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THE UTILISATION OF ALCOHOL IN LIGHT DUTY DIESEL ENGINES

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SUMMARY

This report reviews the various approaches which can be employed to facilitate the utilisation of alcohols - methanol and ethanol - in light duty diesel engines. The characteristic problems and the relative advantages of each approach are discussed. It is concluded that successful application to an engine of any of the available systems would require considerable development efforts. The choice of which system to employ is likely to be most heavily influenced by the proportion of alcohol substitution which is required and the resulting engine first cost penalty which is deemed to be acceptable.

Alcohol utilisation by more or less conventional spark ignited engines appears to be far less problematical than conversion of diesel engines.

1. INTRODUCTION

With the rapidly rising cost of conventional, petroleum based road fuels and increasing uncertainty with regard to their future supply, considerable interest is currently being taken in alternative fuels. Alcohols, particularly methanol and ethanol, have some characteristics which are desirable in future alternative road fuels - they can be produced from a variety of raw materials (some of which are renewable), suitable production technology already exists, they can be easily transported and their storage and handling poses relatively few health and safety problems. Unfortunately alcohols also have some disadvantages when compared with both conventional gasoline and diesel fuel, many of the problem areas are associated with those properties of alcohols which adversely affect their combustion characteristics and hence affect aspects of the performance of any engines in which they are utilised.

The purpose of this report is to examine the suitability of alcohols, particularly methanol, for use as fuels in diesel engines employed in light duty vehicles. Various methods by which alcohols can be used in diesel engines have been investigated and are described in the literature, most of the reported work has been associated with relatively large cylinder displacement, direct injection (DI), engines intended for heavy duty applications; nevertheless consideration of the published data permits an appreciation to be gained of the likely performance of light duty diesel engines when operating on alcohol fuel.

2. PROPERTIES OF ALCOHOLS

The chemical and physical properties which influence their suitability as fuels for diesel engines have been thoroughly examined and are well documented, see Table 1 (mainly from references 1 and 2).

The energy content and the relative densities of alchols are considerably lower than the corresponding figures for conventional diesel fuels. Hence a greater volume of alcohols (in the ratio 2.5:1 for methanol and 1.8:1 for ethanol) is necessary to provide the same amount of energy as unit volume of diesel fuel. This implies that engine fuel consumption will be considerably higher than using alcohol fuels and that changes in fuel metering systems will be necessary.

Stoichiometric air/fuel ratios are considerably different for diesel fuel, methanol and ethanol (approximately 14.8, 6.4 and 9.0:1 respectively). This fact, combined with the differences in the specific energy content of the fuels, implies that for equal equivalence ratios all the fuel/air mixtures will have an approximately equal energy content. Hence an engine operating at a particular condition on any of the fuels should deliver the same power output.

The self ignition characteristics of fuels greatly influence their suitability for use in diesel engines. Diesel fuels for road vehicles normally have cetane numbers in the range 45-60; direct determination of the cetane number of alcohols using conventional methods is not possible but the testing of fuel blends and subsequent extrapolation of the results suggests that the cetane numbers of methanol and ethanol are around 3 and 8 respectively (1). With such low ratings auto-ignition of pure alcohols in a diesel engine is very difficult.

One reason for the low cetane numbers of alcohols is their high latent heat of vaporisation, 3-5 x greater than that of typical diesel fuel. Evaporation of a stoichiometric mixture of diesel fuel and air will cause a drop in mixture temperature of about 17°C: corresponding figures for methanol and ethanol are respectively about 200°C and 110°C. This large difference between alcohols and diesel fuel obviously poses problems in diesel engines since proper engine operation relies on the rapid auto-ignition of the fuel following its injection into the air in the cylinder.

Unlike conventional diesel fuel alcohols have very poor lubricity and hence there is a risk of high wear rates occurring in certain components of an engine's fuel system, particularly the high pressure fuel injection pump, which normally rely on the fuel for lubrication. This problem can usually be overcome, either by component design changes or by the use of suitable fuel additives (3, 4, 5).

Alcohols cause degradation of many of the materials commonly used in vehicle fuel systems (6-15). Many metals are subject to corrosive attack and elastomers and similar materials may swell and/or soften. Methanol appears to be more of a problem in this respect than does ethanol. Corrosive attack by alcohols is accelerated in many instances when water is present.

In high pressure fuel injection systems such as those used in diesel engines the properties of the fuel, e.g. density and bulk modulus, which affect its characteristics as a hydraulic fluid can have a profound effect on the overall performance of the system. The density and bulk modulus of both methanol and ethanol are considerably different to those of conventional diesel fuel hence problems such as cavitation in fuel lines and injection nozzles often occur when using alcohols (4). These problems can usually be overcome by changes to the hydraulic characteristics of the fuel injection system.

Blends of conventional petroleum based fuels and alcohols tend to be very unstable in the presence of very small quantities of water (16) readily separating into their constituent parts. Various techniques may be employed in order to maintain a more stable blend e.g. mechanical emulsifiers (17), chemical additives (18, 19) or ensuring the complete absence of water from the blend (20).

3. METHODS OF UTILISATION

3.1 Direct Injection

As noted above both methanol and ethanol have very low cetane numbers and hence their use in a diesel engine without some additional aid is not generally possible. For successful operation of a diesel engine with direct injection of a single, basically alcohol, fuel it is necessary to significantly increase the cetane number of the fuel, this may be accomplished by using either (a) a special cetane improving additive or (b) by blending the alcohol with a sufficient quantity of conventional diesel fuel (notwithstanding the problems associated with preventing separation or such blends). Other techniques which are not discussed here include use of blends of alcohol and vegetable oils or three component blends of alcohol/vegetable oil/diesel fuel (19, 21), and use of increased engine compression ratio (which raises the temperature of the air in the cylinder prior to injection of the fuel).

a) Alcohol + Cetane Improving Additive

For many years it has been known that various chemicals have the ability to increase the cetane number of fuels to which they are added (22). Most such additives function primarily by reducing the time required for the chemical reactions which must occur during the delay period between the start of fuel injection and the establishment of combustion; some additives also have a beneficial effect on the physical processes - fuel atomisation and local mixture preparation - which must occur during the delay period (23). In either case the effect of the additive is to shorten the ignition delay period, hence improving the cetane number of the fuel. Unfortunately it is usually necessary to use quite a high proportion of additives in order to increase the cetane number of alcohol fuels to a reasonable level, Fig. 1 shows some relevant results (3, 24). It is worth noting that as the load on an engine is reduced a greater proportion of ignition improving additive is required (Fig. 1(b)). Such additives are relatively expensive and the logistics of the supply of a fuel comprising alcohol + cetane improving additive require careful consideration; various strategies are possible, including:-

i] Provision of a single pump unit at retail outlets dispensing 'neat' alcohol. Such a fuel could be used directly in spark ignited engines but would require the addition of cetane improver before it could be utilised in diesel units.

ii] Distribution and retail supply of two alcohol fuels, one being 'neat' alcohol for use in spark ignited engines. The other being alcohol + cetane improver for diesel use.

Strategy [i] is attractive from the point of view of the fuel production and distribution industry but requires the addition of a supplementary cetane improver tank and metering/mixing systems on diesel powered vehicles. Strategy [ii] is fine for vehicle manufacturers and users but poses problems for the fuel supply industry.

It is usually possible to offset to some extent the effects of low cetane number by adjusting fuel injection timing. Retarding the timing may ensure that the fuel is injected when the temperature of the air in the engine cylinder is close to its maximum value so that fuel evaporation and ignition occurs more rapidly; advancing the timing so that injection of fuel commences relatively early provides a longer time during which the necessary processes which take place during the ignition delay period, e.g. fuel evaporation and mixture preparation, may occur before high compression temperatures are reached and ignition occurs. Both approaches have some undesirable side-effects: specific fuel consumption tends to increase when either advanced or retarded timings are employed; when using conventional diesel fuel exhaust smoke is increased with retarded timings (with alcohol fuel smoke is usually at a low level so any such effect may be minimal); advanced timings generally incur a penalty in terms of engine noise, since combustion tends to be very rapid under such conditions giving high rates of rise of cylinder pressure and high levels of engine structural excitation. The most effective injection timings for a particular engine/fuel combination are therefore best ascertained by practical tests.

Results of engine tests during which ethanol + cetane improving additives were used have been reported in several publications (2, 3, 4, 5, 23, 24, 25, 26). The majority of the reported work was performed on fairly large, direct injection (DI), truck engines rather than on the smaller indirect injection (IDI) units commonly used in light duty vehicles. Figs. 2(a) and (b) (3) show results of tests made on a turbocharged DI engine of 11 litres during which ethanol containing various amounts of hexyl nitrate was employed. For these tests the full load power output of the engine was reduced from that normally obtained when operating on diesel fuel and the injection timing was advanced by 4°. At high load conditions at both of the operating speeds shown engine performance was very similar when operating on either diesel fuel or ethanol fuel. At low loads performance was poor on ethanol with a low concentration of ignition improver; examination of the curves of rate of increase of cylinder pressure and HC emissions suggests poor combustion under these conditions.

In the case of most diesel engines operating on conventional petroleum based fuels the majority of the NOx emissions are NO, it is apparent from the curves of NOx-NO in Fig. 2 that this is not the case when using ethanol with a cetane improver, presumably due to the presence of the latter material which is a compound containing nitrogen whose combustion reactions are not fully understood. Nevertheless overall NOx levels with the alcohol fuels are broadly similar to those occurring with diesel fuel (in fact over the 13 mode, heavy duty emissions test procedure NOx emissions from this engine were lower on alcohol fuel). Fig. 2 also shows that HC and CO emissions were generally lower when using alcohol with a fairly high proportion of cetane improver. With alcohol fuels exhaust smoke and particulate emissions are generally very low.

Fuel consumption is much greater with alcohol fuels than with conventional diesel fuel due to the former's much lower specific energy content. On a basis of energy consumption more or less equal figures appear to be returned in both heavy duty DI (3) and light duty IDI (26) engines.

b) Blends of Alcohol & Diesel Fuel

One of the main problems involved in the use of alcohol/diesel fuel blends is their tendency to separate particularly in the presence of water. Fig. 3 (20) indicates the poor stability of an ethanol/diesel fuel blend with different percentages of water present and at varying temperature: methanol/diesel fuel blends appear to be even less stable that this.

Various steps can be taken to minimise blend separation problems. The most obvious approaches are to ensure that the blended fuel is maintained at a fairly high temperature and that water is totally excluded. Both of these approaches are difficult to maintain in normal service; complete removal of water during alcohol production is difficult and hence costly, commercial grade alcohol (either methanol or ethanol) generally contains at least 3% water.

Another possible approach is to produce an emulsion of diesel fuel and alcohol which is stabilised by the addition of a surfactant (18); unfortunately a considerable quanity of the surfactant appears to be necessary to ensure complete blend stability and so permit long term blend storage.

Use of alcohol/diesel fuel emulsions formed at or close to the fuel injection pump on an engine can produce satisfactory results since there is then insufficient time for the emulsion to separate before injection and combustion. This approach has been employed by various investigators (24, 27), an obvious drawback is the need for two fuel tanks and appropriate metering systems. It is claimed that some improvement in emulsion stability, without the use of surfactant, can be achieved by employing a mechanical device to thoroughly mix the emulsion's constituents (17).

Due to the low cetane number of alcohols their addition to diesel fuel produces a blend with a relatively low cetane number, Table 2 (18). Hence the performance of any engine in which such a fuel is used tends to be degraded, and if acceptable performance is to be achieved the proportion of alcohol in the blend must be limited.

Fig. 4 (27) indicates how use of alcohol/diesel fuel blends results in a reduction of engine performance relative to that achieved with neat diesel fuel (when using equal quantities of injected fuel). This is due partly to the lower specific energy content of the blend (which can be at least partly offset by increasing the quantity of injected fuel) and partly due to the lower cetane number of the blend producing poorer combustion conditions within the engine.

Fig. 5 (20) shows comparative efficiency and HC and NOx emissions data for three types of diesel engines operating on various blends of ethanol and diesel fuel. Thermal efficiency at light load falls with increasing ethanol content, HC emissions increase significantly under similar circumstances, NOx emissions with ethanol blends are generally equal to or lower than those produced with straight diesel fuel, while exhaust smoke is significantly reduced. There appears to be no published data available regarding particulate emissions but it would appear likely that use of alcohol/diesel fuel blends would be beneficial in this respect.

3.2 Alcohol Aspiration/Diesel Fuel Injection

The use of aspirated alcohol as a means of partially replacing some of the conventional diesel fuel normally used by an engine has some advantages over alternative methods of alcohol utilisation. The principal benefit is the fact that a relatively simple and hence cheap 'bolt-on' conversion kit can be used with the conventional fuel injection equipment retained to provide reduced quantities of diesel fuel for pilot ignition of the alcohol. The main drawback is that only limited alcohol substitution is normally possible.

Numerous investigations have been made into the use of aspirated alcohol in diesel engines (10, 28, 29, 30, 31, 32). Both methanol and ethanol have been employed and addition of the alcohol to the in-going air stream using both carburettors and low pressure injection into the intake manifold has been evaluated; simple carburation can involve some problems due to 'icing' caused by the high latent heat of vapourisation of alcohols. In all reported work it has been observed that the ignition delay period increases as the quantity of alcohol added is increased. This is attributed to the low cetane number of alcohol and its high latent heat of vapourisation, which depresses the temperature of the in-going charge. These factors tend to promote quenching of combustion, particularly at light loads and high speeds, resulting in engine misfire. At high loads the maximum quantity of alcohol which can be employed is generally limited by the onset of 'knock' - very rapid, uncontrolled, combustion - which can damage the engine.

Several methods including advancing the injection timing, increasing the compression ratio, heating the in-going charge and using cetane number improvers in the diesel fuel or the alcohol have been employed in attempts to overcome the problem of quenching while using a high proportion of alcohol fuel. Some of the approaches have proved beneficial in this respect but have had an adverse effect on knock at high loads. Fig. 6 (10) shows some typical results of tests on a single cylinder DI engine where attempts were made to maximise the substitution of diesel fuel by carburetted alcohol by employing inlet charge heating and an ignition improver (amyl nitrate) added to the diesel fuel. It can be seen that the level of substitution relative to the measures taken is very different between high and low speed. 80 per cent is only reached at 36.7 rev/s by inlet mixture heating to 30°C and use of 2 per cent amyl nitrate whereas, at 16.7 rev/s, 75 per cent substitution was achieved without heating whilst at 80 per cent the engine was knock limited to a lower load. Consequently to achieve maximum levels of substitution over the speed range, both mixture heating and ignition promoting additives would have to be modulated. The latter is clearly not practicable.

At part load the substitution is less if the pilot charge of diesel fuel is held constant. The pilot charge could be modulated with the methanol with some extra complication.

Other investigators (28, 29, 30, 31) generally report similar results to those observed above with substitutions of 25-60% being achieved at different engine operating conditions. To achieve a high overall alcohol substitution rate, e.g. greater than 50%, in an engine operating over a wide duty cycle would require considerably complexity with respect to modulation of alcohol flow rate, diesel fuel pilot injection quantity, injection timing, inlet charge heating and probably the use of a cetane number improving additive. It is also worth noting that much of the relevant research work carried out to date has been conducted on single cylinder engines; in multi-cylinder engines an additional problem would be involved in ensuring even distribution of the aspirated alcohol fuel to each cylinder, this could be largely overcome by using fuel injectors in each inlet port but such a solution would incur a significant cost penalty.

Little comprehensive data have been published on the effects of aspirated alcohol on diesel engine exhaust emissions. Some results of tests on a single cylinder DI engine operating at 1200 rev/min (31) are shown in Fig. 7. Both HC and CO emissions show large increases at low loads with aspirated alcohol. NOx emissions are reported to be decreased (32). Exhaust smoke is generally reduced by using aspirated alcohol, this means that, disregarding any other constraints, e.g. increased cylinder pressures, it is usually possible to achieve a greater power output from an engine at a given smoke limit or, conversely, to operate at the same power output with reduced exhaust smoke. This would suggest that lower particulate emissions would be produced by a diesel engine using aspirated alcohol.

3.3 Dual Injection Systems

The dual injection system approach to employing alcohol fuels in diesel engines has been under investigation for several years. Two separate fuel injection systems each with their own pump and injector in each cylinder are required. A small quantity of diesel fuel is first injected to establish combustion in the cylinder, this is then followed by the addition of the main, alcohol, fuel charge which is ignited by the burning diesel fuel. The most obvious drawback of this approach is the complexity and hence cost involved in providing two high pressure fuel injection systems. The main advantage of such arrangements lies in their ability to efficiently utilise high proportions of alcohol - in excess of 90% at full load and, probably, over 50% in average vehicle usage.

Several experimental investigations in which this approach has been applied to DI and IDI engines have been reported (5, 20, 24, 37, 38, 39, 40) and some heavy duty vehicles employing DI engines with dual injection systems have undergone road trials with some success. Such systems generally employ injection of a fixed quantity of diesel fuel (generally in the region of 5-10% of the normal full load fuelling) which is sufficient to operate the engine under idling (no-load) conditions, the alcohol quantity is modulated to meet variable load requirements.

Comprehensive results of tests made on prechamber and swirl chamber IDI engines together with a DI unit using dual diesel fuel and ethanol injection systems have been published (20). Fig. 8 indicates the combustion chamber configurations employed. Fig. 9(a), (b) and (c) show the performance and emission results achieved with the different engines at 1500 rev/min. Exhaust smoke was considerably reduced on all engines when using dual fuelling suggesting that, other constraints permitting, a greater power output could be achieved. Thermal efficiency was fairly similar when using either diesel fuel alone or diesel fuel + ethanol. For the swirl chamber IDI and the DI engines NOx emissions were reduced throughout the load range, HC and, to some extent, CO emissions were generally increased when using diesel fuel + ethanol. Similar effects have been observed during other work with DI engines in which diesel fuel + methanol dual injection was used and where other fuels, for instance ethanol plus an ignition improver or vegetable oil, have been used for pilot injection (38).

Despite the good performance results achieved with diesel fuel + alcohol dual injection systems there are obvious practical difficulties involved in accommodating two injectors per cylinder on small engines especially where the cylinder bore is of small diameter. It appears that other approaches could be worth investigating. These might include using twin high pressure fuel injection pumps, one for diesel fuel, the other for alcohol, timed so that diesel fuel is injected first followed by the main charge of alcohol both injecting through the same nozzle assembly incorporating separate fuel circuits and separate arrangements of holes spraying the fuel into the chamber. The practical problems involved in producing such nozzle assemblies appear rather daunting.

A less obvious problem associated with the dual injection system approach is the fact that fuel injector nozzles rely to a large extent on the fuel passing through them for cooling of the nozzle tip. The pilot (diesel fuel) injector delivers only a small quantity of fuel even at full load and problems of carbon build-up and hole blocking due to overheating do occur (37).

3.4 Alcohol Injection with Surface Ignition

It has been known for many years that methanol and ethanol have relatively low resistance to pre-ignition (33). Recently some attempts have been made to capitalise on this phenomenon with regard to the promotion of alcohol combustion in diesel engines. Tests have been conducted on modified DI (34, 35) and IDI engines (36) during which 100% alcohol (without the addition of any cetane number improving additives) has been injected into the combustion chambers of engines into which a hot surface has been incorporated. The hot surface ignites the alcohol after which combustion continues in the turbulent air/fuel mixture. Fig. 10 shows versions of DI and IDI engines employing surface ignition, another version of a DI engine (35) used a conventional glow plug extending into the combustion chamber as the hot surface.

Fig. 11 shows some performance data for the engine shown in Fig. 10(a) (36). Ignition delay periods are rather long compared with what might be expected from a conventional diesel engine but peak cylinder pressure and particularly the rate of pressure rise are relatively low. Brake thermal efficiency is also low but this may be due to other factors, e.g. the level of friction of the particular engine used; other work (35) reports indicated thermal efficiencies of the order of 50%. Little data has yet been published on the exhaust emission characteristics of surface ignition alcohol engines; it is suggested that aldehyde emissions are considerably lower than those produced by spark ignited, alcohol fuelled, engines (36).

There is obviously considerable work still needed before a full appreciation of the potential of surface ignition engines can be obtained. Areas which may be anticipated to present problems include durability aspects particularly of the fuel injection equipment and the surface heater.

3.5 Alcohol Injection + Spark Ignition

Considerable work on the application of this concept to fairly large heavy duty DI engines has been reported (41, 42) and prototype vehicles using such engines have been produced. Fig. 12 illustrates the combustion chamber configuration used in MAN-FM engines; obvious practical problems occur when attempts are made to incorporate such an arrangement in engines of small cylinder bore size since for best performance the relative positions of the spark plug and fuel injector are critical. During normal operation most of the injected fuel is sprayed onto the wall of the combustion chamber from where it evaporates to be mixed with the rapidly swirling air in the cylinder and taken past the spark plug where ignition occurs. The MAN-FM engines have a multi-fuel capability and successful operation on gasoline and diesel fuel as well as alcohols has been reported. In general when operating on alcohol fuel power output is similar to that of a conventional diesel engine of equal displacement, thermal efficiency tends to be higher at high loads but rather lower at light load than that achieved by a diesel engine; exhaust smoke is usually negligible. HC emissions are higher than from a diesel engine but NOx is considerably lower.

Limited work has been reported on the application of spark ignition to an IDI diesel engine to permit operation on alcohol (43). The engine chosen for conversion was completely unrepresentative of modern light duty engines but the trends displayed in the test results may provide an indication of what could be expected following conversion of a more typical modern engine. Fig. 13 shows that indicated thermal efficiency was broadly similar whether the engine was operating in the spark ignited mode on methanol or ethanol or in compression ignition mode on conventional diesel fuel. CO and, more especially, HC (unburned fuel) emissions were considerably higher during operation on alcohol but NOx emissions were considerably reduced. No particulate emissions were observed when operating on alcohol.

Other work has been reported during which spark ignition has been applied to an IDI diesel engine with a more conventional combustion chamber layout. In this work successful operation on gasoline was achieved but alcohol use was not attempted (44).

3.6 Conventional Spark Ignition

Much work has been carried out on the use of alcohols and alcohol/gasoline blends in more or less conventional spark ignited engines (16, 26, 45-53). Generally this approach represents the easiest path to utilisation of alcohols as engine fuels. The high octane numbers of methanol and ethanol permit the use of quite high engine compression ratios (circa 12:1) and so enable good thermal efficiencies to be achieved.

Problems involved in alcohol utilisation include fuels/materials compatibility, separation tendency of gasoline/alcohol blends, the poor cold starting characteristics of 100% alcohol (54) and the need to recalibrate fuel metering systems. All of these problems can be fairly readily overcome.

Considerable test data relating to spark ignited engine operation on alcohol fuels has been reported. Fig. 14 (53) shows results obtained from a CFR (single cylinder) engine at 9:1 compression ratio operating at 1200 rev/min on Indolene, methanol and methanol plus 5% water (M5W), two conditions of intake manifold heat addition were applied - in the first a constant inlet mixture temperature (Tm) of 82°C was maintained while in the second a constant quantity of heat (that necessary to maintain the air/Indolene mixture at 82°C) was supplied, in this case the air/methanol mixture temperature was reduced due to the high latent heat of vapourisation of the fuel.

Methanol and M5W fuels exhibited efficiency increases of 2-3% for the range of test conditions. At equal intake mixture temperatures, methanol and M5W produced 5-6% less power output than Indolene. For constant manifold heat conditions (substantially lower mixture temperatures), methanol and M5W produced 5-7% more power than Indolene. Peak NOx emissions were reduced 30-40% with methanol and 45-60% with M5W over the Indolene reference fuel. Mass specific CO emissions were essentially unaffected by fuel type. Mass specific emissions of unburned fuel (UBF) were comparable for Indolene and methanol at all test conditions. Indolene, methanol and M5W exhibited comparable UBF emissions for constant mixture temperature. For the cooler mixture temperatures at constant manifold heat conditions, the M5W fuel demonstrated substantially increased UBF emissions.

It is likely that a substantially higher compression ratio could have been used when operating on methanol resulting in even better thermal efficiency, slightly higher power output and perhaps slightly increased HC and NOx emissions. Production engines for operation on ethanol can employ compression ratios of 10.5:1 or greater (26).

Table 3 shows results of tests on light passenger cars powered by diesel and optimised, ethanol burning, spark ignited engines (26). In each case the vehicle transmission ratios were adjusted to produce approximately equal performance. It can be seen that the ethanol fuelled spark ignited engine returned a fuel economy superior to that of the diesel engine when fuelled with alcohol + ignition improver additive. The first cost of the spark ignited engine would be significantly less than that of the diesel unit.

4. DISCUSSION

Currently all diesel engines used in passenger cars employ IDI combustion systems. Some prototype DI engines already exist and many manufacturers are engaged in development work aimed at bringing such engines to production status. At present small DI engines are at a disadvantage when compared to IDI units in terms of lower specific power output, higher exhaust emissions - especially HC, NOx and particulates, and greater engine noise; but they do offer a gain in fuel economy of around 10% (55, 56). Most reported work in the field of alcohol utilisation by diesel engines have been with large, heavy duty DI engines. It is therefore difficult to make an accurate assessment of the merits of alcohol utilisation in light duty diesel engines. Heavy duty engines generally operate over a restricted speed range when compared with light duty units, have larger diameter cylinders - rendering easier the introduction of additional fuel injectors, spark plugs, etc. and have a much higher first cost so that the incremental costs of the additional components necessary for alcohol utilisation take on less significance.

From the foregoing review of published test work it is apparent that there are several ways in which alcohol may be utilised in a diesel engine. All the possible approaches have disadvantages compared with the operation of an engine on conventional, good quality, diesel fuel; a benefit common to all the evaluated systems is that they permit substitution of at least some of the conventional fuel normally used by an engine.

With regard to the proportion of alcohol fuel which may be used in diesel engines employing various combustion systems only two approaches - fuel injection with either surface or spark ignition - permit the use of 100% alcohol. With compression ignition (as in a conventional diesel engine) the low cetane numbers of alcohols require that a significant proportion, at least 10%, of a vigorous (and expensive) ignition promoting additive is necessary or that a considerable proportion, at least 50%, of good quality diesel fuel be blended with the alcohol. When using alcohol aspiration with injection of diesel fuel an average alcohol utilisation of around 50% may be achieved with some complexity with regard to fuel quantity modulation, use of inlet charge heating and perhaps the use of an ignition promoting additive. Dual injection systems offer the possibility of using around 50-60% alcohol over typical light duty vehicle cycles but with the disadvantages of significant complexity and hence high cost.

In general all of the alcohol utilisation systems appear capable of producing specific power outputs equal to, or in some cases greater than, those achieved by comparable conventional diesel engines. In those cases where higher powers are possible this is largely due to the fact that exhaust smoke tends to be reduced when using alcohol and hence higher fuelling rates may be employed before the smoke limit is reached.

Thermal efficiency of diesel engines fuelled with alcohols is generally similar to that achieved on conventional diesel fuels. On a volumetric or gravimetric basis a greater quantity of alcohol is consumed due to the disparity in the calorific values of the fuels.

Little emissions performance data regarding alcohol fuelled diesel engines has been found in the literature. Hydrocarbon or unburnt fuel emissions produced by all diesel engines when using alcohol appear to be substantially higher, particularly at low loads, than when operating on conventional diesel fuel. It should be noted that HC analysers have a variable response depending on the type of hydrocarbon being measured, hence direct comparison of emissions produced when operating on such radically different fuels as alcohols and diesel fuel may be misleading. It would appear that all the alcohol utilisation systems for which some emission results are available produce 2-3 times greater HC emissions at part load than comparable, conventional, diesel engines, at high loads the increase in HC emissions is generally of the order of 1.5 times. CO emissions levels exhibit similar trends to those observed in respect of HC with increases of the order of 50% at low load operating conditions.

Published NOx emissions levels with alcohol utilisation are generally similar to or lower than those occurring with diesel fuel. Dual diesel/alcohol injection systems appear from the limited data available, Fig. 9(b), to produce significant reductions (around 50%) of NOx emissions in swirl chamber IDI engines, the type of combustion system most commonly used in light duty applications. Use of cetane improvers containing nitrogen compounds may increase NOx emissions; little published data are available on this subject.

Alcohols do not appear to form soot during combustion and they do not contain organic materials or sulphur so that, apart from any condensed droplets of unburnt fuel, particulate emissions arising from the combustion of pure alcohol should be non-existent. It therefore appears likely that in those engine combustion systems where alcohol replaces a proportion of the diesel fuel particulate emissions in terms of total mass and quantity of organic matter should be reduced as the diesel fuel substitution rate increases. The reduction is unlikely to be directly proportional to the quantity of alcohol used since the presence of the alcohol generally impairs combustion of the diesel fuel. In systems where 100% alcohol is utilised, i.e. with surface or spark ignition, particulate emission levels would be expected to be very low and to be largely attributable to combustion of small quantities of lubricating oil. Ignition promoting additives may influence particulate emissions. No reference to measurements of particulate emissions of alcohol fuelled diesel engines has been found in the literature.

Emissions of some materials, especially aldehydes, are likely to be considerably greater when using alcohols as diesel engine fuels. Insufficient data are available to permit quantification of likely levels. Some ignition promoting additives may cause the formation of hazardous hydrogen-carbon-nitrogen compounds - HCN, again no relevant data are available.

All the diesel engine combustion systems capable of operation with alcohol fuel are subject to various practical problems. Alcohols have poor lubricity and hence they may cause accelerated wear of diesel fuel systems and engine components: this may be overcome by adding small quantities of lubricating oil to the fuel or by changing the design of critical engine parts. Chemical attack by alcohols of certain materials may occur; this problem appears to be at its worst when water is also present: changes to the materials normally used in diesel fuel systems can usually provide a remedy. High rates of cylinder bore wear have been observed in alcohol burning engines; again a change in material or perhaps use of a modified lubricating oil could be of benefit. Accommodation of two fuel injection systems or additional spark or surface ignition systems in small displacement engines is difficult and such additional components impose a significant cost penalty.

It is difficult to reach a firm conclusion with regard to which alcohol utilisation system is most suitable for application to light duty diesel engines. Relatively little work has been carried out in applying any of the available systems to light duty engines. The strategy to be employed in alcohol utilisation, e.g; whether engines are to use large or small proportions of alcohol, is of importance as is the level of the first cost penalty which is deemed to be acceptable.

If only a small quantity of diesel fuel, say 10%, is to be substituted by alcohol it would appear that use of a blended alcohol/diesel fuel, perhaps with the addition of a blend stabilising agent, is the best solution. Engine modifications would then be confined largely to re-optimisation of the fuelling schedule with regard to injection timing and quantity and little or no penalty in terms of first cost should result. Some wear/corrosion problems may occur but they should not be insurmountable. Exhaust emission levels should be changed very little.

Use of 100% alcohol in diesel engines is only possible where some supplementary means of ignition, e.g. spark plug or surface igniter, is provided. To date most published work involving spark ignition with alcohol fuels has been carried out on relatively large DI engines (MAN-FM). Good performance on a range of fuels has also been achieved in spark ignited, IDI, swirl chamber engines and although alcohol fuels have not been employed to date it appears likely that they could be efficiently utilised in such engines. HC emissions would be much higher than from a comparable diesel engine, particulates would probably be low. Specific power output and thermal efficiency similar to a diesel engine may be achieved after considerable development. Little work has been carried out on combustion systems using surface ignition. Their characteristics are therefore not fully understood.

Use of direct injection of alcohol + cetane number improver permits total replacement of diesel fuel and involves few changes to the engine. (Depending on the fuel supply strategy adopted some complexity may be involved in providing a vehicle fuel system which meters and mixes ignition improver from one tank with 'neat' alcohol drawn from another). Unfortunately quite a high percentage of (probably) expensive fuel additive is necessary. The impact of such an approach on some (unregulated) exhaust pollutants,especially HCN compounds, would probably be detrimental.

Dual injection systems utilising alcohol plus a small pilot charge of diesel fuel appear to offer some potential, at least in large, heavy duty, engines, for use where around 50-60% alcohol substitution is desired. Application of such an arrangement to a small engine, particularly an IDI unit would be difficult due to the problems involved in effectively locating two fuel injectors and a heater plug (necessary for cold starting) in a relatively small combustion chamber. The necessity for two, independent, fuel systems imposes a significant cost penalty. HC emissions would be markedly higher than those from a conventional diesel engine, particulate emissions would probably be reduced.

Basically conventional, homogeneous charge, spark ignition engines form the easiest route for alcohol utilisation either in blends of gasoline with 10-15% alcohol or with 100% alcohol. Apart from any fuel/materials compatibility problems, which should be fairly readily solved, only relatively small changes in fuel metering systems and some provision for cold starting (when using 100% alcohol) are necessary. For optimum efficiency higher compression ratios should be employed. HC (unburnt fuel) emission levels generally similar to or slightly greater than those of conventional gasoline engines may be anticipated. NOx and CO emissions would be lower. Application of an exhaust oxidising catalyst would probably result in HC emission levels lower than those produced by an alcohol burning diesel engine (with untreated exhaust), while CO and NOx may also be slightly lower, particulate emissions should be virtually non-existent. Specific power output would be considerably higher than from a diesel engine. Vehicle fuel economy (at equal vehicle performance) could well be superior when using an optimised spark ignited alcohol engine than when using alcohol in a diesel power unit.

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5. CONCLUSIONS

5.1 Various methods exist by which alcohol fuels may be utilised in diesel engines. All of the possible systems involve additional complexity and cost and incur additional in-service maintenance requirements. Considerable engine development is likely to be required before satisfactory performance is achieved with any of the available systems.

2. Most of the possible approaches have only been applied to large, heavy duty, engines. Their application to small, light duty, engines is likely to prove difficult.

3. Use of alcohols in diesel engines significantly increases HC emissions but may reduce NOx and particulates compared to operation on diesel fuel. Specific power output and thermal efficiency are likely to be generally similar.

4. The main factors which should influence the choice of alcohol combustion system for a light duty diesel engine appear to be a) the proportion of alcohol to be utilised and b) the acceptable additional engine cost.

5. For the various possible alcohol utilisation strategies different combustion systems appear to be most applicable:-

100% utilisation - alcohol injection + spark or surface ignition

circa 50% utilisation - dual alcohol and diesel fuel injection systems

circa 10% utilisation - single injection of alcohol/diesel fuel blend

Application of any of these approaches to light duty diesel engines will pose problems.

6. Use of single injection of alcohol + cetane number improver is unlikely to prove feasible until an effective, cheap fuel additive is available.

7. Optimised spark ignition engines appear to be by far the least problematical and cheapest means of utilising alcohols and (at equal performance levels) are likely to produce vehicle fuel economy figures at least as good as those provided by alcohol burning diesel engines.

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TABLE 1

PROPERTIES OF ALCOHOLS, DIESEL FUEL & GASOLINE

	METHANOL	ETHANOL	DIESEL FUEL	GASOLINE
Chemical Formula	CH_3OH	C_2H_5OH	Mixtures of Hydrocarbons	
Molecular Weight	32	46	230-250 (typically)	100-110 (typically)
Composition - weight %				
Carbon	37.5	52.2	85-88	85-88
Hydrogen	12.6	13.1	12-15	12-15
Sulphur	-	-	0.2-0.5	<0.1
Relative Density	0.796	0.794	0.81/0.85	0.72/0.76
Distillation Characteristics				
IBP °C	-	-	175/185	28/38
10% volume °C	-	-	225/235	45/55
50% volume °C	-	-	265/275	90/105
90% volume °C	-	-	310/330	150/160
FBP °C	65	78.5	330/350	180/200
Lower Calorific Value MJ.kg	Btu/lb 19.7=8,469.5	Btu/lb 26.8=11,521.9	∿42.5 18,271.7	∿42.5= 18,271.7
Latent Heat of Vaporisation MJ/kg	1.10	0.84	∿.25	∿.35
Stoichiometric Air/Fuel Mixture, by weight	6.4	9.0	14.8	∿14.6
Cetane No.	3	8	45-60	∿10
Research Octane No.	∿110	∿110	-	90-97

TABLE 2

PROPERTIES OF ALCOHOL-IN-DIESEL FUEL BLENDS

Fuel & Composition		Sp.Gr. 15.6°V	Cetane Number	Net Heat of Combustion Mjoule/kg (BTU/lb)
Neat Fuel				
Referee grade II diesel		0.844	47.4	42.38 (18,222)
Micro-emulsions				
10% Ethanol	4% surfactant	0.836	42.4	40.62 (17,465)
20% Ethanol	8% surfactant	0.828	37.8	38.83 (16,695)
30% Ethanol	12% surfactant	0.820	31.8	36.99 (15,906)
10% Methanol	10% surfactant	0.833	41.8	39.47 (16,972)
20% Methanol	20% surfactant	0.823	35.4	36.49 (15,689)
30% Methanol	30% surfactant	0.812	28.5	33.43 (14,373)
Solutions				
10% Ethanol		0.839	40.4	41.27 (17,714)
20% Ethanol		0.833	33.8	39.51 (16,988)
30% Ethanol		0.828	29.3	38.00 (16,335)
40% Ethanol		0.822	24.5	36.45 (15,672)

TABLE 3

COMPARISON OF FUEL ECONOMY OF DIESEL AND SI ENGINES OPERATING ON ALCOHOL

Engine Type	Fuel	Accel. Time (Secs) 0-80 km/h	Urban Fuel Economy (l/100 km)
1.6 litre CI	Diesel	12.9	7.0
1.6 litre CI	Ethanol + Cetane Improver	12.8	12.4
1.5 litre SI	Ethanol	12.3	11.6

FIG. 1(a) - Influence of ignition improver on cetane number. Base fuel is 95% ethanol.

—— hexyl nitrate

---- 2-ethylhexyl nitrate

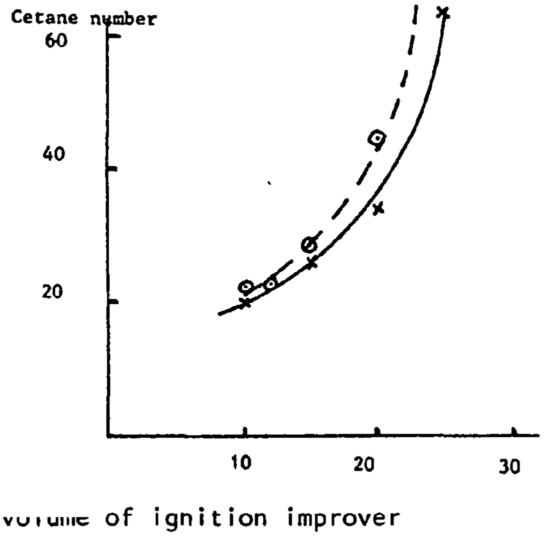


FIG. 1(b) - Percentage needed of Cetanox in methanol and cetane number in order to minimise HC-emissions to 400 ppm. Part load, engine speed 2200 rev/min, ambient air temperature 25°C.

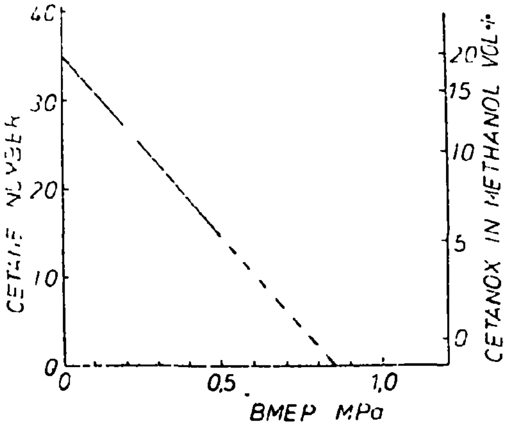
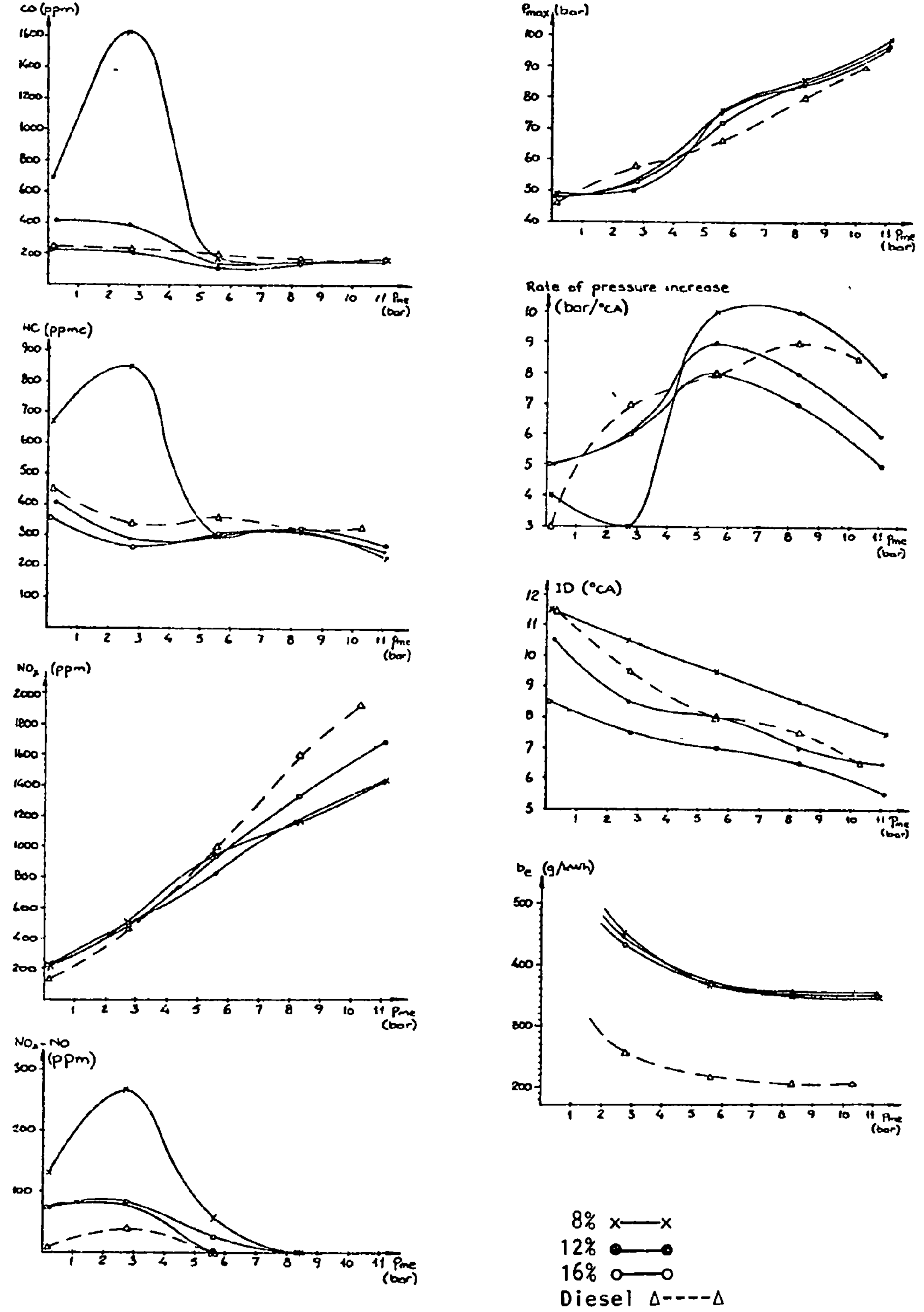


FIG. 2 - Emissions, combustion pressure, rate of pressure increase, ignition delay, and specific fuel consumption versus BMEP for 8, 12 and 16% ignition improver (hexyl nitrate) in alcohol and for diesel fuel oil. (a) Engine speed 1300 rev/min.



(b) - Engine speed 2200 rev/min

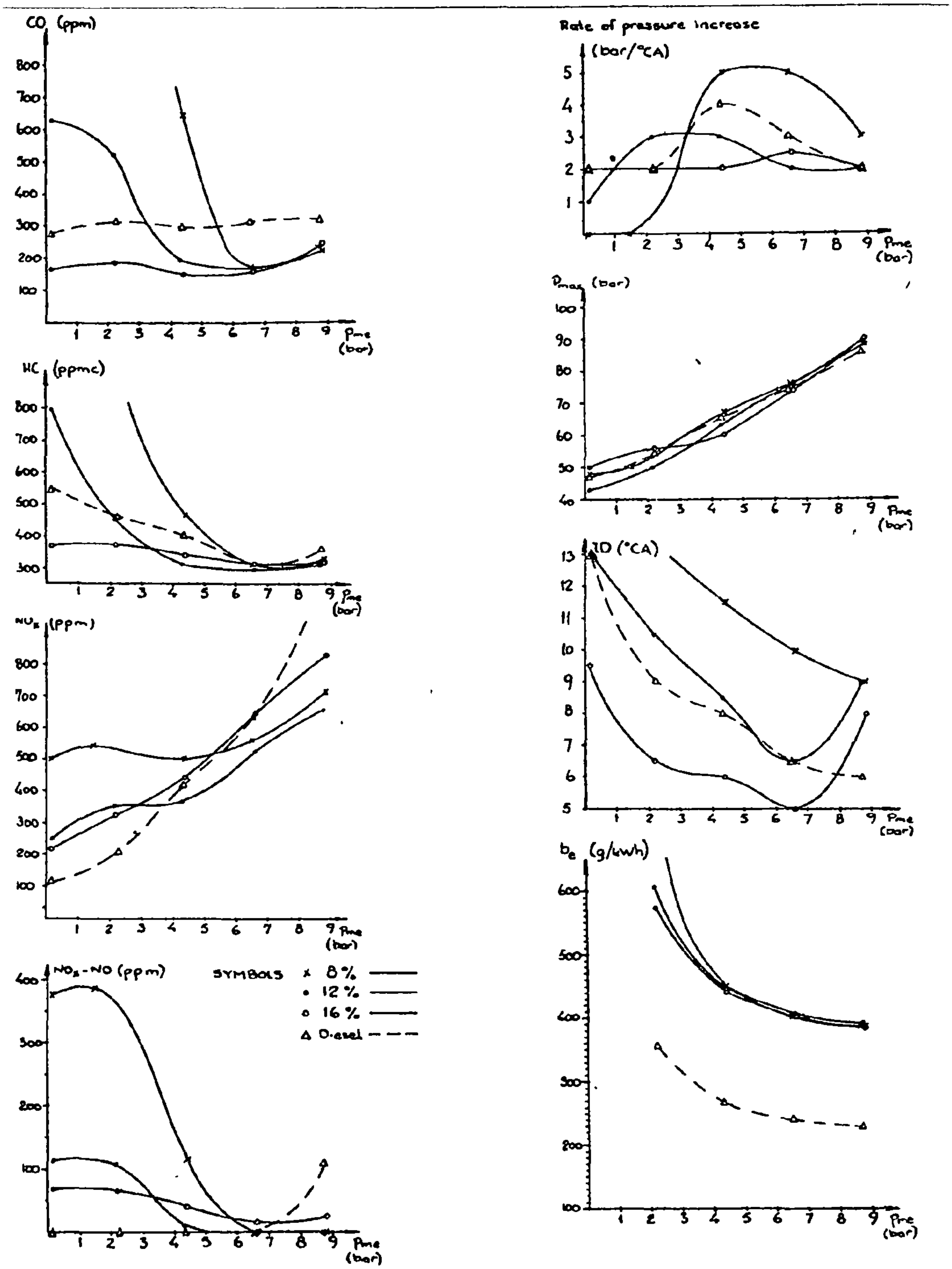


FIG. 3 - Ethanol solubility in diesel fuel

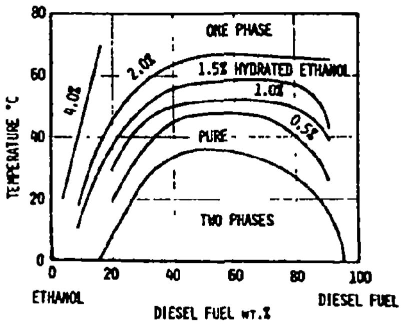


FIG. 4 - Full load brake mean effective pressure for Ford and John Deere engines as influenced by the ethanol content of the fuel

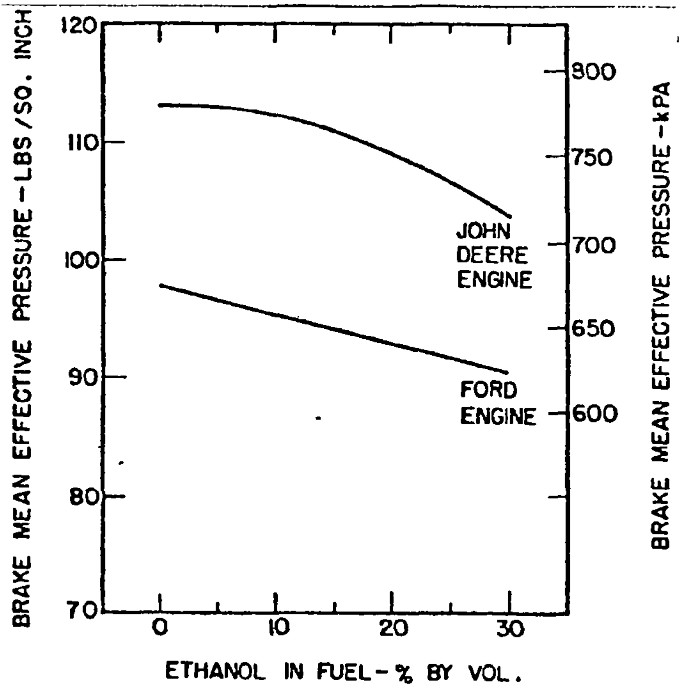


FIG. 5 - Influence of the proportion of Ethanol in diesel fuel on efficiency and exhaust emissions for three different engines (speed 1500 rev/min)

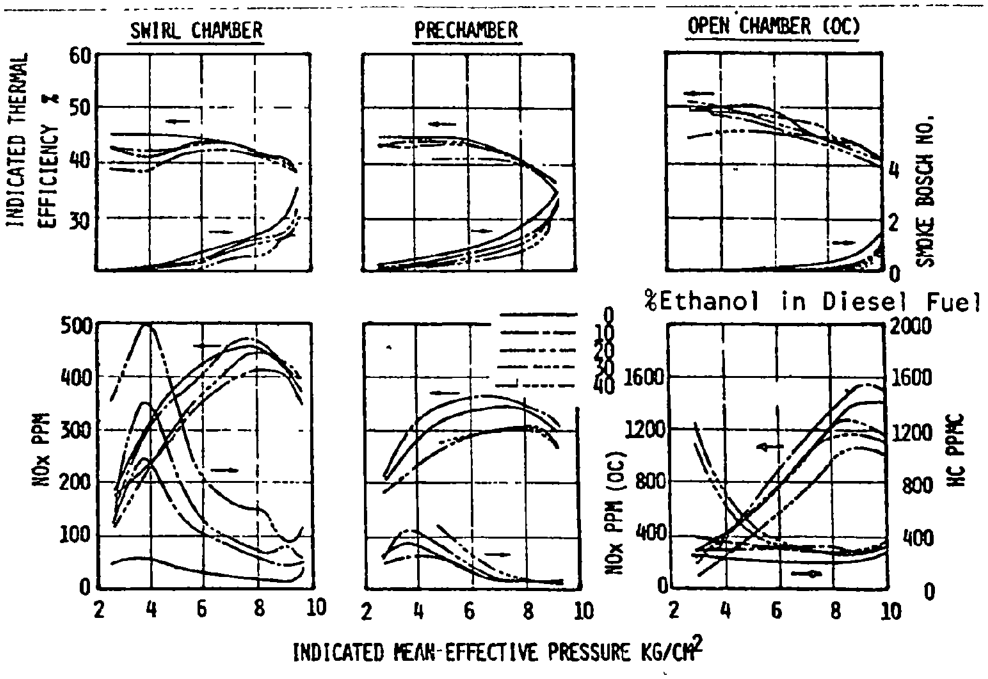


FIG. 6 - Percentage methanol substitution to give normal diesel performance at full load (Bosch 3 smoke)

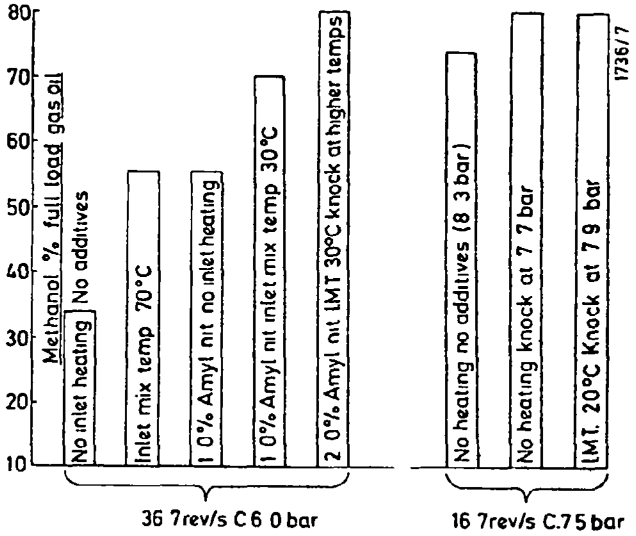


FIG. 7(a) - Effects of carbureted alcohol on unburned hydrocarbon emissions at various torque levels

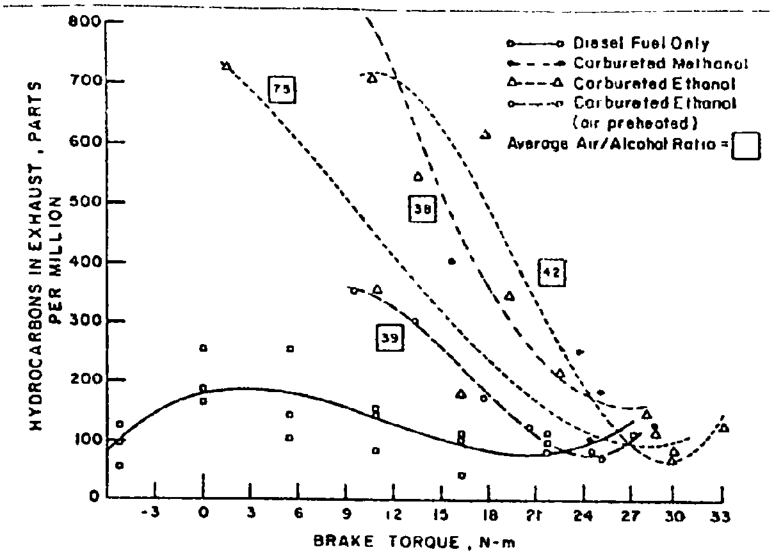


FIG. 7(b) - Effects of carbureted alcohol on carbon monoxide emissions at various torque levels

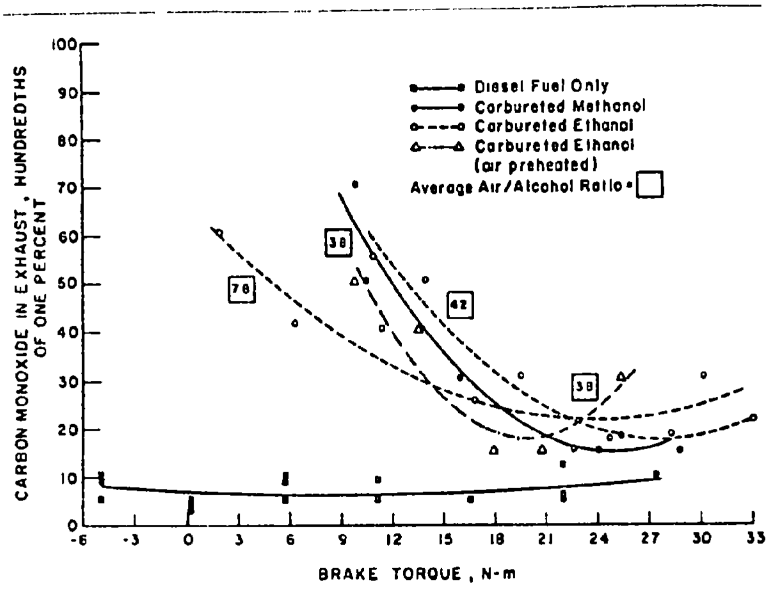
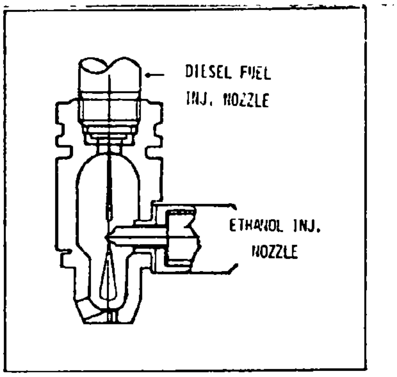
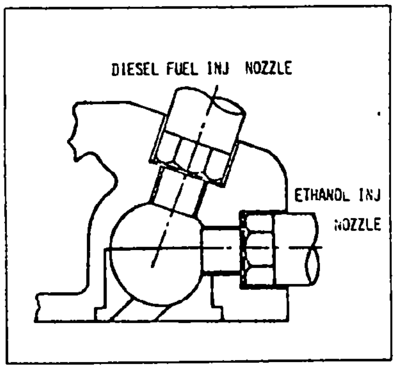


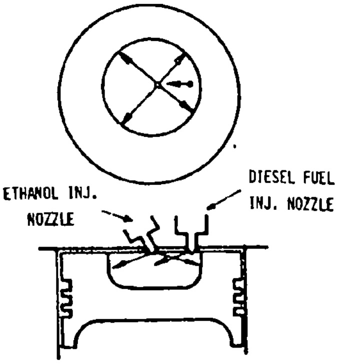
FIG. 8 - Examples of combustion systems employing dual injection



a) Prechamber with Two Injection Nozzles.



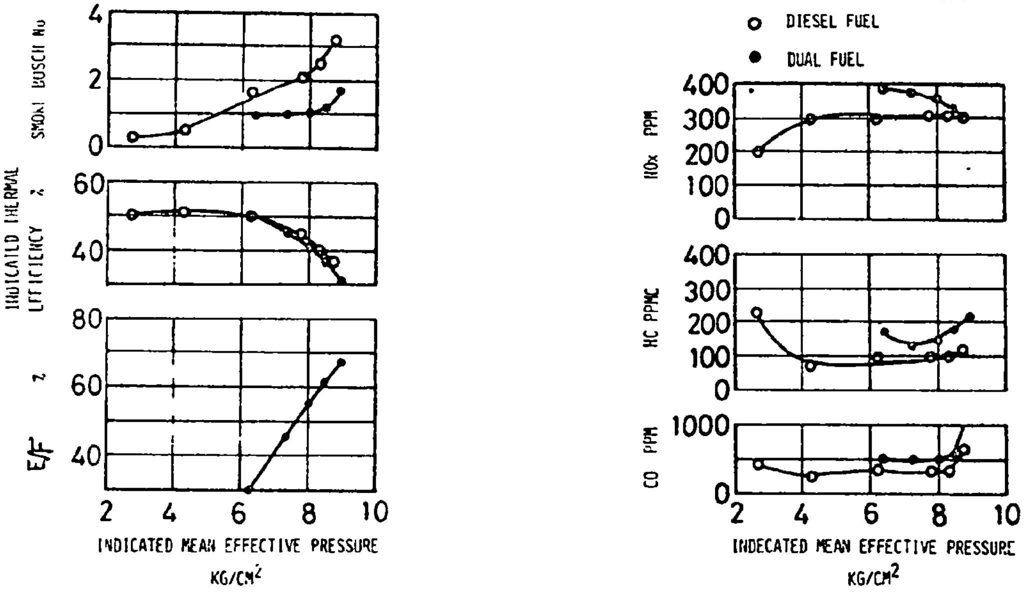
b) Swirl Chamber with Two Injection Nozzles.



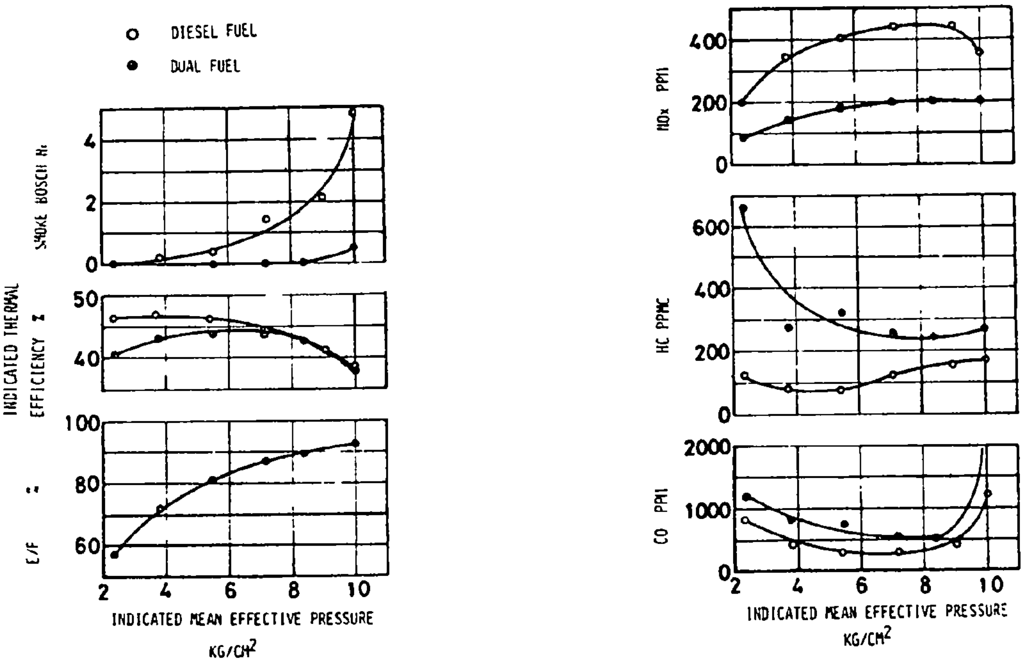
c) Open Chamber with Two Injection Nozzles.

FIG. 9 - Performance & emissions of engines using dual injection (speed 1500 rev/min)

(a) Efficiency, exhaust emissions and ethanol replacement rate (E/F) of dual injection pre-chamber engine and original engine



(b) Efficiency, exhaust emissions and E/F of dual injection swirl chamber engine and original engine



(c) Efficiency, exhaust emissions and E/F of dual injection open chamber engine and original engine

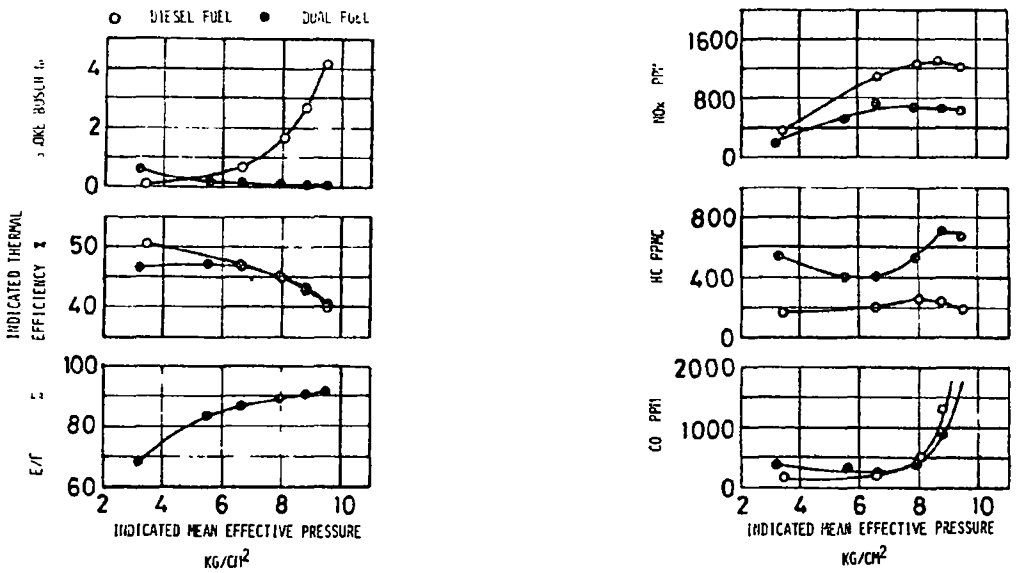


FIG. 10 (a) - Modified DI engine with surface ignition

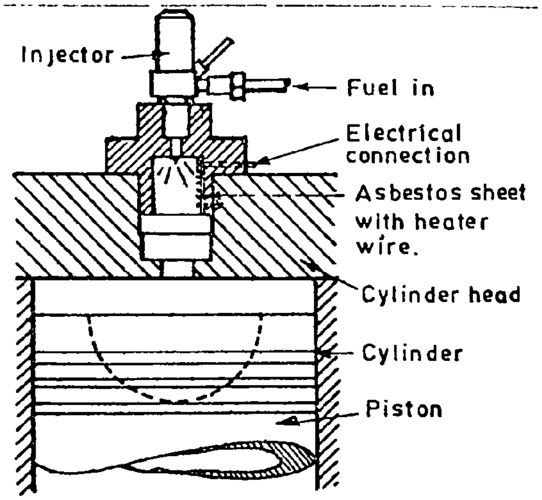
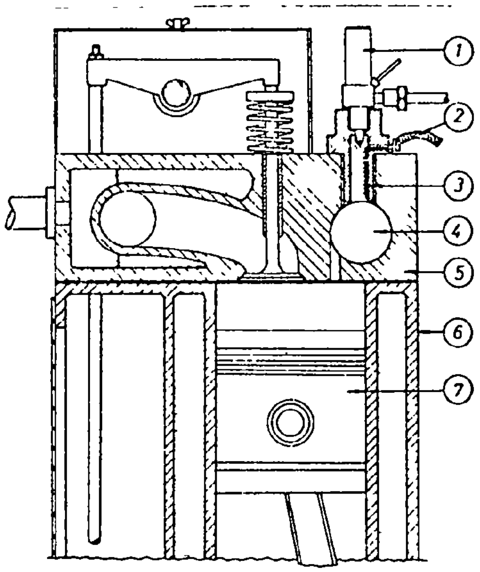


FIG. 10(b) - IDI engine with surface ignition



1-Pintle nozzle spraying alcohol 2-Terminal to low voltage electrical supply (power requirement 6V x 8amps = 48Watts) 3-Asbestos surface wound with heating wires 4-Spherical-shaped swirl combustion chamber 5-Cylinder head 6-Cylinder 7-Piston

FIG. 11 - Performance of surface ignition engine using alcohol fuels (speed 1500 rev/min)

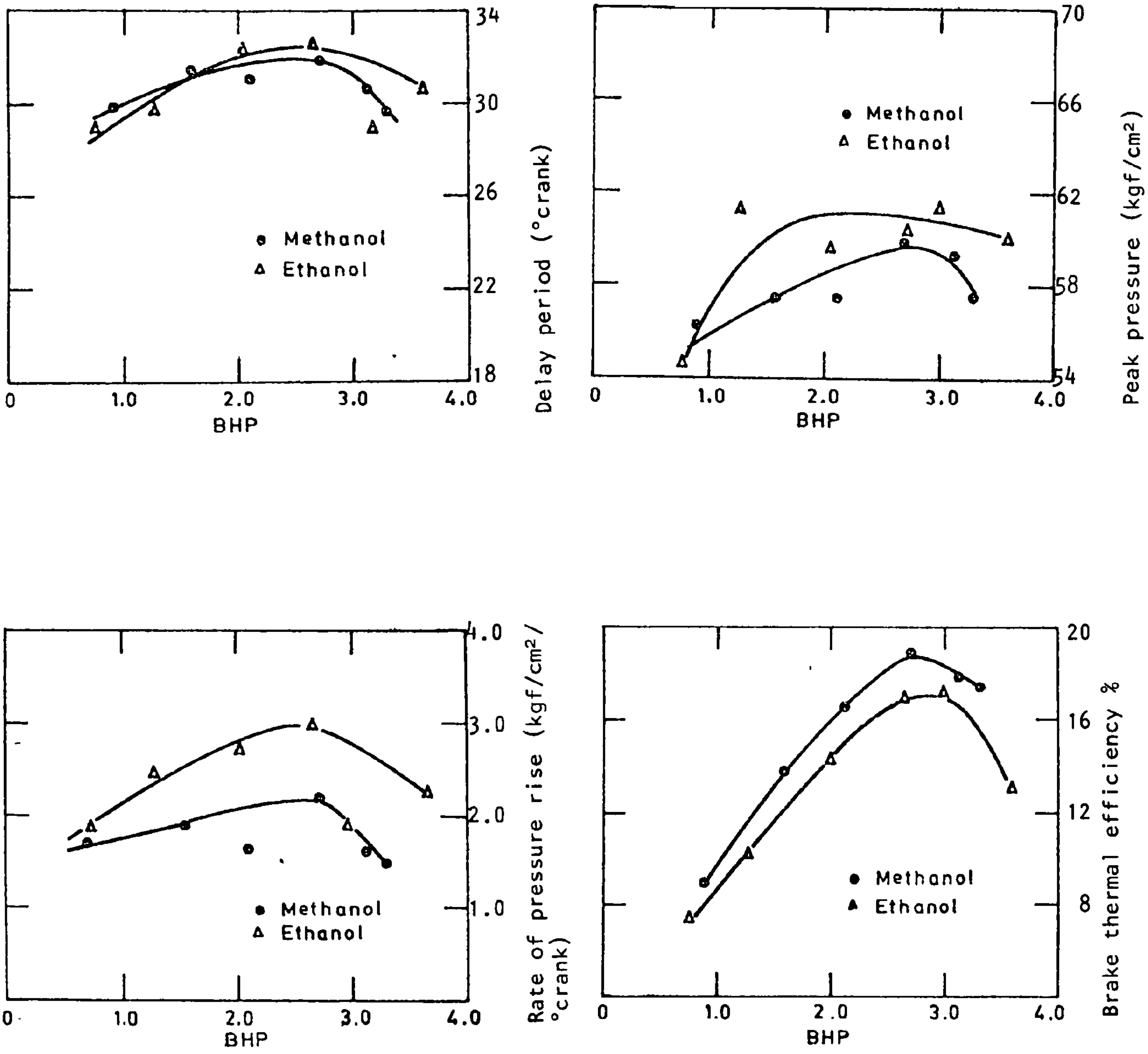


FIG. 12 - Combustion chamber of D2566 FMUH methanol engine

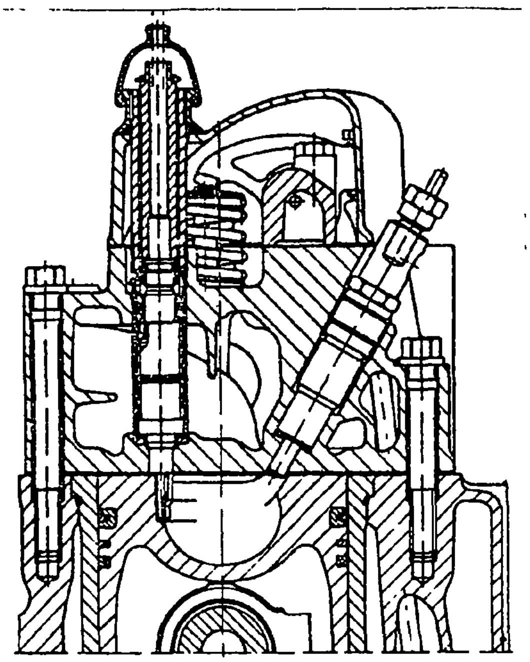
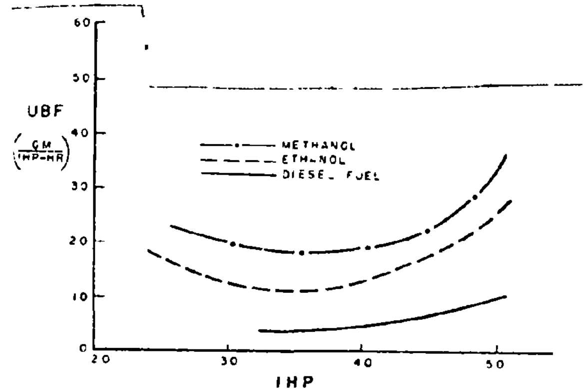
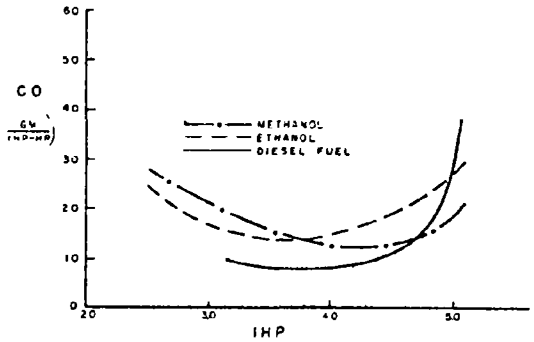


FIG. 13 - Performance of a spark ignited pre-chamber engine on alcohol fuels (19:1 compression ratio; 900 rev/min)

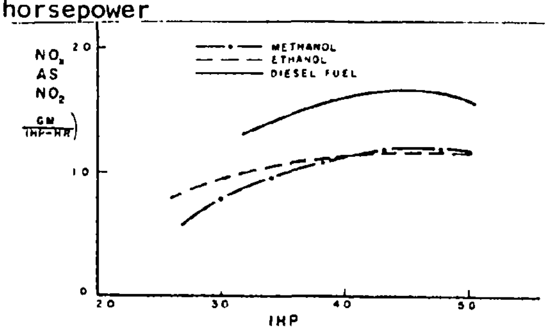
(a) Unburned fuel emissions versus indicated horsepower



(b) Carbon monoxide emissions versus indicated horsepower



(c) Oxides of nitrogen emissions versus indicated horsepower



(d) Indicated thermal efficiency versus indicated horsepower

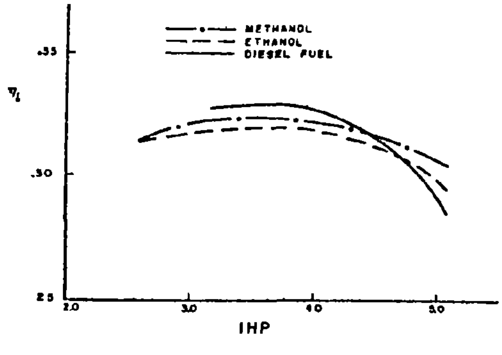
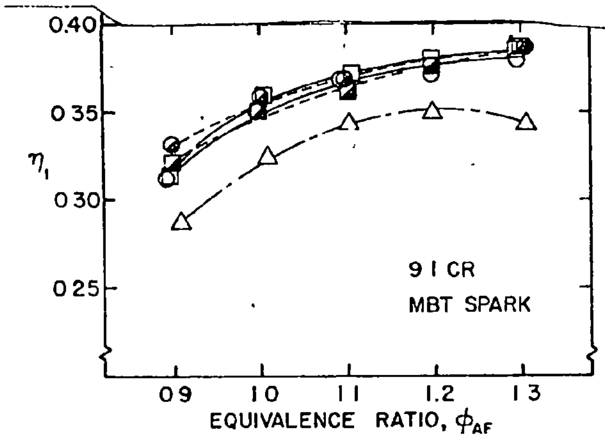
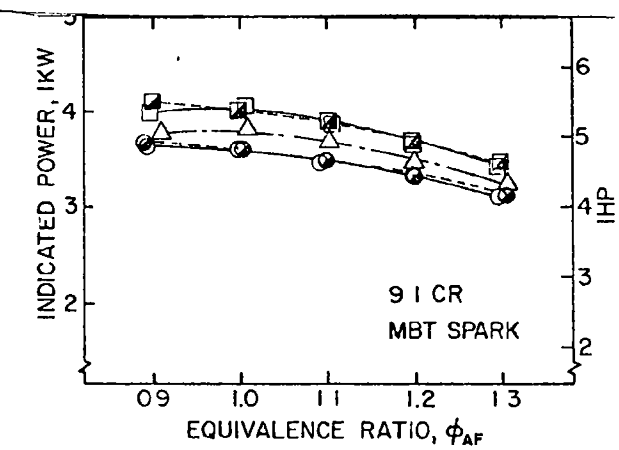


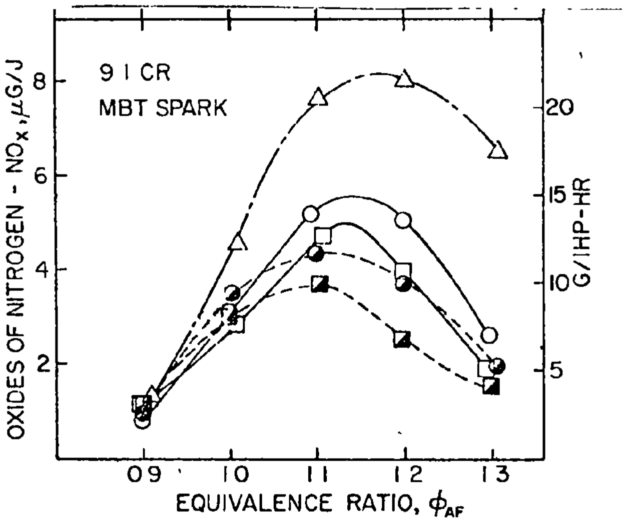
FIG. 14 - Performance of a CFR engine on methanol fuels (9:1 compression ratio, 1200 rev/min)



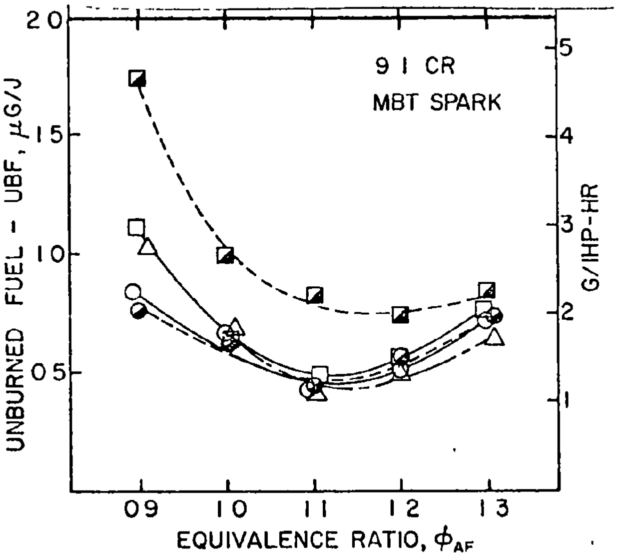
- INDICATED THERMAL EFFICIENCY



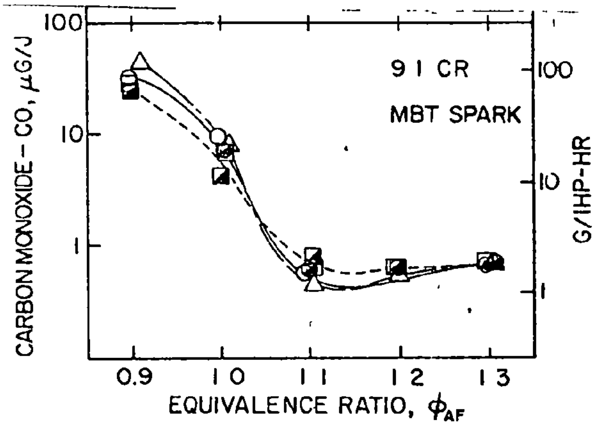
- INDICATED POWER OUTPUT



- MASS SPECIFIC EMISSIONS: OXIDES OF NITROGEN (NO_x)



- MASS SPECIFIC EMISSIONS: UNBURNED FUEL (UBF)



- MASS SPECIFIC EMISSIONS: CARBON MONOXIDE (CO)

INDOLENE	METHANOL	M5W
△- -T_m=82°C	○—T_m=82°C	◐--T_m=82°C
	□—Q_m=CONST	◩-- Q_m=CONST