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# PERFORMANCE AND EMISSION CHARACTERISTICS OF HYDROGEN FUELED SPARK IGNITION ENGINE

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**Abstract**—A study of alternate fuels leads to hydrogen as a candidate fuel for the future. Its remarkable properties provide the potential of high thermal efficiency at part load by operating the engine unthrottled with lean mixtures. The problems of pre-ignition and backfiring could be overcome at a wide range of operation by providing a cold spark plug with a narrow gap and by keeping combustion chamber walls clean. Hydrogen operation of spark-ignited engines has been found to be very profitable at low equivalence ratios both from the point of view of increased thermal efficiency and reduced nitrogen oxides emissions.

## INTRODUCTION

The problems of fast-dwindling resources of petroleum fuels and the hazard of environmental pollution caused by their combustion have focused attention on the task of finding 'clean'-burning renewable fuels for use in automobiles. Hydrogen's renewable nature and clean-burning characteristics make it the most suitable future fuel. Hydrogen can be manufactured from nuclear energy through electrolysis or thermal decomposition of water.

Hydrogen would be a particularly good fuel for spark-ignited (S.I.) engines, because it mixes easily with air and the wide flammability limits of the resulting mixture could permit high thermal efficiency and unthrottled engine operation. Engine emissions of hydrocarbons, carbon monoxide and carbon dioxide would be completely eliminated. In addition its exceptionally high flame velocity leads to such rapid combustion that the "instant combustion" idealization of the Otto cycle is approached, which should lead to higher thermal efficiency.

The wide flammability limits of hydrogen make it possible to use very lean or very rich mixtures. The use of very lean mixtures in a hydrogen fueled engine is very attractive because it leads to high thermal efficiency. Further, it provides the possibility of controlling the power output by regulating the fuel flow rate, while keeping the air flow unthrottled. This "quality regulation" has the potential of providing higher overall engine efficiency than that of gasoline engines. However, certain aspects of hydrogen utilization relating to its rapid rate of combustion, pre-ignition, engine knock, etc., require considerable experimental and analytical effort before introducing it as an S.I. engine fuel.

In the last 10 years extensive theoretical and experimental work has been carried out in the Mechanical Engineering Department and Centre of Energy Studies at I.I.T. Delhi on utilization of hydrogen and hydrogen "carriers" in I.C. engines. This work is being carried out under an ongoing project entitled "Utilization of Unconventional Fuels for National Energy Needs" and is aimed at various aspects such as engine performance, fuel economy, combustion characteristics, optimization of engine design and operating parameters, knock-free operation and exhaust emission characteristics of a hydrogen fueled engine. Apart from successfully trying ammonia — a hydrogen carrier [1] and hydrogen supplementation in existing engines [2]—utilization of hydrogen 'neat' as an S.I. engine fuel has been extensively experimented and this paper reports some of the findings pertaining to the performance and exhaust emission characteristics of hydrogen fueled S.I. engines.

## EXPERIMENTAL SET-UP

In order to evaluate the performance of hydrogen as an S.I. engine fuel, extensive experimental investigations were carried out on a single-cylinder Varimax Variable Compression engine. The feasibility study of alternate fuels requires an engine system in which operating conditions and other parameters could be controlled independently. The Varimax engine is ideally suited for comparative evaluation of different fuels.

Figure 1 is a schematic layout of the experimental set-up employing a 95.25 × 114.3 mm single-cylinder Varimax Variable Compression engine coupled with a DC swinging-field dynamometer. The engine was fitted with a gas carburettor with wide-open throttle for providing a pre-mixed hydrogen–air mixture. The quantity of hydrogen was controlled with the help of a needle valve provided before the pressure regulator. A cold spark plug with a gap of about 0.3 mm was used and the spark advance was set at MBT (minimum for best torque) for each operating point.

In order to assess the performance of a hydrogen-fueled engine it was found necessary to obtain minimum spark advance for best engine torque. Therefore, initially a series of experiments were conducted to

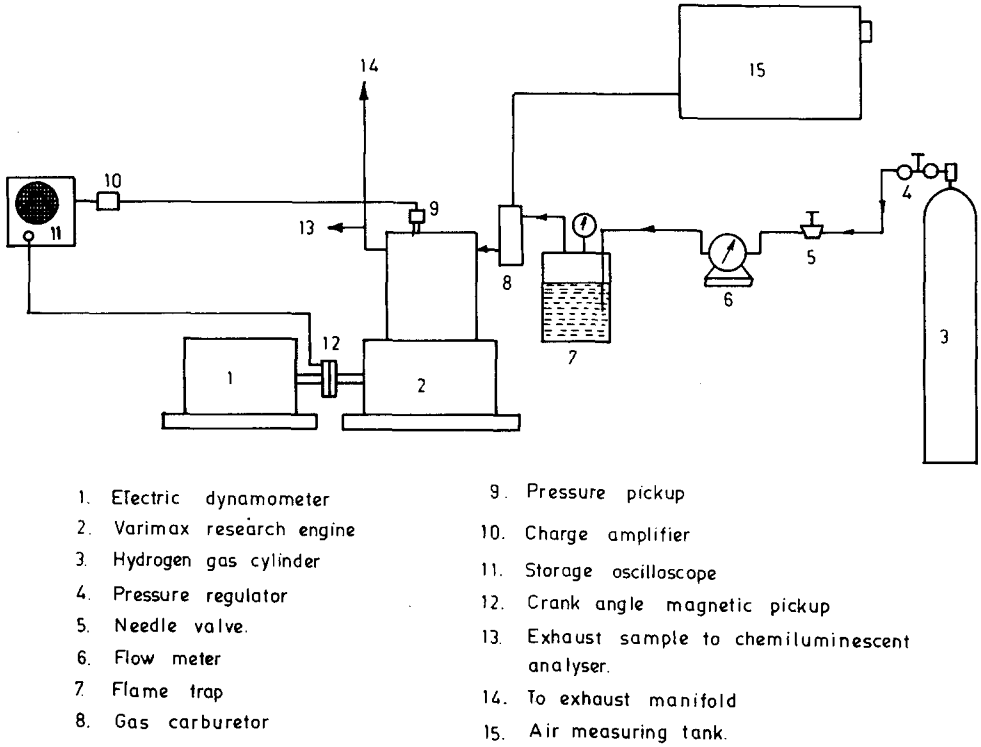


Fig. 1. Flow diagram of experimental set-up.

obtain best torque ignition timings. From the experimental data the ignition timings were plotted as a function of equivalence ratio as shown in Fig. 2.

In the next series of experiments, engine performance tests were carried out. These tests were conducted at five different compression ratios [7–11]. At each

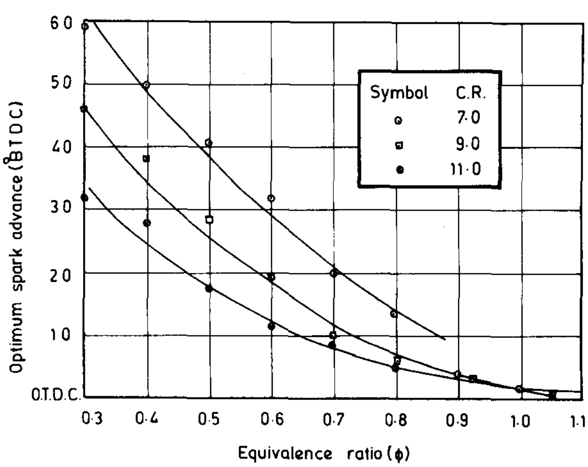


Fig. 2. Optimum spark advance as a function of equivalence ratio for various compression ratios.

compression ratio constant speed test runs were made for four different speeds (1000, 1200, 1400 and 1600 revs/min). During these performance tests the throttle was kept wide open and the load was varied from no load to full load. At each load set the speed was kept constant by controlling the hydrogen flow rate and the spark timing was adjusted for best torque as determined earlier. Rates of air and fuel consumption were measured and the brake mean effectives pressure values were obtained from dynamometer readings and they were converted to indicated values using motor test data. At each setting exhaust $NO_x$ concentrations were also recorded, using a chemiluminescence analyser.

## RESULTS AND DISCUSSION

On the basis of extensive experiments carried out with hydrogen as fuel on a Varimax engine under different engine operating conditions, a series of graphs were plotted showing the intereffect of various parameters on the engine performance and emission characteristics. A set of typical graphs are shown in Figs 3–13.

Figure 3 shows variation of indicated thermal efficiency with fuel–air equivalence ratio at various speeds and three different compressions ratios of practical utility. These graphs indicate that indicated thermal efficiency is higher at low equivalence ratio and use of

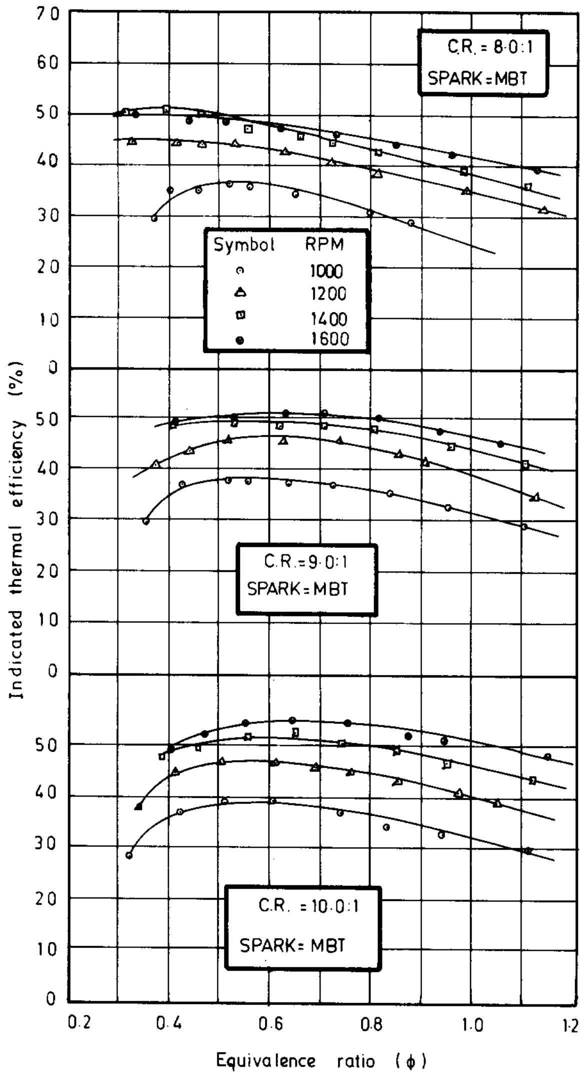


Fig. 3. Indicated thermal efficiency as a function of equivalence ratio ($\phi$) at constant compression ratio for various speeds at WOT and MBT.

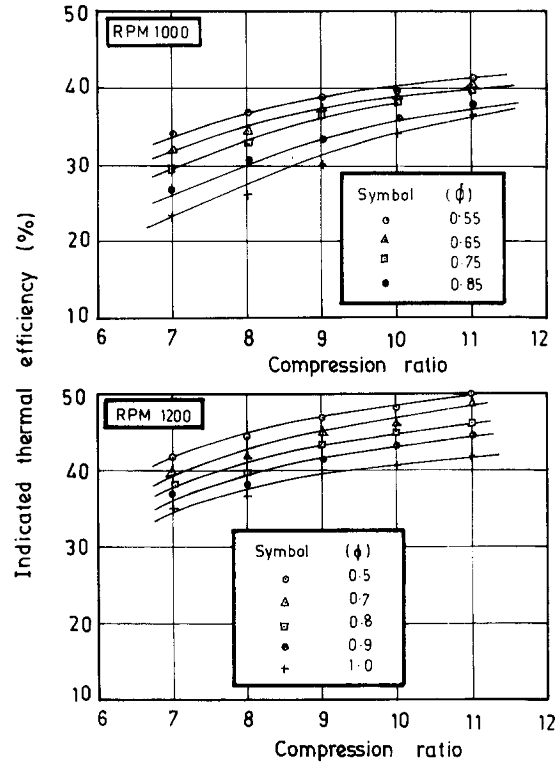


Fig. 4. Indicated thermal efficiency as a function of compression ratio at constant speed for various equivalence ratios ($\phi$) at MBT and WOT.

hydrogen permits efficient engine operation even at equivalence ratio as low as 0.3. There is an improvement in efficiency with increase of speed. With hydrogen operation maximum indicated thermal efficiency of the order of 50% is obtained, which is much higher than that obtainable with hydrocarbon fuel.

There can be two major possible reasons for higher efficiencies. Use of hydrogen permits higher compression operation of the engine; the only limiting factor being the onset of pre-ignition which can be avoided by a number of means including fuel injection, water injection, use of appropriate spark plug and keeping the combustion chamber free of deposits. If pre-ignition is avoided, it is possible to use compression ratios which are much higher than those acceptable for gasoline engines. Apart from this ability of higher compression operation, the wide flammability limit of hydrogen permits engine operation with a large excess of air. This lean operation increases the value of adiabatic index of compression significantly. Both these factors contribute towards improvement in the indicated thermal efficiency of hydrogen-fueled engine.

At higher equivalence ratios the indicated thermal efficiency is reduced. This may be due to the fact that the availability of oxygen is depleted and there is fall in volumetric efficiency at higher equivalence ratios. For instance at a given pressure and temperature of the inducted stochiometric mixture of hydrogen and air, hydrogen is estimated to take up about 30% of the volume while the figure of gasoline vapor in the corresponding gasoline air mixture is only about 2%. This shows less oxygen is introduced per engine cycle into the cylinder of a carburetted hydrogen-fueled engine than of a gasoline engine.

Figures 4 and 5 show the variation of indicated thermal efficiency, compression ratio for various equivalence ratios at different constant speeds. The increase in efficiency is quite obvious and the reduction in indicated thermal efficiency with increase in equivalence

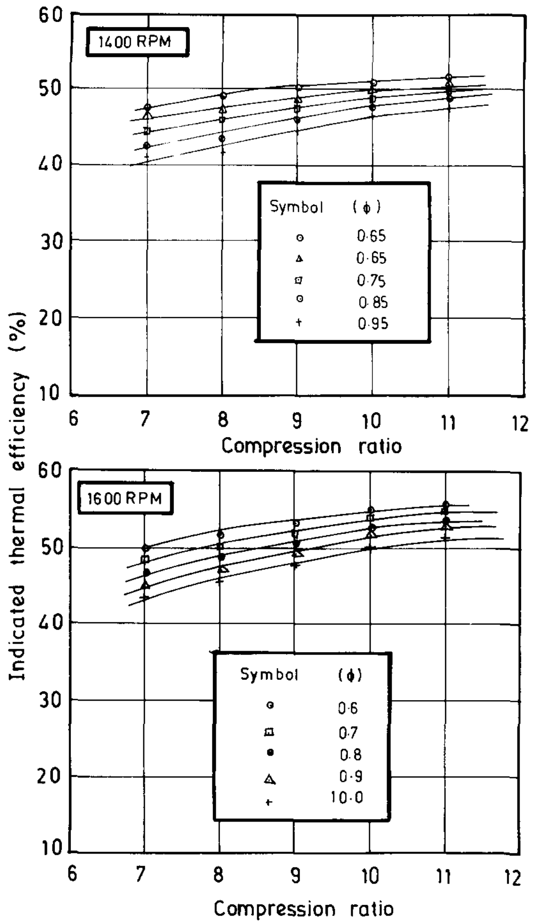


Fig. 5. Indicated thermal efficiency as a function of compression ratio at constant speed for various equivalence ratios ($\phi$) at MBT and WOT.

ratio is also glaringly brought out in these figures which confirms the observation made in the previous paragraph. These trends are in conformity with those reported by other investigators [4, 8, 9].

Figures 6 and 7 show the variation of indicated mean effective pressure (IMEP) with fuel–air equivalence ratio ($\phi$) at various compression ratios of practical utility and four different engine speeds of operation. These graphs show that IMEP increases with equivalence ratio as also with compression ratio. IMEP values are maximum at equivalence ratio around 0.9. Another noteworthy trend indicated by these figures is that in low equivalence range the effect of compression ratio is not significant, particularly at higher speeds.

Hydrogen has wide flammability limits which make it possible to use very lean mixtures. Present results indicate that a more practical lean limit for combustion in engines is around 0.3. The use of lean mixtures in a hydrogen fueled engine not only results in fuel economy but also opens up the possibility of controlling the power output of the engine by changing the fuel flow rate while keeping the air flow unthrottled. Thus "quality governing", as opposed to "quantity regulation" provided by throttling, has the very important advantage of eliminating air pumping losses which account for a significant fraction of engine power output under light load and idle conditions where many engines operate most of the time.

Figures 8 and 9 show the variation of IMEP with compression ratio at various fuel–air equivalence ratios and at four different engine speeds. As expected, IMEP increases with compression ratio as well as with equivalence ratio. Although it was possible to have higher compression operation of the engine, compression ratios were restricted in the range 7–11 as higher compression ratios aggravate the problem of undesirable combustion such as pre-ignition and backfiring. Backfiring could be prevented by keeping the engine scrupulously clean and by using a cold spark plug with an appropriate narrow gap. Any other modification resulting in reducing flame speed, increasing ignition energy and quench distance should eliminate backfiring. This can be achieved by using lean mixtures, exhaust gas recirculation or by water injection.

The brake thermal efficiency as a function of power output (brake mean effective pressure) at various compression ratios are plotted in Figs 10 and 11. The highest efficiencies are obtained with a hydrogen engine operating unthrottled with quality governing and these values are much higher than those obtainable with gasoline operation. These curves show the standard trend of brake thermal efficiency increasing with compression ratio.

The experimental results pertaining to nitrogen oxide emissions with hydrogen operation of the engine are shown in Figs 12 and 13. These diagrams show the variation of exhaust $NO_x$ concentrations with fuel–air equivalence ratio at various compression ratios and speeds. As seen in these figures $NO_x$ emission reaches maximum value at an equivalence ratio of around 0.8. In the lower equivalence ratio range $NO_x$ concentration are negligibly small.

These trends can be explained by the fact that NO formation reactions depend upon temperature and available oxygen, and they occur primarily in the post flame gases. The type of the fuel used affects the flame temperatures and, through the stoichiometry, the available oxygen. For equivalence ratios below 0.8 NO formation is restricted due to thermal quenching during the formation process. For mixtures richer than 0.8, thermal dissociation of NO is the limiting factor.

## CONCLUSION

On the basis of the work done so far it can be safely concluded that a hydrogen-fueled S.I. engine is a feasible proposition. Such an engine having quality governing can operate with very lean mixtures giving 25–100% higher values of the maximum thermal efficiency as compared to that obtainable from the conventional

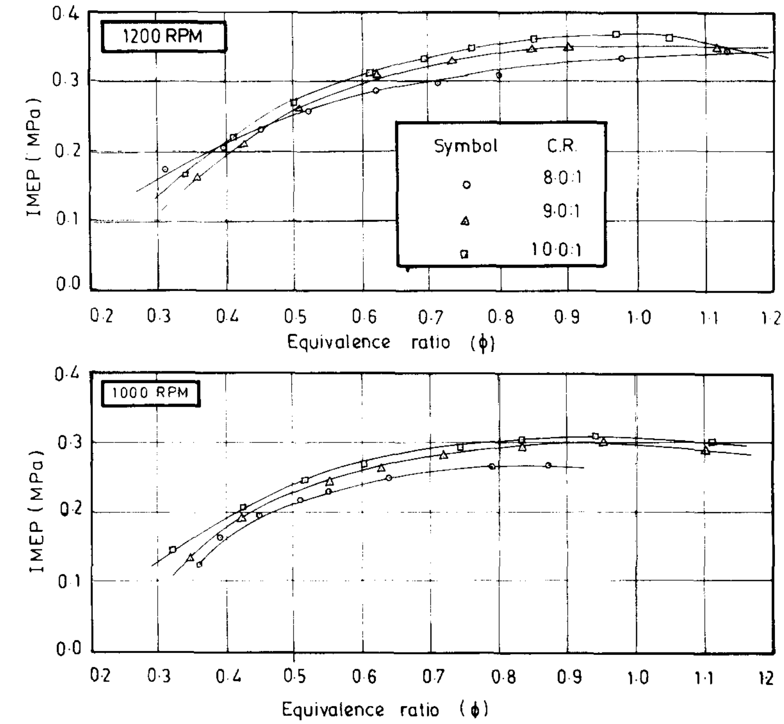


Fig. 6. Indicated mean effective pressure (IMEP) as a function of equivalence ratio at constant speed for various compression ratios at MBT and WOT.

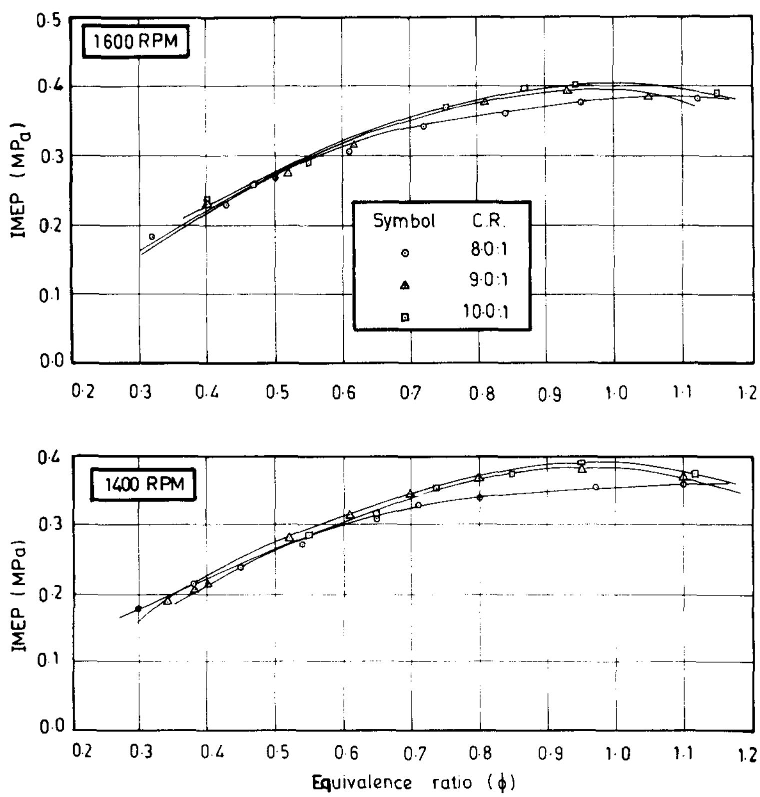


Fig. 7. Indicated mean effective pressure (IMEP) as a function of equivalence ratio at constant speed for various compression ratios at MBT and WOT.

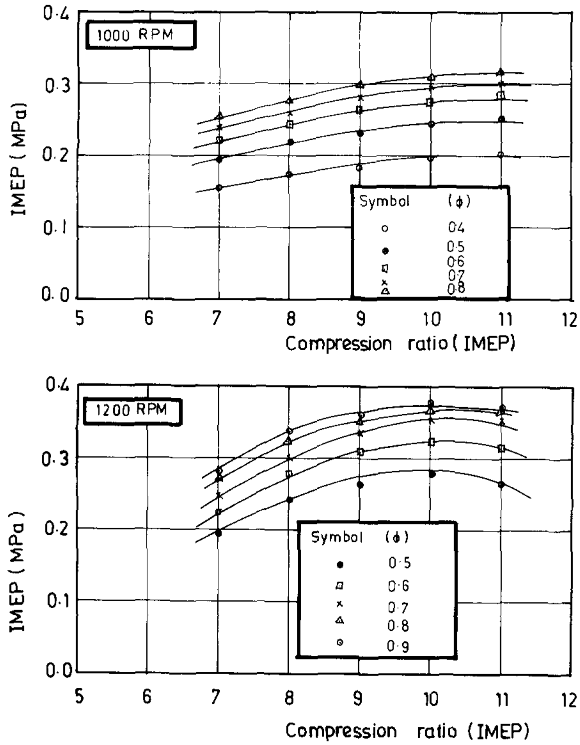


Fig. 8. Indicated mean effective pressure as a function of compression ratio for various values of equivalence ratios (ϕ) at constant speed and WOT and MBT.

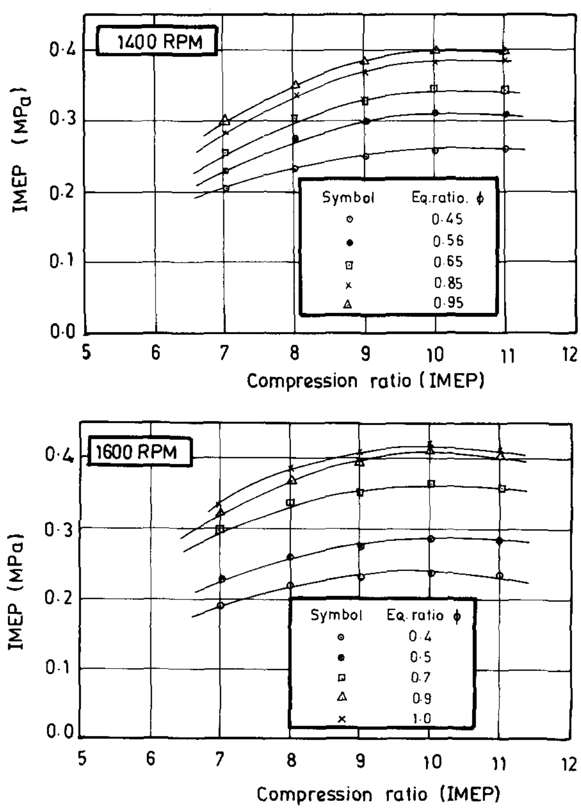


Fig. 9. Indicated mean effective pressure as a function of compression ratio for various values of equivalence ratios (ϕ) at constant speed and WOT and MBT.

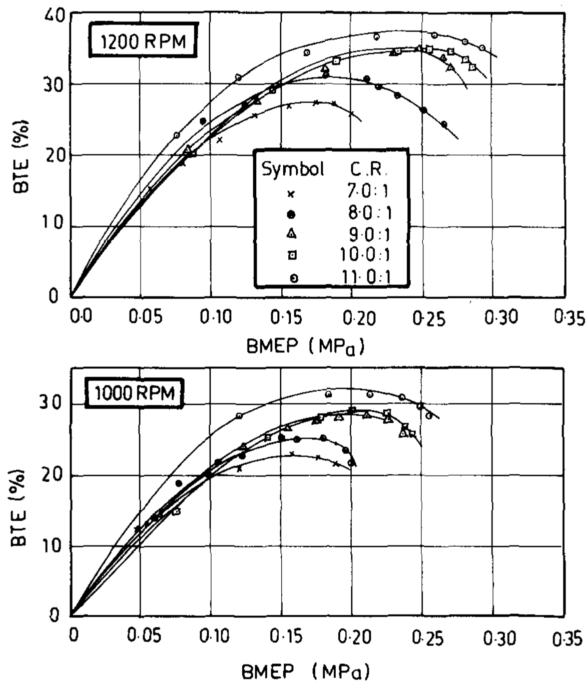


Fig. 10. Brake thermal efficiency (BTE) as a function of brake mean effective pressure (BMEP) at constant speed for various compression ratios at MBT and WOT.

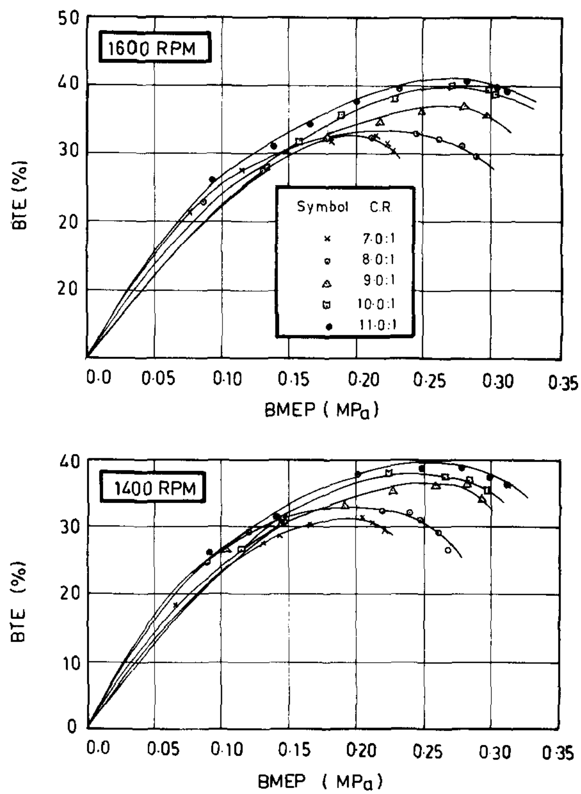


Fig. 11. Brake thermal efficiency (BTE) as a function of brake mean effective pressure (BMEP) at constant speeds for various compression ratios at MBT and WOT.

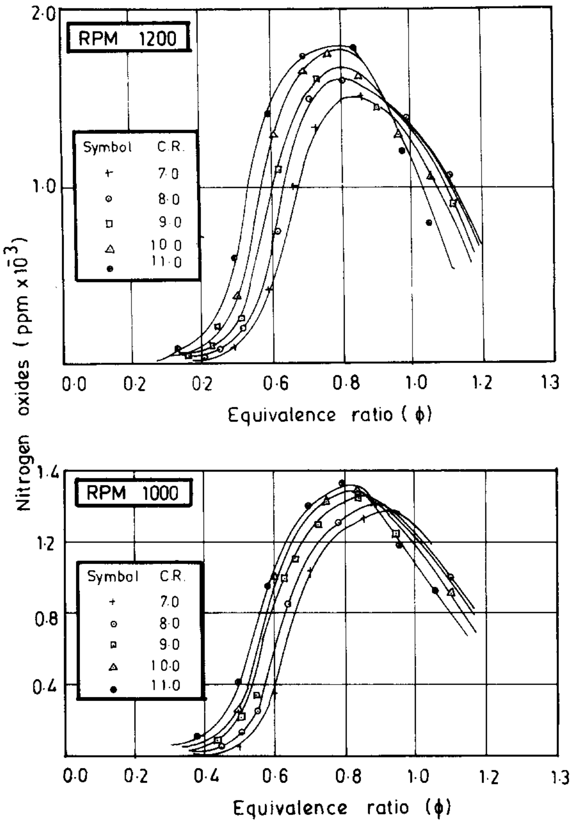


Fig. 12. Nitrogen oxide emissions as a function of equivalence ratio at constant speeds for various compression ratios.

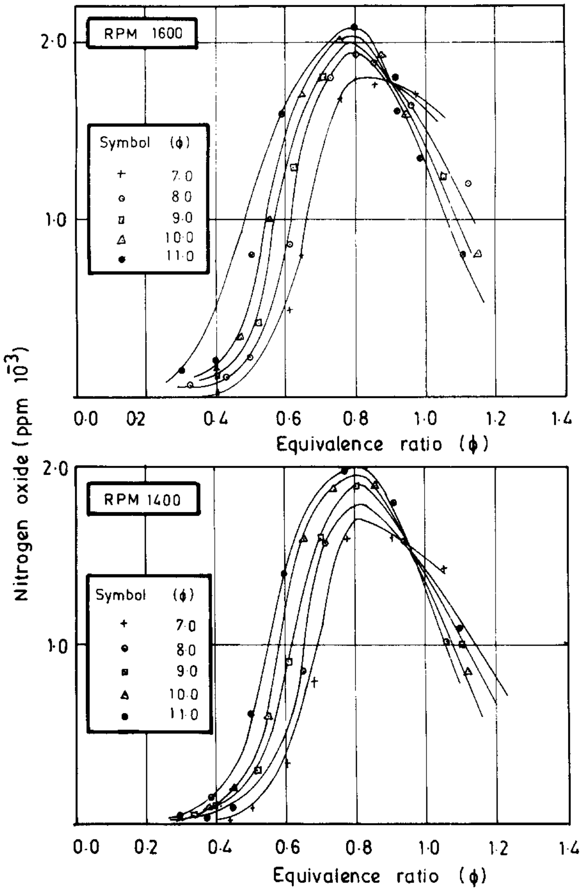


Fig. 13. Nitrogen oxide emissions as a function of equivalence ratio at constant speeds for various compression ratios.

gasoline engine. It will have the additional advantage of giving a cleaner exhaust, free from hazardous carbon-containing pollutants and as much as 90% lower NO emission level as compared to that given by the gasoline engine.

The engine will require some charge dilution such as use of EGR for smoother operation at higher equivalence ratios for higher output. A narrower spark plug gap will have to be used to account for hydrogen's "low quench" distance and low ignition energy, which can also be taken care of by the use of water injection. These coupled with a deposit-free combustion chamber can ensure smoother operation without the problems of flashback during induction or pre-ignition during compression.

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