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THE OXIDATION, DECOMPOSITION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES: XIX - OPTIMUM TIMING OF COMPRESSION OR SPARK IGNITION AS DETE

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THE OXIDATION, DECOMPOSITION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES

XIX. OPTIMUM TIMING OF COMPRESSION OR SPARK IGNITION AS DETERMINED BY ADJUSTMENT OF COMPRESSION RATIO; ACETALDEHYDE AND DIETHYL ETHER AS ENGINE FUELS

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THE OXIDATION, DECOMPOSITION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES

XIX. OPTIMUM TIMING OF COMPRESSION OR SPARK IGNITION AS DETERMINED BY ADJUSTMENT OF COMPRESSION RATIO; ACETALDEHYDE AND DIETHYL ETHER AS ENGINE FUELS[1]

By R. O. King,[2] E. J. Durand,[3] A. B. Allan,[3]
and E. J. T. Hansen[4]

ABSTRACT

Acetaldehyde and diethyl ether were used as the fuels for a C.F.R. carburetor type engine run in the cool conditions required to ensure the presence in the charge of liquid drops during compression. Charge density was subnormal and compression ratio was then always adjustable to the value required for maximum power output (the optimum value), without inducing knock of intolerable intensity when using rich mixtures. The spark plugs of the engine were replaced by blind plugs for experiments with compression ignition and both fuels were used with mixture strengths varying from 75% weak, B.H.P. then being zero, to 140% rich. The graphs relating optimum C.R. to mixture strength are of a W form with two minimum values of optimum C.R. and an intermediate maximum value. Spark ignition was not effective with mixtures leaner than 40% weak or more than 80% rich. A relatively low engine speed of 400 r.p.m., and the presence of liquid drops in the charge during compression, provided conditions suitable for liquid phase cracking and the compression ignition obtained in the conditions of the experiments is attributed to the effect of nuclei formed accordingly. The experimental results afford evidence of thermal efficiency being affected adversely by the loss during compression of the heat required by the endothermic cracking reaction which produces the nuclei required for compression ignition.

INTRODUCTION

The experiments with acetaldehyde and diethyl ether described in Part XVIII (5) were made with a cool engine, wet carburetion, and normal charge density. Spark ignition was fixed at 10° advance and on adjusting compression ratio to obtain a standard knock intensity, as indicated by a bouncing pin meter, the engine would run with the spark switched off and with no appreciable change of power output.

The term "compression ratio" will be replaced hereafter by the initial letters C.R.

When using a particular mixture strength and continuously increasing C.R., power output increased to a maximum value and then decreased. An optimum C.R. was thus obtainable at which compression ignition timing was such that maximum combustion pressure probably occurred at the suitable piston position which was shown by indicator diagrams to be approximately 10° to 12° after top dead center, for liquid fuels.

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The optimum C.R. could be determined in the manner described for extremely weak mixtures only. Knock intensity became intolerably severe when C.R. was increased to the optimum value for relatively rich mixtures. Knock intensity decreases with a decrease of charge density and the experiments of this Part were therefore carried out with charge density reduced sufficiently to allow the use of optimum C.R. regardless of mixture strength. Mixtures varying from 75% weak to over 300% rich were used for the experiments but the results obtained with mixtures more than 140% rich are not presently described. Knock intensity varied accordingly but was never intolerably severe.

The bouncing pin was not required in the circumstances and was replaced by a blank steel plug.

Two sets of experiments with acetaldehyde and diethyl ether are described in this Part: one with the three spark plugs of the engine replaced by mild steel blanks, "blind plugs"; the other with one spark plug and ignition timing fixed at 10° advance in order to reduce the number of variables. C.R. was always adjusted for maximum power output which occurs necessarily with optimum ignition timing.

No difficulty was experienced in starting from cold when using either fuel, even when blind plugs replaced the spark plugs, if C.R. were set at approximately half a ratio higher than the optimum value.

ARRANGEMENTS MADE TO PROVIDE THE CONDITIONS OF EXPERIMENT

Wet Carburetion

Vaporization of the fuel in the carburetor was restricted by maintaining the air supply at the relatively low temperature of 50° F. and by removing the diffuser. The standard C.F.R. mixture heater was removed, allowing attachment of the carburetor directly to the engine head. The cooling water entered the cylinder jacket at 95° F. and the rise in temperature was restricted to 5° F. by automatic thermostatic control, as described in Appendix (*b*) Part XIII (6). These arrangements ensured the presence of a wet mixture at the start of compression and vaporization may not have been completed during compression. Completion would depend on mixture strength.

Air Conditioning

It is necessary in the operating conditions required for wet carburetion that relatively dry air be used in order to avoid the formation of ice in the carburetor throat. Air sufficiently dry was obtained for experiments described in earlier Parts by drawing the supply in mid-winter from outside the laboratory building. Air conditioning equipment provided subsequently made possible the continuation of cool engine experiments irrespective of weather conditions. A lagged 45 imperial gallon oil drum fitted internally with three concentric spiral cooling coils of copper tubing, and with suitable air baffles, was used as an addition to the air metering arrangement described in Appendix (*c*) of Part XIII (6, pp. 154-155) and incidentally increased the air oscillation damping capacity. A ½ h.p. Freon-12 air cooled condensing unit and three Alco T.K.O.F. Freon expansion valves, one for each cooling coil, sufficed to maintain an air temperature of approximately 5° F. in the cooling drum while air from the laboratory atmosphere was drawn through it at the rate required by the engine. The cooling coils were always defrosted on completion of a set of experiments. The temperature of the air leaving the drum was raised to 50° F. by an electric strip heater before entering the carburetor. The relative humidity was then 25% approximately and ice was not formed in the carburetor.

The Engine

A C.F.R.-F. 2. engine was used for the experiments. It was fitted with balancing pistons and three spark plugs. It was similar otherwise to the C.F.R. knock testing engine used for experiments described in preceding Parts. The standard shrouded inlet valve was replaced by one of the common variety—a spare exhaust valve. The spark plugs and the bouncing pin were replaced by mild steel blanks, "blind plugs". An engine speed of 400 r.p.m. was used for the experiments.

Carburetor for Subnormal Charge Density

The standard C.F.R. carburetor was modified to provide the subnormal charge density required for the experiments. Thus the diffuser was removed and the expanding nozzle replaced by a choke tube as illustrated by Fig. 5. The choke tube was curved to discharge the wet fuel–air mixture into the engine head well containing the inlet valve. This arrangement led to greater regularity of engine running than when an expanding nozzle was used and the liquid drops in the fuel–air mixture tended to adhere to the rough surfaces in the induction passage in the engine head. The 9/16 in. throat diameter of the venturi in the standard carburetor is overlarge when the engine speed is reduced from the usual 900 r.p.m. to the 400 r.p.m. used for the experiments of this Part and the reduction in charge density due to the use of choke tubes of relatively small diameter was consequently less than would otherwise have been expected. Thus even with a choke tube of 0.25 in. internal diameter the charge densities, which vary with the boiling points and heats of vaporization of the fuels used, were 62% and 67% of the normal value for diethyl ether and acetaldehyde respectively, at the engine speed of the experiments; the normal value being that obtained when the standard C.F.R. carburetor is used, and volumetric efficiency 85%, as determined by measurement of rate of air supply.

Metering of the Fuel and Air

The standard C.F.R. method of controlling the fuel supply to the engine depends on varying the "head" on a small orifice in the fuel passage leading to the carburetor. Orifices less than 0.010 in. in diameter were required at an engine speed of 400 r.p.m. when extremely weak fuel–air mixtures were used. The flow through the orifices, as used with the C.F.R. method of control, was then unstable. It was found that steady flow at the extremely small rates required was obtainable by using a fine adjustment needle valve; fuel supply being from a constant head. The flow was metered by the weighing method. The air supply to the engine was metered by the orifice method described in Appendix (*c*) Part XIII (6). The acetaldehyde and diethyl ether used as engine fuels were as described in Part XVIII (5).

Spark Ignition System

The standard C.F.R. spark ignition system was found to be unsatisfactory when weak mixtures of gaseous fuels were used at relatively high compression ratios. It was replaced by a special Auto-Lite system suggested by Mr. Chester Cipriani (6, pp. 152-153). The system has been used since for all experiments for which spark ignition was required. Sparks over an inch in length in air at atmospheric pressure were obtainable with the system as used, and spark ignition was obtained in the engine when using fuel gases at a C.R. of 20: 1, with normal charge density.

Measurement of Brake and Indicated Horsepower

Brake horsepower was measured by a swinging field direct connected electric dynamometer and the indicated horsepower obtained by adding the lost horsepower as determined by the motoring method. The horsepower lost in friction was reduced as far as possible by lubricating the engine with a low viscosity oil, S.A.E. 10, and maintaining the temperature of the oil in the crank case at 120° F. Measurements of lost horsepower, made later than 12 sec. after firing ceased, were not recorded.

TEMPERATURE CONDITIONS FOR COOL ENGINE EXPERIMENTS

It was possible in consequence of the use of refrigeration to maintain the air supply to the carburetor of the C.F.R. engine at an invariable and relatively low temperature. 50° F. was selected as not being significantly different from the temperatures used for the cool engine experiments described earlier, which were dependent on variable winter air temperatures. It is probable that the use of a relatively low air supply temperature, in conjunction with the carburetor attached directly to the engine head, ensured that even a weak mixture entering the cylinder contained some proportion of the fuel as droplets. The temperature of such a mixture would vary with the nature of the fuel and, in any event, it is indeterminate and measurement was not attempted.

The temperature of the cooling water entering the cylinder jacket was maintained at 85° F. for the cool engine experiments with benzene (3), pentane (4), and acetaldehyde (5). A lower temperature of 75° F. was used for experiments with ether (5) mainly because that substance is reputed to "detonate more readily than any other," (8, p. 85). The flow of cooling water was in all instances regulated automatically for a rise of 5° F. in the jackets. Exceptionally low jacket coolant temperatures were found to be unnecessary for experiments with ether and in order to reduce piston friction and thus increase the accuracy of measurement of indicated thermal efficiency, an inlet temperature of 95° F. was adopted for a new series of nuclear ignition experiments of which those of this Part are the first to be described.

The relation between the coolant temperature and that of the *mean* temperatures of surfaces in the cylinder has been determined by others for some conditions of engine operation. There is, however, no information available concerning the *true* surface temperatures which must undergo extreme cyclic changes and be an important factor in respect of the surface oxidation reactions which in turn influence fuel performance.

EXPERIMENTAL RESULTS

Acetaldehyde

The *B* graphs of Fig. 1 exhibit experimental results obtained when the spark plugs and bouncing pin were replaced by blind plugs, the charge density reduced to 67% of normal and the compression ratio always adjusted to the optimum value. The correct air to fuel ratio for acetaldehyde is 7.84: 1 by weight. Mixtures varying from 75% weak to 140% rich were used. *Brake horsepower* was zero with a mixture 75% weak. The air to fuel ratio was then 31.4: 1, by weight.

The optimum C.R., lower B graph, Fig. 1, decreased from 11.9 to 8.1 as mixture strength was increased from 75% weak to 44% weak but on further

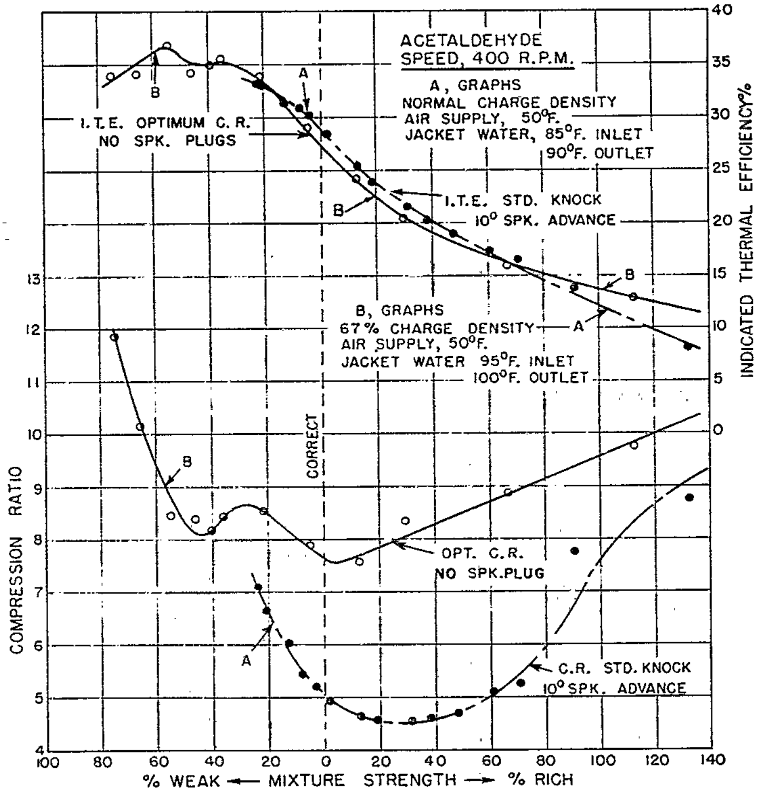

FIG. 1. Acetaldehyde. Results obtained with compression ignition, blind plugs, and reduced charge density compared with those obtained with spark ignition, standard knock intensity, and normal charge density.

increasing mixture strength to 28% weak, optimum C.R. *increased* to 8.7, and then decreased to a minimum of 7.5 on further increasing mixture strength to be 5% rich. Thereafter the increase of optimum C.R. with increase of mixture strength was nearly linear. Thus in the conditions of the experiment there were two minimum but unequal values for the optimum C.R. The first, occurring with the mixture 45% weak, is reflected in the graph for indicated thermal efficiency. There is no inflection in the graph in respect of the second minimum.

Combustion was silent when extremely weak mixtures were used but became audible as mixture strength was increased. Light knock occurred with a mixture 40% weak. Knock intensity continued to increase with increase of mixture strength to become medium heavy and somewhat irregular for the correct mixture. It became irregularly heavy and was accompanied by some missing as the mixture strength was increased to be 140% rich. The observations of knock intensity were made when using the optimum C.R.

It is of interest to compare the experimental results described above with those obtained when using normal charge density and always adjusting C.R. for a standard knock intensity as indicated by the bouncing pin meter; circumstances in which the engine would run with or without spark ignition. The broken line, *A* graphs of Fig. 1, have been reproduced accordingly from Part XVIII (5).

It will be seen by reference to Graphs *A* that the earlier experiment was discontinued when the mixture was 25% weak. Both spark and compression ignition were then ineffective and knock exceeded that adopted as a standard intensity as indicated by the knock meter, on attempting to continue with compression ignition by raising the C.R. It was indicated, however, that compression ignition might remain effective as the mixture was progressively weakened while spark ignition would not. This difference between compression and spark ignition was not confirmed until charge density was reduced in order to mitigate the severity of the knocking combustion which occurred with mixtures even as rich as 25% weak. It appears, however, that Graph *A* would have intersected Graph *B* if it had been practicable to carry on with compression ignition after spark ignition had become ineffective, without reducing charge density.

A second significant feature displayed by the experimental results given by the *A* and *B* graphs of Fig. 1 is that the higher C.R. required for optimum compression ignition timing yielded a somewhat lower value for indicated thermal efficiency than was obtained when ignition was with or without spark ignition and C.R. adjusted for the lower value then required for a standard knock intensity. Relative values are given in Table I for mixture strengths in the range commonly used.

It is shown by the data of Table I that with a 15% weak mixture equal values were obtained for thermal efficiency although C.R. was 6.1, *A* graph, and 8.2, *B* graph, whereas according to the ordinary rules of calculation there should have been a 10% difference. A *decrease* in thermal efficiency is shown for the correct mixture on raising the C.R. from 5 to 7.6, a change which should have given a percentage *increase* of 17. The anomalous effect is even greater for the 40% rich mixture for which, on increasing C.R. from 4.6 to 8.3, a decrease in thermal efficiency of 5% was observed, instead of a calculated *increase* of 22%.

TABLE I

COMPRESSION RATIO AND INDICATED THERMAL EFFICIENCY

Mixture	*A* Graphs		*B* Graphs	
	Standard knock intensity normal charge density. With or without spark ignition		Optimum compression ignition timing, 67% charge density blind plugs	
	C.R.	I.T.E., %	C.R.	I.T.E., %
15% weak	6.1	32	8.2	32
Correct	5.0	29	7.6	27½
40% rich	4.6	20	8.3	19

Diethyl Ether

The *B* graphs of Fig. 2 exhibit results of experiments made with ether when the spark plugs and the bouncing pin were replaced by blind plugs, the charge density reduced to 62% of normal, and C.R. always adjusted to the optimum value. The correct air to fuel ratio for diethyl ether is 11.2: 1 by weight. Mixtures varying from 75% weak to 140% were used. Brake horsepower was zero with a mixture 75% weak. The air to fuel ratio was then 44.8: 1.

The broken line *A* graphs of the figure are reproduced from Part XVIII (5) and exhibit experimental results obtained when using normal charge density and always adjusting C.R. for a standard knock intensity as indicated by the bouncing pin meter, circumstances in which the engine ran with or without spark ignition.

A comparison of Graphs *A* and *B* shows that the inflection in Graph *A* which in the earlier experiment was considered as possibly due to experimental irregularity (5, p. 385) did in fact indicate a real effect which, when using the new method of experiment, became the first of two minimum and equal values of the optimum C.R.; the corresponding mixture strengths being 40% weak and 25% rich respectively. The intermediate maximum value of the optimum C.R. occurred with a mixture 10% weak and was as shown by Graph *B*, 1.75 C.R. higher than the minimum values. A nearly symmetrical W form is imparted accordingly to the graph for optimum C.R. over the mixture range 65% weak to 80% rich.

It will be noted that the *A* and *B* graphs, Fig. 2, for the relation between compression ratio and mixture strength, intersect when the mixture is 25% weak and the compression ratio 6.0. On the rich side of the intersection, thermal efficiency decreases with increase of C.R. This anomalous effect is similar, though somewhat smaller than was obtained when using acetaldehyde as the engine fuel. On the weak side, a higher thermal efficiency corresponds with the use of a higher C.R. but the relation is not in accordance with known factors. Graph *B* of Fig. 2, for I.T.E., would be of more nearly conventional form if it were as shown by the dotted line. Too much reliance cannot be placed on the observation made with the mixture 70% weak.

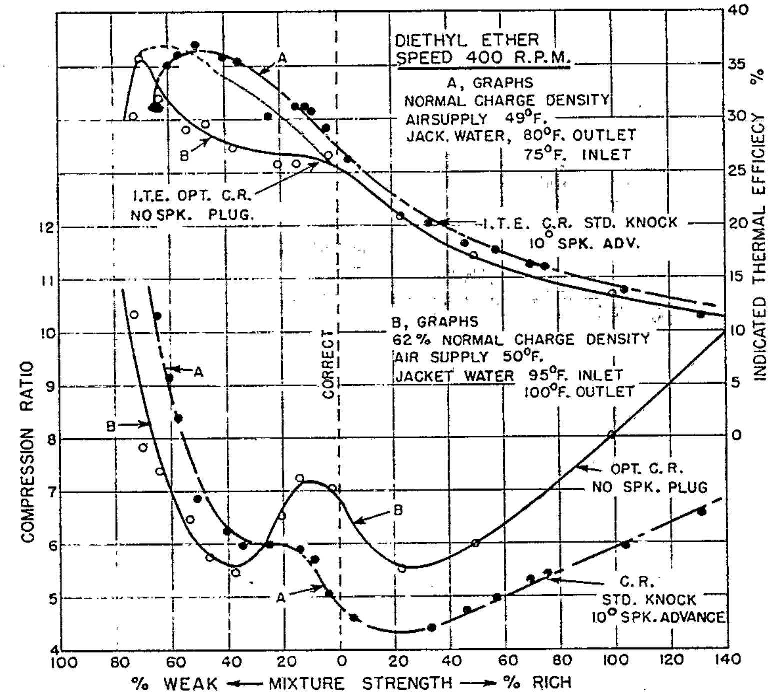

FIG. 2. Diethyl ether. Results obtained with compression ignition, blind plugs, and reduced charge density compared with those obtained with spark ignition, standard knock intensity, and normal charge density.

Combustion was silent when extremely weak mixtures were used. Light knock developed as mixture strength was increased to 40% weak. It continued to increase with increase of mixture strength and to become medium heavy for mixtures approximately correct. The intensity became somewhat variable as between medium heavy, and heavy, with mixtures ranging from correct to 140% rich. Misfiring occurred occasionally. Knock intensity characteristics were, as nearly as could be judged by ear, similar to those observed during the experiments with acetaldehyde although that substance required higher values of the C.R. for optimum ignition timing. The running of the engine with ether as the fuel was noticeably smoother than when acetaldehyde was used.

Acetaldehyde. Results of Experiments with Spark Ignition Compared with Results Obtained with Compression Ignition; 67% of Normal Charge Density

It was shown by experiments described in Part XVIII (5), and reviewed earlier in this Part, that ignition of acetaldehyde–air mixture varying from 25% weak to 140% rich would occur with or without spark ignition if C.R. were adjusted for a standard knock intensity. The experiments were made with normal charge density, and spark ignition was always set at 10° advance. Spark ignition failed when mixture strength was leaner than 25% weak. Compression ignition also failed if C.R. were restricted to the value for standard knock intensity.

The results of reducing the charge density to 67% of normal and using the optimum C.R. while retaining spark ignition are exhibited by the *C* graphs of Fig. 3. Spark ignition was ineffective when the mixture was leaner than 40% weak, but it was possible to continue into weaker mixtures with ignition by compression, always using the optimum C.R., until the mixture became 75% weak and power output zero.

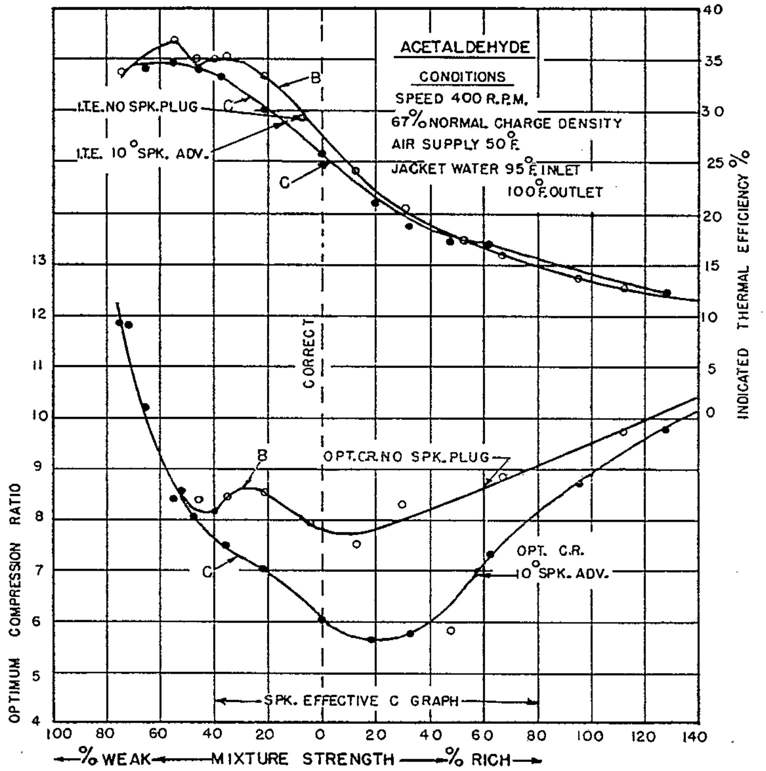

FIG. 3. Acetaldehyde. Results obtained with and without spark ignition and in both cases using optimum compression ratio, reduced charge density, and same temperature conditions.

Combustion was silent with extremely weak mixtures. Knock became audible and very light on increasing mixture strength to 40% weak and became light only, even on increasing mixture strength to 80% rich. It became medium heavy for a mixture 140% rich.

The *B* graphs of Fig. 3 are reproduced from Fig. 1, and exhibit experimental results obtained with charge density 67% of normal, and with blind plugs instead of a spark plug; the optimum C.R. for compression ignition always being used. Graphs *B* and *C* thus represent experimental results obtained in like conditions of charge density and engine and air supply temperatures.

Comparing the two graphs, giving the relation between optimum C.R. and mixture strength, it will be seen that for mixtures leaner than 40% weak, the experimental points for both sets of experiments fall on a single line as would be expected in view of spark ignition having become ineffective. It also became ineffective, as already mentioned, when mixture strength was more than 80% rich but the graphs do not then coincide. It is evident that the spark plug introduced an igniting effect not due to the spark.

It is of interest to compare the relation between thermal efficiency and C.R. observed when blind plugs were used with the similar relation observed when ignition was by spark; C.R. being adjusted for optimum ignition timing in both cases. The comparison is made only for mixtures increasing in richness from 40% weak, in part because of spark ignition being ineffective with weaker mixtures. Relevant data from the originals of the graphs of Fig. 3 are tabulated below.

TABLE II

RELATIVE EFFECTS OF COMPRESSION AND SPARK IGNITION ON INDICATED THERMAL EFFICIENCY (I.T.E.) WITH ACETALDEHYDE AS ENGINE FUEL, SAME CHARGE DENSITY BOTH CASES

Mixture	Opt. C.R. (spark)	Opt. C.R. (blind plugs)	I.T.E. (spark), %	I.T.E. (blind plugs), %	% Increase I.T.E.	Calculated inc., %
40% weak	7.7	8.2	33½	35	4.5	2.0
20% weak	7.0	8.5	30	33	10.0	6.3
Correct	6.0	7.8	25½	27½	7.8	9.3
20% rich	5.6	7.8	21	22½	7.2	12.8
40% rich	5.9	8.2	18	19	5.5	12.0

The compression ignition obtained when using blind plugs appears to yield an increase in thermal efficiency for mixtures weaker than correct and a decrease for correct and richer mixtures.

Diethyl Ether. Results of Experiments with Spark Ignition Compared with Results Obtained with Compression Ignition; 62% of Normal Charge Density

The *B* and *C* graphs, Fig. 4, exhibit experimental results obtained when charge density was 62% of normal. The *B* graphs are reproduced from Fig. 2 and give results obtained without spark plugs and with the optimum

C.R. for compression ignition. The *C* graphs give results obtained with one spark plug, spark timing being set 10° advance, and the C.R. adjusted for maximum power.

Comparing the *B* and *C* graphs, giving the relation between optimum C.R. and mixture strength, it will be seen that the characteristics are in general similar to those observed when acetaldehyde was used as the fuel for the engine. Thus spark ignition failed when the mixture became leaner than 40% weak and the experiment was continued by using compression ignition until the mixture was 75% weak and power output became zero. Spark ignition also failed, as with acetaldehyde, when the mixture became more than 80% rich, and again it was possible to carry on with still richer mixtures by using compression ignition. The *B* and *C* graphs coincide when the mixture is leaner than 40% weak and spark ignition is ineffective but not when the mixture is more than 80% rich and spark ignition again ineffective. It was suggested when describing the similar experiments with acetaldehyde that this rather puzzling phenomenon might be due to the spark plug having an igniting effect independently of the spark. This was found to be so in the course of experiments to be described in another Part. They demonstrate

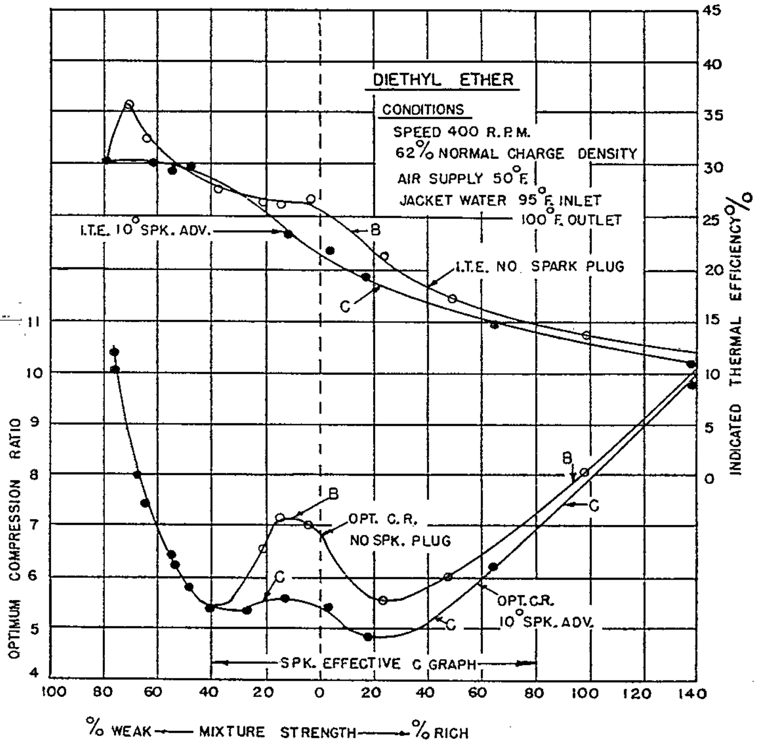

FIG. 4. Diethyl ether. Results obtained with and without spark ignition and in both cases using optimum compression ratio, reduced charge density, and same temperature conditions.

TABLE III

RELATIVE EFFECTS OF COMPRESSION AND SPARK IGNITION ON INDICATED THERMAL EFFICIENCY (I.T.E.) WITH DIETHYL ETHER AS FUEL, SAME CHARGE DENSITY BOTH CASES

Mixture	Opt. C.R. (spark)	Opt. C.R. (blind plugs)	I.T.E. (spark), %	I.T.E. (blind plugs), %	Observed inc., %	Calculated inc., %
30% weak	5.3	5.7	27	27	0	3.1
10% weak	5.6	7.1	23½	26	10.6	9.5
Correct	5.5	6.8	22	25½	15.8	8.8
20% rich	4.8	5.6	19	21½	13.2	6.9
40% rich	5.2	5.8	17	18½	8.8	4.8

that the ceramic core of an unfired plug, not its points, possesses an igniting effect when ignition is by compression.

Combustion was silent with weak mixtures and as for the spark ignition experiments with aldehyde in similar conditions, it became light only on increasing mixture strength to 80% rich.

The relative effects of compression and spark ignition on thermal efficiency differed from those observed when acetaldehyde was used in that for mixtures ranging from correct to 40% rich the effect of compression ignition was beneficial rather than deleterious. Relevant data are tabulated above.

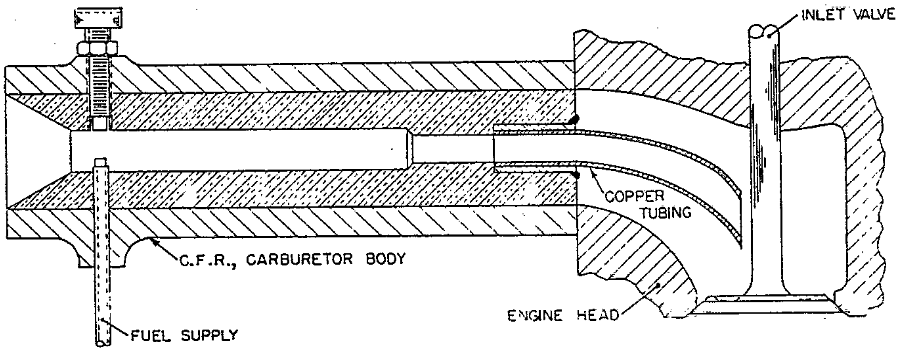

FIG. 5. Carburetor arrangement for experiments with reduced charge density.

DISCUSSION

The novel features of the method of experiments described in this Part are the use of the C.R. for optimum timing of either spark or compression ignition and a subnormal charge density in order to prevent knock intensity becoming intolerably severe on increasing mixture strength from very weak to very rich. The experimental arrangements were otherwise similar to those of the experiments on nuclear ignition described in Parts XVI (3), XVII (4), and XVIII (5). That is, the engine was run "cool" at the relatively low speed of 400 r.p.m. and with wet carburetion in order to facilitate the formation of an igniting concentration of nuclei by liquid phase decomposition or cracking of the fuel and to reduce the tendency of hot surfaces in the combustion chamber to ignite the combustible mixture or to promote preflame oxidation.

The W form of the graphs relating C.R. for optimum compression ignition timing and mixture strength is in general similar to that described by Campbell as having been obtained when using *pentane* in standard knock rating conditions, see discussion of paper on *Precombustion reactions in the spark ignition engine* by Retailliau, Richards, and Jones (9), Standard Oil Development Co. The especially interesting features of Campbell's experiments were the finding that aldehyde was formed in great profusion in mixtures too weak to be ignited by the spark if C.R. were raised to induce greater than "borderline" knock intensity and that compression ignition occurred on further increasing C.R.

The authors of the paper mentioned above consider that during compression, oxidation precedes decomposition. Their experiments were, like those of Campbell, made with a hot engine; the jacket coolant being maintained at 212° F. and the fuel–air mixture raised to 300° F. before entering the cylinder. It would be expected, therefore, that oxidation of fuel on hot surfaces in the combustion chamber would begin immediately on admission of the charge in the conditions of turbulence induced by the passing of the charge with high velocity through the restricted opening of the inlet valve.

Further experiments on precombustion reactions, carried out in the du Pont Petroleum Laboratory, were described by Pastell (7) six months later. A *motored* engine was used with the jacket coolant maintained at 212° F. and the inlet mixture temperature varied over the range 100 to 400° F. A special feature of the experiments was that manifold air pressures were varied over the range 15 to 75 in. Hg. Both oxidation and decomposition must have occurred during compression in the temperature conditions. Oxidation seems to have been regarded as the predominant reaction because the *heat liberated* is taken into account when discussing thermal efficiency, no allowance being made for the heat absorbed by an endothermic decomposition reaction. The hot engine may be regarded as a heated chamber into which reacting mixture is admitted suddenly and its temperature raised by contact with uncooled surfaces and by compression. It is of interest accordingly that the combustion characteristics described by Pastell are in general similar to those determined by Townend (10) when compressed mixture was admitted suddenly to a heated bomb.

Cold fuel–air mixture was admitted into a cool engine in the experiments of this Part and it is considered that decomposition was the primary reaction and provided the nuclei on which oxidation occurred in the body of the mixture. It is difficult to account otherwise for the profuse formation of aldehyde in extremely weak mixtures, as reported by Campbell, and for the fact that such mixtures can be ignited by the heat of compression but not by a spark. What is thus regarded as nuclear ignition was obtained in the experiments described in this Part, with mixtures 75% weak to 140% rich. The range has moreover been extended at both ends. Spark ignition, on the other

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