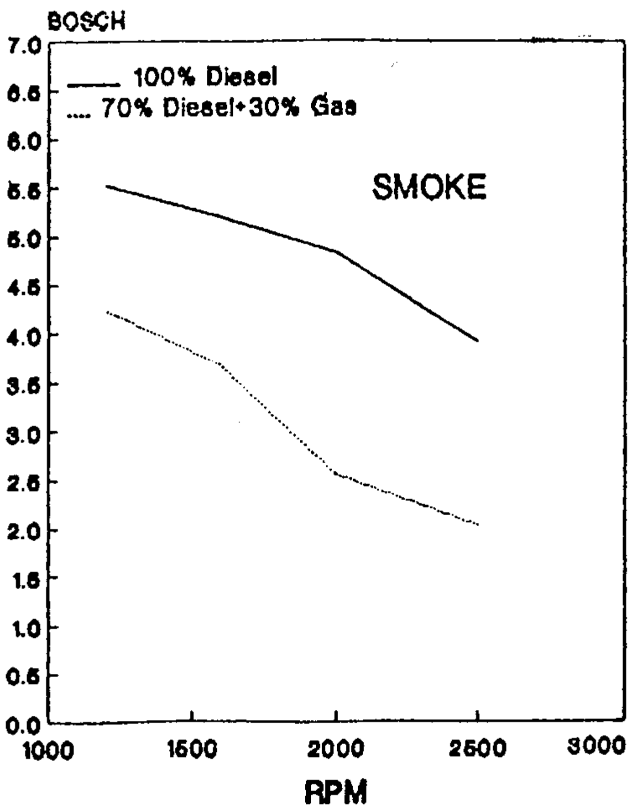

Figure 4. (a) Comparison of smoke curves for pure diesel and diesel-gas engines at full load.

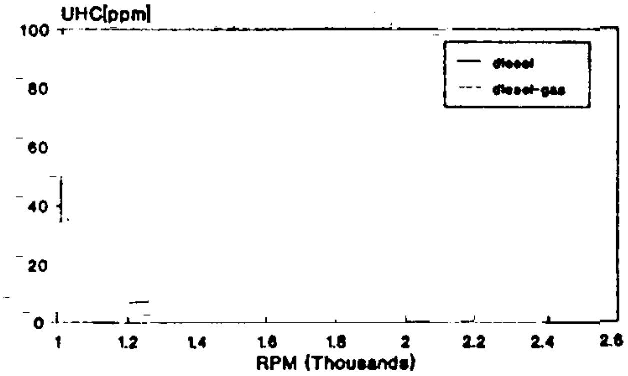

Figure 4(b). Comparison of unburned hydrocarbon gas curves for diesel and diesel-gas engines at full load.

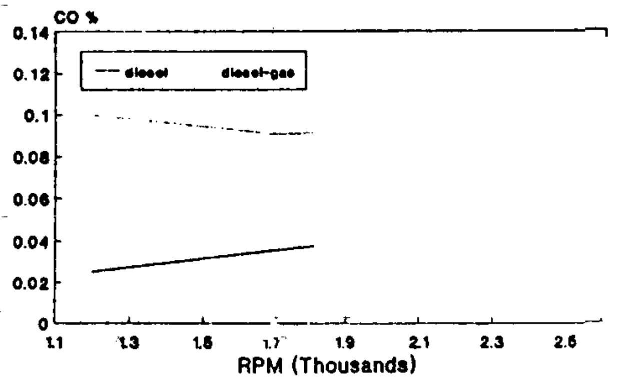

Figure 4(c). Comparison of carbon monoxide curves for diesel and diesel-gas engines at full load.

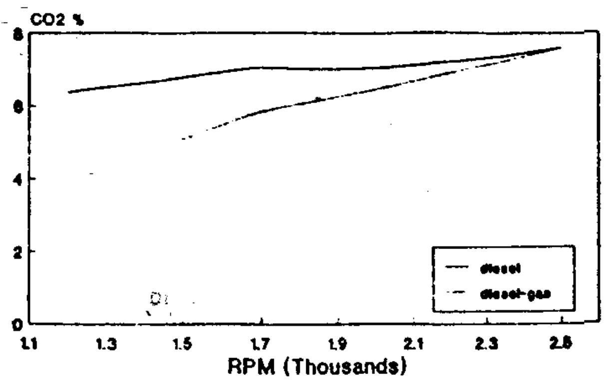

Figure 4(d). Comparison of carbon dioxide curves for diesel and diesel-gas engines at full load.

shorter with the increasing of engine speed).

Figure 4(d) compares the curves of carbon dioxide (CO_2) gas from exhaust gas of both engines versus engine speed. As indicated in this figure, the volume percentage of CO_2 in diesel engine is more or less constant and mostly independent of engine speed. However, volume percentage of CO_2 for diesel-gas engines is always less than that for diesel engines and increases with speed. At higher engine speeds the curve of CO_2 in the diesel-gas engine reaches that of the diesel engine. This trend is due to a higher amount of CO and UHC gases in the diesel -gas engine, since the total number of carbon atoms in the dual-fuel must be equal to the number of carbon atoms existing in the exhaust gases.

From emission studies of the diesel-gas engine, it can be concluded that, in spite of the considerable reduction in black smoke, other pollutants, i.e. UHC and CO gases are increased in the diesel-gas engine. Further research is underway to verify this trend and possibly to reduce these pollutants.

Figure 5 shows exhaust gas temperature versus speed for both diesel-gas and diesel engines. The exhaust gas temperature of the diesel-gas engine is 3.5%-7.2% less than that of the diesel engine. This is due to lower consumption of fuel mass per unit power. Hence the air-fuel ratio in the diesel-gas engine is higher than that in the pure diesel engine and there is a lower proportion of diffusion combustion. This leads to a lowering of flame temperature and consequently exhaust gases temperature. Clearly, the lower exhaust temperature decreases thermal stress in cylinder head, piston, exhaust valve, and rings, and increases the useful service life.

Table 2 compares some important performance parameters of both engines at 2500 RPM.

COMPARISON OF PERFORMANCE TEST RESULTS WITH PREDICTED RESULTS

As mentioned earlier, for the prediction of actual diesel-gas engines performance parameters, an engine cycle model was also developed [6]. In this model prediction of the cycle, that is, compression stroke, combustion process, and expansion stroke has been considered. During the whole cycle of events, heat transfer from cylinder charge to the

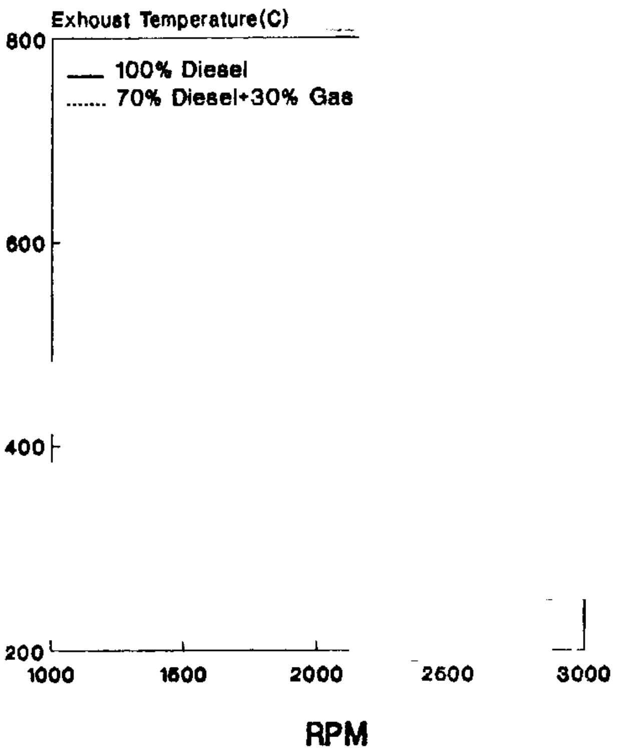

Figure 5. Comparison of exhaust gas temperature curves for pure diesel and diesel-gas engines at full load.

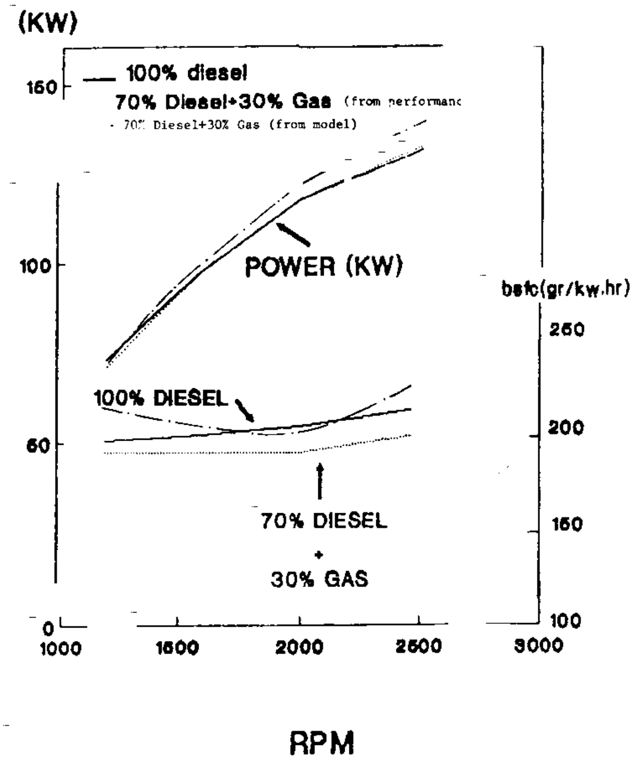

Figure 6. Comparison of performance curves of diesel-gas engine obtained from performance test and model.

TABLE 2. Comparison of Diesel-Gas and Pure Diesel Engines Performance Parameters at 2500 RPM.

Performance parameter	diesel-gas engine	pure diesel engine	deviation%
Brake power, Kw	132.5	131.36	+0.9%
Torque, Kg-m	379.6	379.6	+0.96%
Brake specific fuel Consumption, gr/Kw. hr	200.34	213.86	-6.32%
Smoke Bosch	2.03	3.91	-48.1%
UHC, (PPM)	34	15	+126.7
CO, (%)	0.125	0.06	+108.3
Exhaust temperature,°C	594.0	640.0	-7.2%

wall has been taken into account by using a suitable instantaneous heat transfer correlation. Calculation of the combustion process is based on a synthetic single zone combustion model with appropriate burning pattern. For a calculation of the dual-fuel mass burning rate, the burning pattern has been modified and used in this model. Further information about the structure of the engine cycle model can be found in Reference [6]. In the present work the performance of diesel-gas engine versus engine speed has been predicted by using the above model.

Figure 6 shows the power and specific fuel consumption curves of a diesel-gas engine, obtained from both the test and the model. The test results verify the predicted results satisfactorily.

CONCLUSIONS

The following are the results obtained by comparing the performance and emission parameters of a diesel-gas engine with a diesel engine:

1- Diesel-gas method is a suitable and an economical method for using LPG in diesel engines. By this method, it is possible at any time to convert the diesel-gas engine for only diesel operation.

2- By converting the diesel engine into a diesel-gas engine, thermal efficiency increases by 2%-5%, the amount of smoke decreases by 25%-48.1%, and exhaust gas temperature decreases by 3.5%-7.2% (all for fuel proportions of 30% LPG, 70% diesel oil).

3- Considerable reduction of smoke in a diesel-gas engine leads to a decrease of environmental pollution, but other pollutants, such as UHC and CO gases are increased.

4- Performance test results are in good agreement with predicted results, obtained from modelling of the diesel-gas engine cycle.

5- It is found that substitution of LPG for 30% diesel oil is the optimum proportion for this particular engine.

Under this condition, in addition to improving the performance, its operation is smooth and has no increased noise and vibration.

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