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by

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The Hydrogen Engine: Combustion Knock and the Related Flame Velocity[*]

R. O. King[†], S. V. Hayes[‡], A. B. Allan[§], R. W. P. Anderson[¶], and E. J. Walker[¶]

A C.F.R. Otto cycle engine modified to prevent the accumulation of lubricating oil in the combustion space was used for the experiments. The relatively weak hydrogen-air mixture required for maximum thermal efficiency was usable at a compression ratio of 20 : 1 at speeds rising to 1800 r.p.m. The usable compression ratio diminished as mixture strength was increased and became 14 : 1 for the nearly correct mixture required for the development of maximum power output. There was none of the backfiring, preignition or detonation that had occurred in earlier experiments in which lubricating oil had accumulated in the combustion space but combustion knock was not eliminated. Hydrogen-air mixtures are known to burn with exceptionally high velocity and it was shown by indicator diagrams that the observed combustion knock was related to the flame velocity at the temperature and pressure attained by compression in the engine.

INTRODUCTION

THE use of hydrogen as the fuel for Otto cycle engines gives rise to difficulties that are not encountered when gasoline or natural gas, which contains methane in a concentration of 96% approximately, is used in similar conditions of operation. The difficulty first arose during the era of the widespread use of gas engines to provide the power required for industry, and Lucke in a text book on Gas Engines[1] states "Gases rich in hydrogen preignite easily and approximately one atmosphere should be deducted from the compression pressure allowable with no hydrogen, for each 5% of hydrogen present". Thus the use of hydrogen as the sole fuel was regarded as impossible.

The development in Germany and England of the rigid airship as a transatlantic passenger carrier followed the Great War, 1914-18. Hydrogen was used to provide lift and high speed Otto cycle gasoline engines to drive screw propellers. The buoyancy of the ship increased as the load of liquid fuel was consumed and was compensated for by the release of hydrogen from its containers. If the wasted hydrogen could have been used as an alternate fuel for gasoline the fuel load could have been reduced with a proportionate increase in pay load.

Experiments were in consequence carried out by Ricardo with his E 35 single cylinder variable compression ratio engine which in respect of power output was comparable with a single cylinder of the airship engines. The engine was operated at the comparable speed of 1500 r.p.m. and a compression ratio of 5.45. Then on changing from gasoline to hydrogen it was found that, as mixture strength approached the value required for maximum power output, violent combustion knock accompanied by firing back into the carburettor occurred and rendered further running impossible, even if the compression ratio were lowered to 3.8 : 1. Ricardo attributed the difficulties to preignition.[2] Similar effects were obtained by Burstall[3] at Cambridge when operating an E 35 engine at the lower speed of 1000 r.p.m., but combustion knock was attributed to detonation.

Many schemes for the use of hydrogen in mixtures with air or oxygen were proposed by Erren in Germany, beginning in 1928. The novel feature was the admission of pressurized hydrogen during the compression stroke. Some degree of supercharging was thus obtained and as the inlet valve had closed, backfiring could not occur. Claims were made subsequently that many advantages would accrue from the use of hydrogen as the fuel for the engines of submarines and transport vehicles, and the Erren method of use was investigated by Oemichen[4] on behalf of the German Ministry of Transport. An especially built engine was operated at speeds rising from 500 to 1500 r.p.m. by increments of 200 r.p.m. and compression ratios of 7.5, 8.5, 9.3, 10.0, and 12.0 were used at each speed. Power output was measured and thermal efficiencies determined. Combustion knock always occurred as mixture strength approached the correct value, and became so severe that correct and richer mixtures could not be used. The values for indicated thermal efficiency obtained when using the optimum weak mixture were higher than those obtainable with a normally aspired engine, as would be expected. Thus at 1500 r.p.m. and a compression ratio of 12, the value was 52%. Oemichen appeared to regard knocking combustion as an inherent property of hydrogen, but did not attempt to ascertain the cause of the phenomenon.

King, Wallace and Mahapatra[5] used hydrogen as the fuel for a Co-operative Fuel Research (C.F.R.) variable compression ratio engine, bore 3¼ in., stroke 4½ in. The engine was designed for the knock rating of gasolines according to the A.S.T.M. standard method for which a speed of 900 r.p.m. and a jacket coolant temperature of 212°F. are specified. As mixture strength approached the correct value, preignition occurred and was accompanied by frequent backfiring as had been observed by Ricardo. The cylinder was then removed, and a layer of finely divided carbon was found on the piston. After thoroughly cleaning all surfaces in the combustion space and the induction system, the engine ran quietly at 900 r.p.m. over a complete range of mixture strength at a compression of 10 : 1 when the jacket coolant was maintained at 140°F. Some degree of knock occurred when the jacket coolant temperature was raised

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to 212°F. and mixture strength approached and exceeded the correct value. Knocking combustion was also obtained when powdered charcoal was added to the mixture entering the engine and when the laboratory atmosphere carried an unusual concentration of concrete dust.

Downs, Walsh and Wheeler[6] adopted the clean engine technique for experiments with hydrogen as the fuel for a Ricardo E 6 engine of dimensions differing little from those of the C.F.R. The bore and stroke were 3 in. and 4⅜ in. respectively, and the compression ratio was variable over the range 4.5 to 20 : 1. The usable compression ratio with maximum power mixture strength was 8 : 1 when the engine was operated at 1500 r.p.m. and the jacket coolant maintained at 140°F. The authors concluded that higher compression ratios were not usable because of the development of a chain reaction in the gas ahead of the flame front, which caused its self ignition and consequent detonation. The authors considered this conclusion to be supported by the fact that combustion knock ceased when the vapour of tetraethyl lead was added to the mixture entering the engine. The lead was supposed to break the chain reaction. The mechanism of the chain reaction was not described.

Anzilotti and Associates[7] used a C.F.R. engine for experiments in which either hydrogen or pentane was used as the fuel. The engine was operated at 900 r.p.m. and the jacket coolant maintained at a temperature of 212°F. as specified for the knock rating of gasolines. The results obtained with hydrogen were generally similar to those of Downs, Walsh, and Wheeler in that combustion knock made it impossible to use a maximum power mixture at compression ratios higher than 8 : 1. The knocking combustion was attributed to the chain reaction mechanism devised by Lewis and Von Elbe to explain the auto-ignition of hydrogen-oxygen mixtures.[8] The published results, like those of Downs, Walsh and Wheeler, do not include data for thermal efficiency or power developed.

King and Rand[9] used hydrogen as the fuel for the C.F.R.-F4 engine which is balanced for high speed operation and fitted with a swinging field electric dynamometer. Knock free operation, as in the earlier experiments, was obtained at a compression ratio of 10 : 1 when the combustion space was clean, the speed 900 r.p.m., and the jacket coolant maintained at 140°F. When, however, the speed was raised to 1200 r.p.m., operation was not possible over a mixture range extending from 25% weak to 85% rich, because of preignition with frequent backfiring. This range extended into the richer mixtures as speeds were further increased to 1500 and 1800 r.p.m.

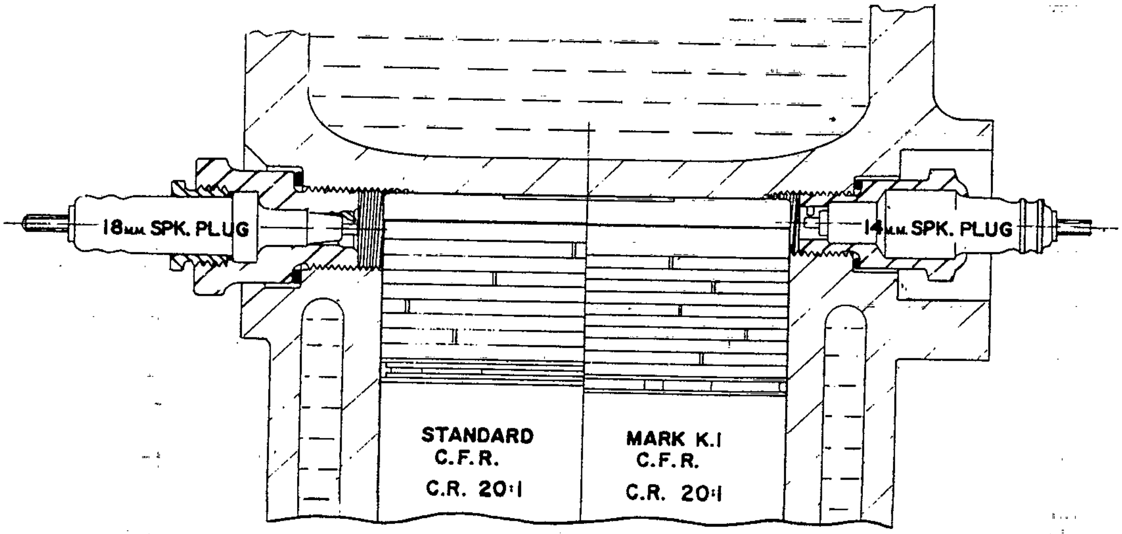
It was concluded as a result of further experiments, that because of increases in the heat load carried by the engine consequent upon increases in speed, the spark plug core and then the exhaust valve, attained igniting temperatures in respect of the hydrogen-air mixture. A hot variety of spark plug and a solid exhaust valve, both as specified for the knock testing of liquid fuel, had remained in use when changing from liquid fuels to hydrogen.

A cool variety of spark plug and a sodium-cooled exhaust valve were used for further experiments in which the temperature of the jacket coolant was reduced to 100°F. Trials were again carried out at a compression ratio of 10 : 1 and with speeds of 900, 1200, 1500 and 1800 r.p.m. Mixtures ranging from 70% weak to 60% rich were used. A maximum value of 130 p.s.i. for indicated mean effective pressure was obtained when the mixture was 5% rich and the speed 1500 r.p.m. A maximum value of 44% was obtained for indicated thermal efficiency when the speed was 1800 r.p.m. and the mixture 60% weak. There was no backfiring and it was shown by indicator diagrams that neither preignition nor detonation occurred. Knocking combustion was, however, not eliminated.

A trial was then run at a compression ratio of 12 : 1, but, although it was begun with a clean piston and combustion space, backfiring and preignition occurred; with rich mixtures especially. It was then found after removal of the cylinder that carbon had collected in piston ring grooves and had formed patches on the piston crown at positions adjacent to the three spark plug holes in the cylinder wall. These holes were overlapped by the top ring of the piston at the compression ratio of 12 : 1 with the result that lubricating oil tended to collect in the pockets provided by the spark plug and in the crevices provided by the two blank plugs.

The oil collecting as described would tend to be vaporized and burnt during the combustion period when weak mixtures were used and oxygen was in excess, but with rich mixtures and a consequent deficiency of oxygen, incomplete combustion of the vapour sufficed to account for the deposition of carbon. Thus, by occasionally interrupting a trial to use weak mixtures to burn off the carbon it was possible to

Fig. 1. Comparison of cylinder and piston designs.



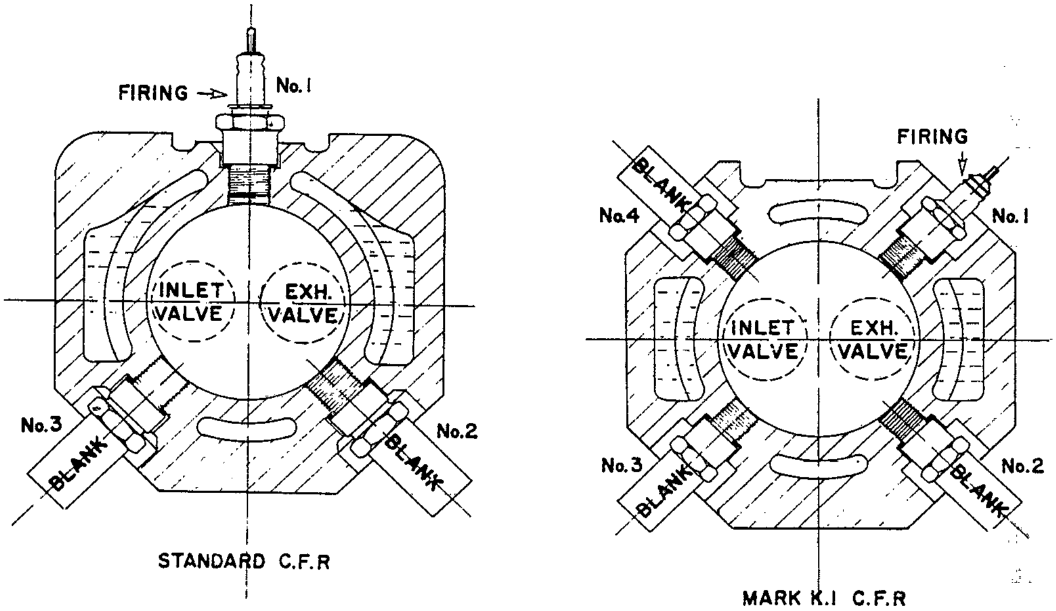


Fig. 2. Spark and blank plug positions

carry out trials at a compression ratio of 12 : 1, with mixtures ranging from 70% weak to 60% rich and at speeds of 1200, 1500, and 1800 r.p.m. The indicated mean effective pressure attained a maximum value of 146 p.s.i. with an indicated thermal efficiency 37% when the mixture was 5% rich and the speed 1500 r.p.m. and when the mixture was 55% weak a value of 47% was obtained for indicated thermal efficiency with 96 p.s.i. for I.M.E.P. These were "record" values for an unsupercharged hydrogen engine.

EXPERIMENTAL ARRANGEMENTS

A continuation of experiments on the combustion of hydrogen at compression ratios of 12 : 1 and higher was assisted by the co-operation of the Waukesha Motor Company in respect of necessary modifications in the C.F.R. cylinder and piston. Thus it will be seen by reference to Fig. 1 that overlapping of the spark plug holes by the top ring of the piston, even at a compression ratio of 20 : 1, was avoided by using 14 mm. instead of 18 mm. spark plugs and by increasing the width of the land above the top piston ring. The piston was moreover fitted with five narrow pressure rings instead of the four wider ones of the standard piston, in an endeavour to reduce the rate of oil passing the piston.

The number and arrangement of spark plug holes in the wall of the C.F.R. Standard and Mark K.I. cylinder are shown by Fig. 2. The gaseous mixture was always ignited by a single spark plug in the position shown on the figure. Spark timing was always adjusted to that required for maximum power.

The methods of measurement were as described by King and Rand.[9] A single variety of synthetic lubricant was used, namely L.B. 300 X, as supplied by the Carbide and Chemical Corporation. The temperature of the lubricating oil in the crank case sump was maintained at 140°F. by an external electric heater with manual control.

Hydrogen, supplied by the Linde Air Products Company, was reputed to be 99.95% pure. The lower calorific value was taken as 274.5 B.t.u. per cu. ft. at 60°F. and 30 in. Hg. Mixtures with air are described as per cent weak or rich according to the percentage by which the hydrogen to air volume ratio is less or more than that required for a chemically correct mixture.

Camshafts suitable for low and high speed operation of the engine were available. Particulars of valve timing, lift and overlap are given in the appendix to Part 27.[9] Spark plugs were always of varieties rated at the bottom of the "heat scale". The exhaust valve was of the sodium cooled type as described in the appendix mentioned. The temperature of the hydrogen-air mixture and that of the jacket coolant was always maintained at 65°F.

All of the experiments of this Part[9] were carried out when the engine had been fitted with a plain inlet valve. This type was used for the purpose of avoiding the reduction in volumetric efficiency and power output consequent upon the use of the shrouded valve as specified for knock rating.

Table I. Maximum Values of I.T.E. and Related Data

R.P.M.	C.R.	M.S.	V.E.%	OPT SPK.	I.H.P.	I.M.E.P.	I.T.E.%
1200	12	51%W	88	18°	5.68	100	45.3
"	14	52%W	87	18°	5.66	100	46.4
"	16	52%W	85	18°	5.75	101	47.3
"	18	52%W	86	15°	5.79	102	47.9
"	20	52%W	85	10°	5.75	103	48.2
1500	12	56%W	88	25°	6.64	93.6	46.4
"	14	56%W	88	25°	6.71	94.7	46.9
"	16	57%W	89	22°	6.97	98.3	48.4
1800	12	64%W	80	31°	6.39	75.2	48.0
"	14	64%W	80	30°	6.52	76.8	49.3
"	16	64%W	80	28°	6.68	78.8	50.6
"	18	61%W	81	25°	7.25	84.5	51.3
"	20	61%W	81	20°	7.42	87.5	51.7

Abbreviations

The terms, compression ratio, mixture strength, indicated thermal efficiency, indicated mean effective pressure, volumetric efficiency, and top dead centre are, when convenient, abbreviated to C.R., M.S., I.T.E., I.M.E.P., V.E., and t.d.c. respectively. It is to be understood that numerical values given on graphs for I.M.E.P. and Engine Speed are in pounds per square inch, p.s.i., and revolutions per minute, r.p.m., respectively. Values of C.R. are given generally as single numbers only.

RESULTS OF ENGINE TRIALS

Trials were carried out at compression ratios of 12, 14, 16, 18 and 20 : 1 and with speeds of 1200, 1500 and 1800 r.p.m. The cylinder was removed after every trial for inspection of possible carbon deposits. The surfaces of the combustion space and the piston, including the rings and their grooves, were always found to be clean. There was then no backfiring or detonation and no preignition attributable to carbon deposits.

1. Maximum Indicated Thermal Efficiency and Related Data.

The data of Table I show that the M.S. required for maximum I.T.E. diminished as speed was increased while remaining nearly independent of C.R. at any particular speed. Compression ratios rising to 20 were usable at speeds of 1200 and 1800 but the highest usable C.R. was 16 at a speed of 1500. This limit was fixed by the onset of preignition. At 1200 and 1800 r.p.m. the values for I.T.E. were consistent with increases in C.R. and with decreases in M.E. The values of I.T.E. at 1500 r.p.m. for a mixture 56% weak were however not consistent with those at 1200 r.p.m. for a mixture 52% weak.

The out-of-line values for I.T.E. at 1500 r.p.m., and the occurrence of preignition at compression ratios higher than 16, are attributed to effects arising from the change in valve timing that was made when speed was increased from 1200 to 1500 r.p.m. The low speed camshaft was used for trials at 1200 r.p.m., and provided for the closing of the inlet valve as the exhaust valve was opening. The high speed camshaft was used for trials at 1500 and 1800 r.p.m., and provided for both valves being partly open for nearly 30° of crank revolution and for a greater maximum opening. Thus it is shown by the data of Table I, that the valve timing provided by the high speed camshaft was more suitable for a speed of 1800 than for one of 1500 r.p.m.

2. Maximum Indicated Thermal Efficiencies Compared with Ideal Values.

It was shown by the engine trials, Section 1, that the M.S. required for maximum I.T.E. at a particular engine speed remained nearly constant as C.R. was raised from 12 to 20. The relations between C.R. and M.S. obtained accordingly at speeds of 1200 and 1800 r.p.m. are given by the A graphs of Fig. 3. Similar relations for ideal values of I.T.E. are given by the B graphs of the figure.

The calculation of ideal values was based on the method proposed by Leah,[10] allowance being made for dissociation, change of specific heat of the working fluid with temperature and for the volume contraction that occurs because of the combustion of electrolytic gas. The observed values depend as well on engine speed, valve timing and the loss of heat from the working fluid to relatively cool surfaces. This loss is of especial importance when hydrogen is used as an engine fuel because of the low value of the volumetric heat of combustion of the weak mixtures that are required to give maximum I.T.E.

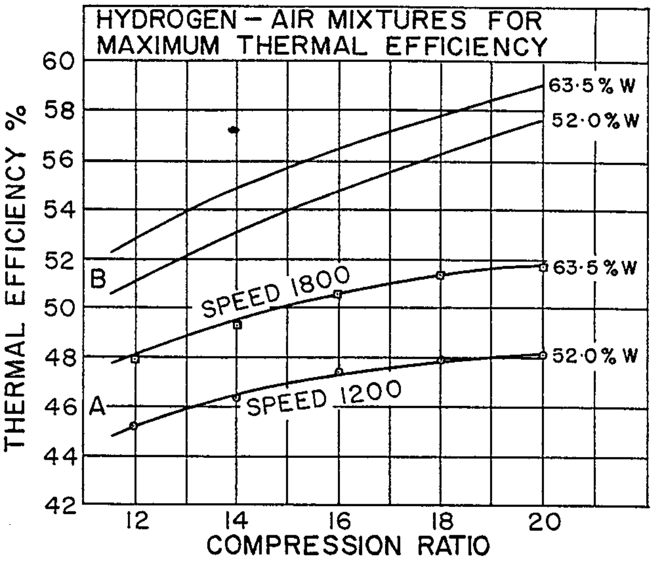
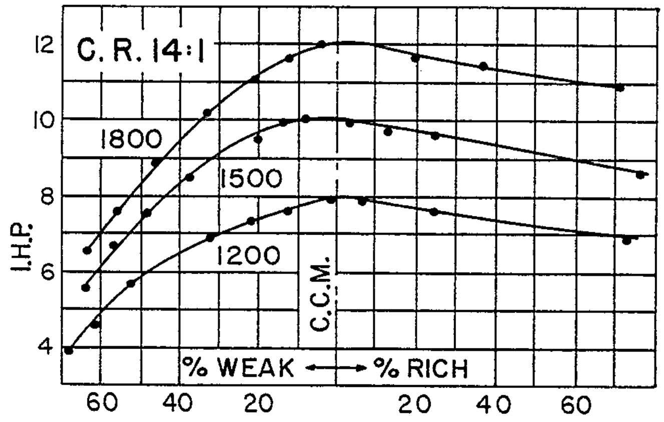


Fig. 3. Relation between thermal efficiency and compression ratio. A graphs: indicated values; B graphs: ideal values.

Fig. 4. I.H.P. at a compression ratio of 14 : 1 as affected by M.S. and engine speed.



The net result is that as C.R. is raised, and the M.S. required for maximum I.T.E. decreases with increase of speed, the percentage by which the observed fall below the ideal values decreases rapidly, as shown by the graphs of Fig. 3.

3. Highest Usable C.R. with Maximum Power Mixture Strength.

Hydrogen-air mixtures approximately correct were always required. These were usable at a C.R. of 14 and with speeds of 1200, 1500 and 1800 r.p.m. as shown by the relevant graphs of Fig. 4. The highest value for indicated mean effective pressure, 143 p.s.i., was obtained when the speed was 1500 r.p.m., and the performance data obtained are given by the graphs of Fig. 5, for mixtures ranging from 65% weak to 75% rich.

When the C.R. was raised to 16, preignition became evident when a correct mixture was used at a speed of 1000 r.p.m. The mixture strength range in which operation of the engine was rendered impossible by preignition increased as speed was increased, as shown by the graphs of Fig. 6. Thus at 1500 r.p.m. for example, operation of the engine was not possible over a range of M.S. extending from 25% weak to 55% rich.

4. Flame Velocity and Combustion Knock.

It was significant that severe knock occurred under operating conditions in which there was neither preignition nor detonation and that it persisted into extremely rich mixtures. When, however, methane or natural gas, 95% methane, was used as the engine fuel, without change of operating conditions, there was no occurrence of knock, preignition or detonation. Maximum power was then obtained with a mixture 10% rich. Regularity of spark ignition was obtained with mixtures ranging only from 35% weak to 40% rich.

Hydrogen and methane differ widely in respect of flame velocity after spark ignition. Thus according to experiments by Francis A. Smith,[11] carried out at normal temperature and pressure, flame velocity in a correct hydrogen-air mixture was 170 cm./sec. and 40 cm./sec. only in a correct methane-air mixture. Flame velocity in the hydrogen-air mixture increased as the concentration of hydrogen increased and attained a maximum value of 250 cm./sec. when the mixture was 80% rich. In methane-air mixtures, flame velocity attained a maximum value of 40 cm./sec. when the mixture was correct. The velocity decreased as the concentration of methane increased until, with a mixture 80% rich, it was near the upper limits of inflammability. It was then 8.0 cm./sec. only.

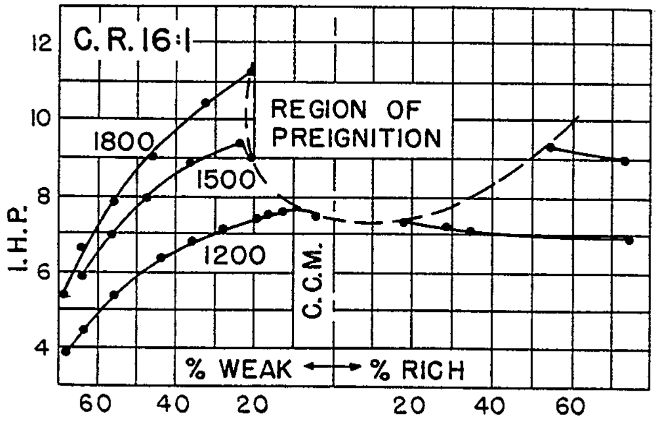
The difference in flame velocities between hydrogen and methane in mixtures with air, appeared to afford an explanation for the differences between the fuels in respect of combustion knock in the engine. It became of interest therefore to determine, by means of indicator diagrams, the rate of pressure rise and the flame velocity in conditions in which knock occurred in the engine in the absence of preignition or detonation.

A Photocon capacitance type of pressure pickup with a flush diaphragm and rated for a maximum pressure of 5000 p.s.i., the associated electronic equipment, and one beam of a dual beam Dumont oscilloscope, were used to obtain the pressure time diagrams. The other beam was used to register timing blips fed into the electronic circuit at top dead centre and at intervals of 10° of crank revolution for 30° before and after t.d.c. Blips were also fed into the circuit at 60° before and after t.d.c. The times of passage of the spark were indicated similarly and more clearly by short vertical lines drawn on the diagrams. Top dead centre is indicated by long vertical lines. The spark plug was fitted into the cylinder wall, the points being not quite flush with the wall. The length of flame travel after ignition was however taken as 3¼ in., the diameter of the cylinder. One degree of crank revolution requires a time of 1.11×10^{-4} second at the speed of 1500 r.p.m. and it is shown by the pressure-time diagrams A and B of Fig. 7 for compression ratios of 12 and 14 respectively, that combustion pressure rise began 1.5° or 1.6×10^{-4} sec. after passage of the spark.

Table. II. Flame Velocity and Related Data

C.R.	Compression Pressure	Compression Temperature	Burning Time	Flame Velocity
12	437 p.s.i.	1035°F.	15.7° (0.00174 sec.)	4830 cm./sec.
14	556 p.s.i.	1120°F	14.4° (0.00160 sec.)	5160 cm./sec.

Fig. 6. I.H.P. at a compression ratio of 16 : 1 as affected by M.S. and engine speed.



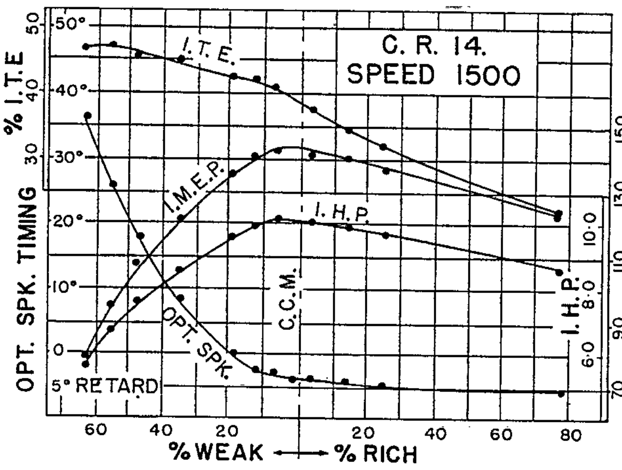


Fig. 5. Performance data C.R. 14 : 1; speed 1500 r.p.m.

The passage of the spark was followed immediately by small pressure waves which are shown by the diagrams to persist into the expansion stroke. The shape of the diagrams indicated that combustion had been virtually complete when combustion pressure attained a maximum value. Flame velocity values computed from the indicator diagrams together with related data are set out in Table II which includes calculated values for compression temperatures and pressures. These are based on an initial temperature of 120°F. and a value of 1.38 for the ratio of the specific heats.

The velocities of 4830 and 5160 cm./sec. are based on data obtained from single cycles and although successive cycles do not repeat exactly they are consistent with the related values of compression ratio. They are 28 and 30 times respectively greater than the laminar flame velocities in a correct hydrogen-air mixture at atmospheric temperature and pressure, as measured by F.A. Smith, *loc. cit.*, but are extremely small compared to the velocity of the detonation wave, of approximately 2800 metres per second, that can be generated after spark ignition of a correct hydrogen-oxygen mixture in a long closed tube. Laffitte[12] with a glass tube 100 cm. long at a temperature of 15°C. and with a correct hydrogen-*oxygen* mixture found that after spark ignition at one end, a flame run of 60 cm. occurred prior to the setting up of a detonation wave. The required length of run increased as temperature was increased until at 300°-320°C. detonation did not occur. The length of flame run in the C.F.R. engine was 8.25 cm. only and the generation of a detonation wave after spark ignition, of a hydrogen-air mixture that was dependent upon a preliminary length of flame run, would not be possible.

CONCLUSION

The experimental results obtained by means of indicator diagrams show that when hydrogen is used as the fuel for an Otto cycle engine combustion knock can occur in the absence of preignition or detonation because of the high rate of burning of mixtures with air. Then if the combustion of successive layers of mixture is completed in the flame front as it passes through the mixture, the rate of burning can be taken as the velocity of flame propagation. This in turn is dependent upon the temperature coefficient of the oxidation reaction. Tizard[13] as the result of experiments with hydrogen as the fuel for a Ricardo E 35 engine attributed combustion knock to the relatively high value of the temperature coefficient. He was in error only in describing

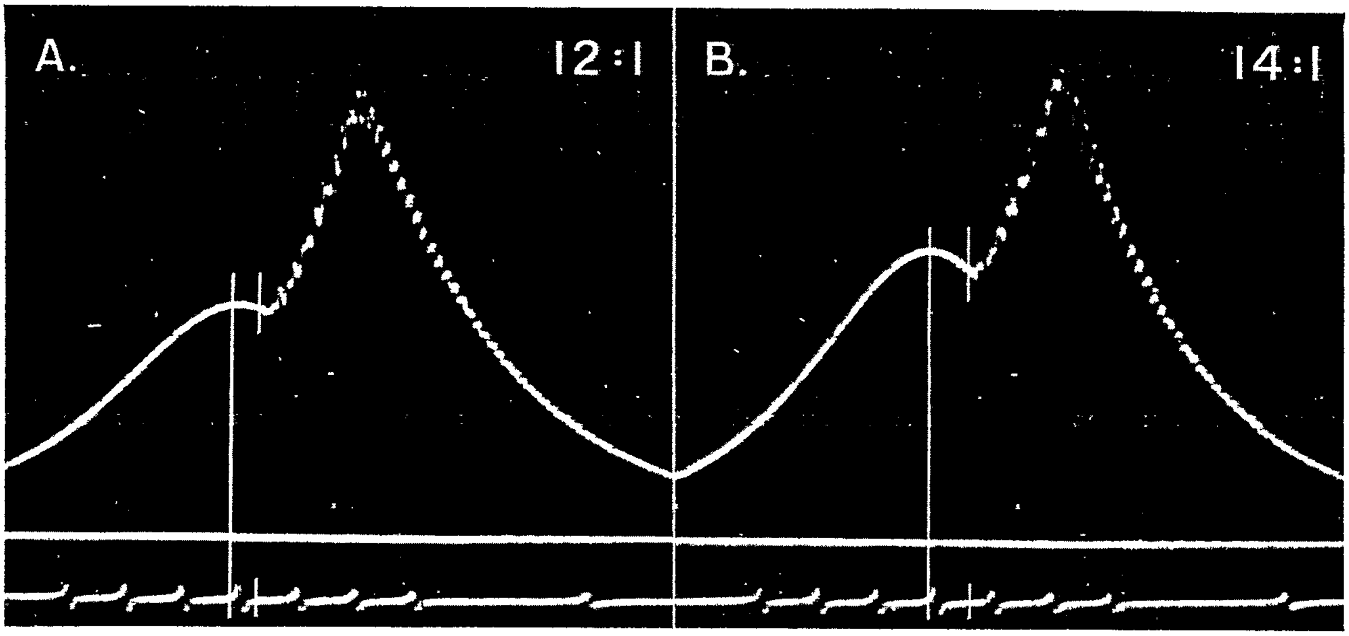


Fig. 7. Pressure-time indicator diagrams, 1500 r.p.m.
A, Compression Ratio 12 : 1; B, Compression Ratio 14 : 1.

knock as "detonation", in accordance with commonly accepted theory.

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