# United States Patent [19]

**Wyczalek**

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[54] **PLASMA JET IGNITION ENGINE AND METHOD**


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[73] Assignee: **General Motors Corporation,** Detroit, Mich.



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[21] Appl. No.: **525,028**

**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 439,352, Feb. 4, 1974, abandoned.

[52] **U.S. Cl.** ..... **123/143 B;** 123/148 R; 123/169 R; 123/191 S; 313/231

[51] **Int. Cl.²**.. **F02P 23/00;** F02P 1/00; H01T 13/20

[58] **Field of Search** ...... 123/169 EL, 169 R, 148 E, 123/148 AC, 148 R, 148 C, 143 R, 143 A, 143 B, 191 S; 313/128, 139, 140, 141, 143, 231



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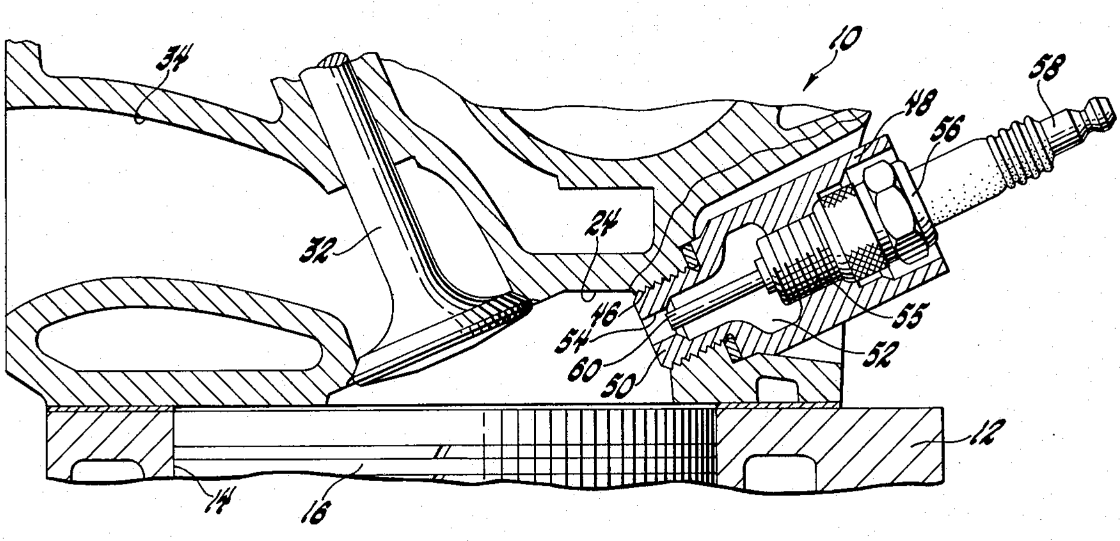
[57] **ABSTRACT**

A blind cavity precombustion chamber engine has a plasma jet ignition system including a spark plug for each cylinder having an extended electrode with its spark gap located in the turbulent gas zone between the center of the prechamber and the mouth of a restricted orifice connecting the cavity with the main combustion chamber. A high energy ignition system is included which causes a sustained high current arc at the spark gap that avoids arc blowout and is capable of ionizing and igniting very lean turbulent air-fuel mixtures. The sustained arc initiates and continues combustion in the prechamber, raising its pressure and expelling burning gases through the orifice into the main chamber. The arc may be maintained for a period sufficient to further ionize the gases as they move through the arc and into the main chamber to create a plasma torch or jet of burning products that ignites the lean mixture in the main chamber. In one embodiment, a higher level of energy is created in the combustion products being expelled from the blind chamber by discharging a high current across the spark gap at the time the burning gases are being expelled through the orifice, thus further ionizing the gases and creating a higher energy plasma of burning and burned gases that is expelled into the main chamber to ignite the mixture therein.

**4 Claims, 5 Drawing Figures**

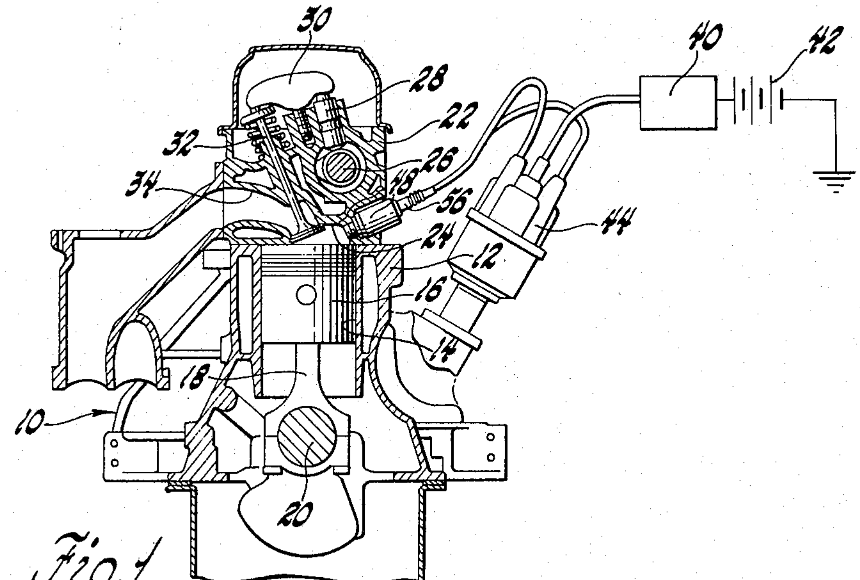



Fig. 1

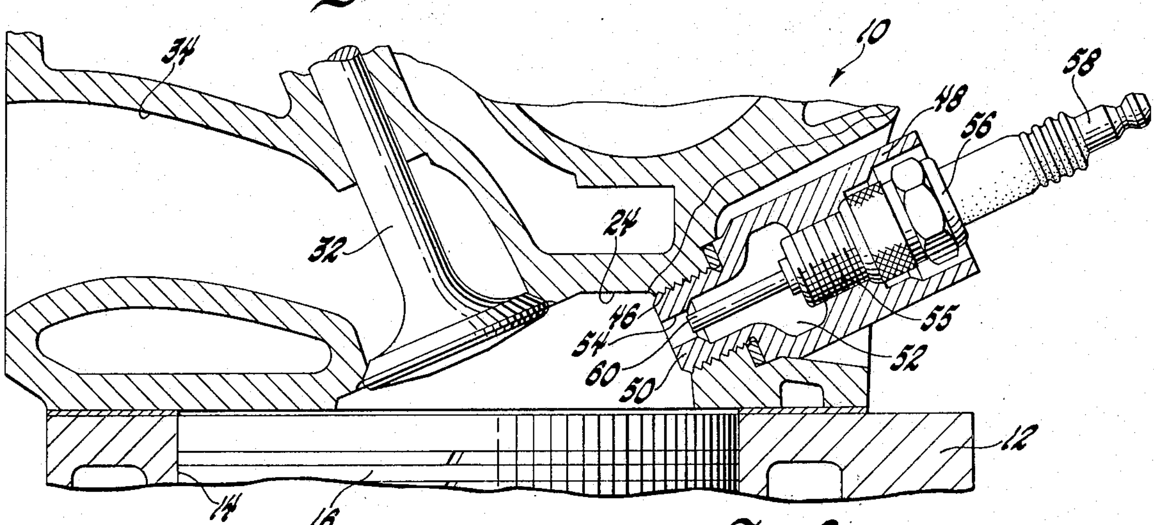



Fig. 2

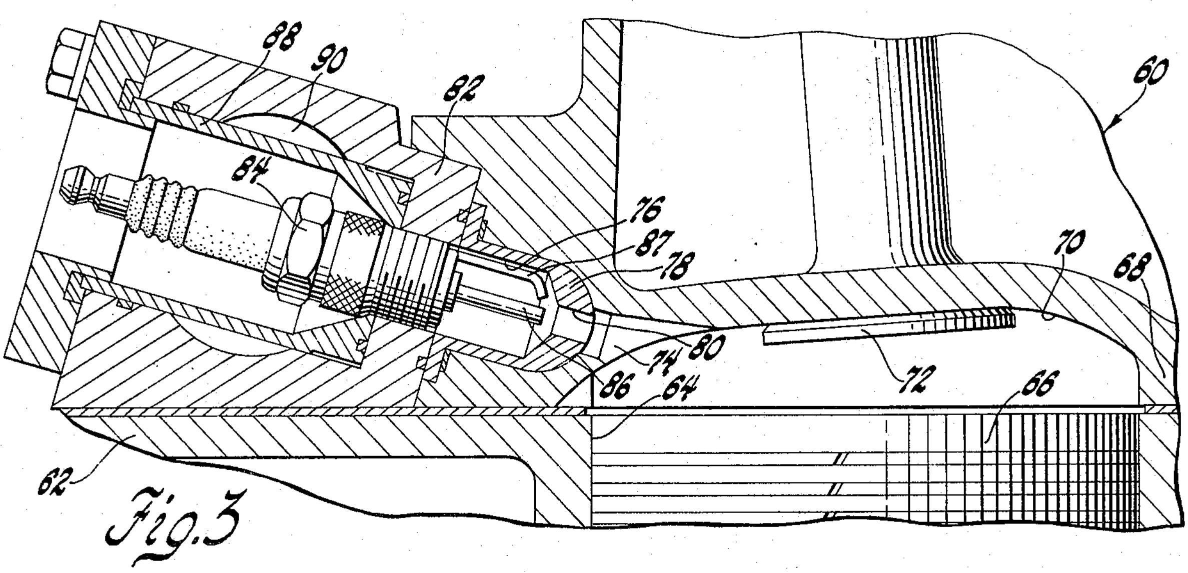



Fig. 3

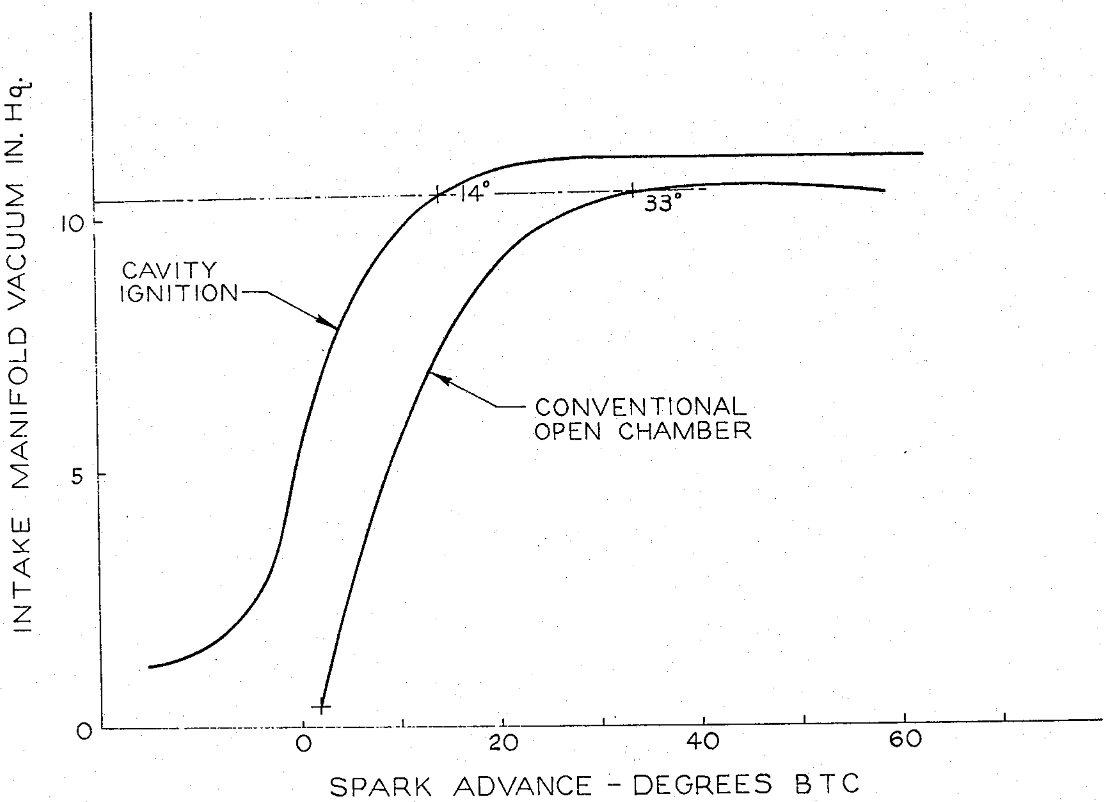

INTAKE MANIFOLD VACUUM IN. Hg.
10
5
0
-14°
33°
CAVITY IGNITION
CONVENTIONAL OPEN CHAMBER
0
20
40
60
SPARK ADVANCE - DEGREES BTC

Fig. 4

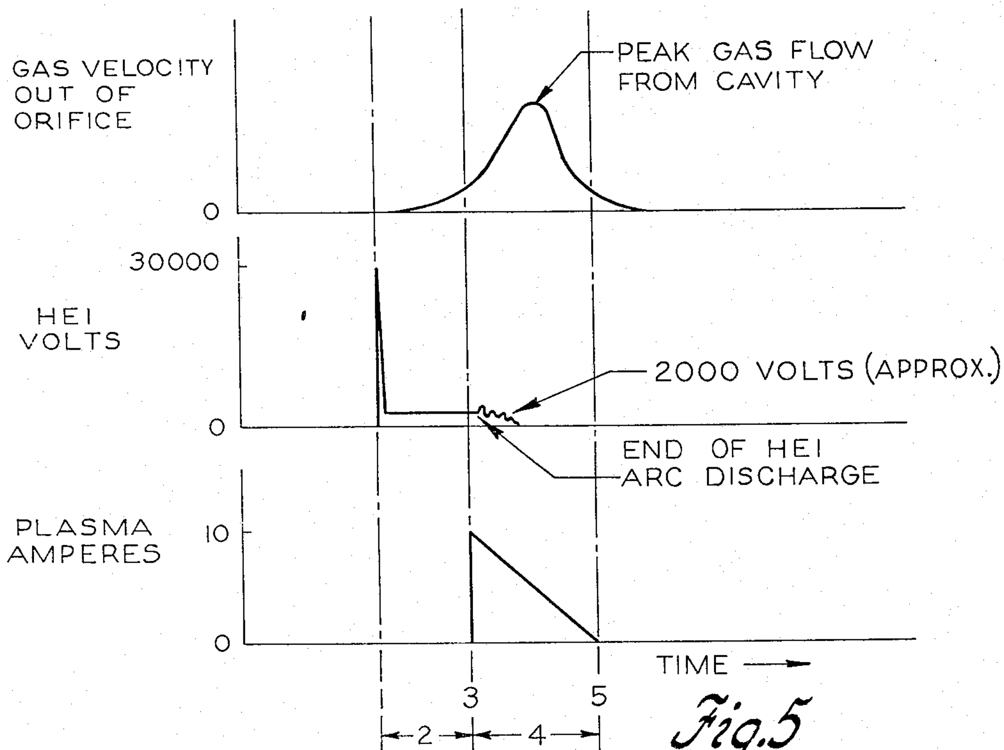

GAS VELOCITY OUT OF ORIFICE
0
PEAK GAS FLOW FROM CAVITY
30000
HEI VOLTS
0
2000 VOLTS (APPROX.)
END OF HEI ARC DISCHARGE
PLASMA AMPERES
10
0
TIME
3
5
2
4

Fig. 5

# PLASMA JET IGNITION ENGINE AND METHOD

## CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. Pat. application Ser. No. 439,352, filed Feb. 4, 1974, now abandoned, in the name of Floyd A. Wyczalek, and assigned to the assignee of this application.

## FIELD OF THE INVENTION

This invention relates to internal combustion engines and, more particularly, to engines of the type having blind cavity precombustion chambers connecting with the main combustion chambers and arranged for torch or jet ignition of fuel mixture in the main chambers. The invention also relates to methods for operation of such engines.

## BACKGROUND OF THE INVENTION

One of the aims of recent development work on internal combustion engines has been to develop engines capable for burning air-fuel mixtures substantially leaner than stoichiometric mixtures while retaining satisfactory fuel economy and drivability or smoothness of vehicles in which such engines are installed. This goal stems from a recognition that combustion of sufficiently lean mixtures may substantially reduce the creation of oxides of nitrogen in an engine while also aiding the burning of hydrocarbons and carbon monoxide in the combustion chambers or exhaust system.

Numerous engine design proposals have been made in the past for accomplishing similar purposes. These have included so-called torch or jet ignition stratified or segregated charge engines in which a small precombustion chamber is located adjacent the main combustion chamber and connected therewith by a restricted orifice. Generally, in such engines, the precombustion chamber is supplied with a rich air-fuel mixture through a separate intake valve or by direct fuel injection, while a lean air-fuel mixture is supplied to the main combustion chamber. The rich mixture in the prechamber is easily ignited by a conventional ignition system and spark plug or the like. The burning products are then expelled by combustion pressures into the main chamber causing a jet of flame which extends into the body of lean mixture with sufficient energy to ignite the lean mixture and propagate combustion therein.

Engines of this type are generally less desirable than conventional engines since they include additional components and add complexities to components which would otherwise be provided. Such added components and complexities have included, for example, special inlet valves and auxiliary conduits or passages to feed the precombustion chambers, a separate carburetor or auxiliary passage in the main carburetor to feed the auxiliary passages, and provisions for supplying substantial heat from the engine exhaust system to the auxiliary passages.

Blind cavity type precombustion chamber engines have also been previously proposed in which the jet ignition principle was utilized while the prechambers were supplied with homogeneous (non-stratified) air-fuel mixtures received from the main combustion chambers and of similar air-fuel ratios. However, tests of such engines using air-fuel mixtures substantially leaner than stoichiometric (18:1 or greater air-fuel ratios) indicated ignition systems of conventional construction and energy level were inadequate to dependably ignite and propagate flame combustion in the turbulent areas of the prechambers. Rather, repeated arc blowout and inconsistent combustion resulted when conventional ignition systems were applied to ignite lean mixtures from a spark gap in the turbulent zone of a prechamber between the orifice and the center of the prechamber, within the direct gas flow path.



## SUMMARY OF THE INVENTION

The present invention provides spark ignition engine arrangements which utilize blind cavity precombustion chambers connected with the main combustion chambers and having specifically located spark gaps and high energy ignition means which provide a capability of burning air-fuel mixtures substantially leaner than stoichiometric mixtures in both the precombustion and main combustion chambers. The invention further provides methods for the operation of such engines.

It is an object of the present invention to provide engines having simpler and more producible construction features than prechamber type stratified charge engines and operating methods for the combustion of lean air-fuel mixtures in such engines.

A further object of the invention is to provide an improved engine having high energy ignition means for dependably igniting and propagating flame combustion in lean air-fuel mixtures in a precombustion chamber cavity.

Another object of the invention is to provide for creation of a high energy arc of extended duration within the turbulent zone between the center of the prechamber cavity and the entrance to the orifice connecting it with the main combustion chamber so that a substantial volume of burning gases and air-fuel mixture passes through the arc during engine operation.

A still further object of the invention is to provide blind cavity precombustion chamber members and spark plugs having extended electrodes which can be applied to spark ignition engines of conventional configuration with little or no modification thereto.

The invention involves the application of a small precombustion chamber connected by a restricted orifice with each main combustion chamber of a spark ignition engine which may otherwise be of generally conventional configuration. The precombustion chamber may be formed as a part of the cylinder head or cylinder wall, or may be formed in a separate adapter arranged for installation in or in place of the usual spark plug opening. The adapter is designed to receive a special spark plug.

The precombustion chamber and orifice are subject to certain design parameters which should fall within the following specified ranges:

1. Volume of the cavity should equal between about 2 and 10 percent of the total clearance volume of the cylinder at the piston's top dead center position. A preferred size appears to be about 3 percent.

2. The relationship of the volume of the cavity to the area of the orifice connecting it with the main chamber should range between 5 to 15 cubic inches of cavity volume for each square inch of orifice area.

3. The ratio of the length of the orifice to its diameter should be between 0.2 and 2.0.

The special spark plug preferably has a long electrode forming a spark gap within the prechamber cavity and located between its center and the inner end of the orifice connecting the prechamber with the main chamber. This places the point of ignition of the charge in the path of the turbulent charge of fresh mixture forced into the cavity on the compression stroke and away from the relatively quiescent residual gases along its sides and back. The spark gap is preferably located near the inner end of the orifice where there is a maximum flow of gases passing between the main and precombustion chambers. This position is believed to obtain the best combustion results, while moving the arc toward the center of the blind cavity reduces electrode temperatures and improves durability.

To provide for dependable ignition of the lean mixtures with which the engine is intended to operate, the invention further includes a high energy ignition system having a minimum arc energy level of about 50 millijoules. This system provides very high initial voltages up to 30,000 volts for the initial spark which acts to pre-ionize or break down the resistance of the spark gap, forming a conductive path across it and igniting the combustible mixture. The arc is then maintained for a minimum of 0.5 milliseconds by a continued voltage application of up to 2,000 volts with a peak current capability of 150 milliamps or more, thus extending the charge ignition process over a portion of the engine cycle during which mixture is first passed into the ignition cavity and subsequently begins to be forced out of it. The motion of the gas through the orifice and past the spark gap causes the high energy arc to contact a substantial portion of the mixture so as to aid in propagating flame combustion throughout the prechamber cavity even in the turbulent portion of the chamber and with relatively lean air-fuel mixture ratios of 19 to 1 or more. The high energy level of the arc prevents the turbulent gas flow past the spark gap from extinguishing the arc before positive flame propagation is achieved.

In one embodiment, the ignition system additionally includes a high capacity current coil capable of passing a high current across the arc path developed by the high voltage system. Such current may reach a maximum of 5 to 15 amperes and is dumped across the pre-ionized arc gap at the end of the extended arc period and over a further period of up to 1 or 2 milliseconds to create a higher energy plasma jet as will be subsequently described.

Methods of burning lean mixtures in engines according to the invention involve the steps of:

1. Providing a preferably homogeneous lean mixture to the main combustion chamber.

2. Compressing the mixture in the main chamber, thereby forcing a portion of the mixture into the precombustion chamber cavity through the orifice and into contact with the spark gap.

3. Igniting the mixture near the end of the compression stroke by a high energy voltage discharge on the order of 50 millijoules generating a peak current of 150 milliamps or more across a spark gap between the prechamber orifice and the center of the prechamber to ignite and ionize the lean mixture as it passes by the spark gap and thereby promoting propagation of flame combustion within the prechamber.

4. Combustion within the prechamber causes expansion of the gases, forcing burning mixture through the orifice into the main chamber and creating a flaming jet which ignites lean mixture in the main chamber. Mixtures of at least 19 to 1 air-fuel ratio may be successfully burned by this method.

5. The energy of the jet flame may be increased by the additional step of discharging a high current up to about 10 amperes across the spark gap during the period when the burning gases are being forced out through the orifice into the main chamber.

The high flow of current further ionizes the burned and burning gases, creating a higher energy plasma which is forced by the gas flow out into the main chamber. The flaming jet thus becomes a high energy plasma torch having not only the energy provided by the burning gases, but in addition, that added by the electrical ionization process caused by the high current flow. In this way substantially leaner mixtures of about 23 to 1 air-fuel ratio may be ignited by the burning plasma jet.

The foregoing and other objects and advantages of the invention will be more fully understood from the following description of certain specific embodiments and methods of operating the invention taken together with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings,

FIG. **1** is a transverse cross sectional view of a spark ignition internal combustion engine including prechamber and ignition means according to the invention;

FIG. **2** is an enlarged view of a portion of the engine of FIG. **1** showing the configuration of the main and auxiliary or precombustion chambers and the associated spark plug for one cylinder;

FIG. **3** is a view similar to FIG. **2** but showing another embodiment of engine combustion chamber and ignition means;

FIG. **4** graphically compares data from tests of an engine according to the invention with one having a conventional combustion chamber configuration; and

FIG. **5** is a time plot illustrating the relationship of orifice gas flow to ignition system operation for one embodiment of the invention.

## DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

Referring first to FIG. **1** of the drawings, there is shown an internal combustion engine generally indicated by numeral 10. Except for the ignition and precombustion chamber arrangements to be subsequently described, the illustrated engine is a production 1.9 liter, four cylinder, spark ignition, cam-in-head type.

Conventional parts of the engine include a cylinder block **12** having a plurality of cylinders **14** each having a piston **16** reciprocably disposed therein. Each piston is connected by a connecting rod **18** to a crankshaft **20** supported in the cylinder block in conventional manner. The upper ends of the cylinders **14** are closed by a cylinder head **22.** Combustion chambers **24** are defined by wedge shaped recesses in the cylinder head and by the upper ends of the respective cylinders **14** and pistons **16.**

The cylinder head also carries a camshaft **26** rotatably driven by the crankshaft through means, not shown, and engaging a plurality of cam followers **28.** Rocker arms **30** are actuated by the cam followers and each in turn engages one of a plurality of inlet and exhaust valves **32** reciprocably mounted in the head. The valves control associated inlet and exhaust ports **34** connecting with each of the combustion chambers **24** to control the admission of air-fuel mixtures to the combustion chambers and the exhaust of burned gases therefrom in conventional fashion. The engine operates on a conventional four-stroke cycle including intake, compression, and exhaust strokes with combustion taking place during a period beginning near the end of the compression stroke and extending partially into the expansion stroke.

A high-energy ignition system is applied to the engine which may, for example, be of the type disclosed in the co-pending application for U.S. Pat. Ser. No. 401,505, filed Sept. 27, 1973 by M. E. Preiser, R. W. Johnston, and J. G. Neuman and assigned to assignee of the present invention. The ignition system includes electronic circuitry **40** of the type disclosed in the abovementioned application powered by the usual battery **42** and connected with an engine driven distributor **44.**

Alternatively, the engine can be operated using a known type of electronic ignition system similar to but of higher energy output than those now in commercial use on some automobiles and disclosed in U.S. Pat. No. 3,838,672 Richards et al assigned to the assignee of this invention. This type of system has the advantage of commercial availability of components; however, its energy level and peak arc current of about 150 milliamps give only limited plasma energy to the prechamber gases and accordingly would not be expected to give satisfactory engine operation over the extended range of operating conditions possible with the higher energy ignition system first mentioned.

As shown in FIG. **2,** each combustion chamber **24** has a threaded opening **46** through the cylinder head at the thick end of the wedge shaped recess and generally centered in the combustion chamber which, in production engines, is adapted to receive a conventional spark plug. The present invention, however, provides a tubular adapter **48** having a reduced diameter threaded portion **50** at one end which is received within the threaded opening **46.** Adapter **48** defines a mushroom shaped auxiliary combustion chamber or blind cavity prechamber **52** having a reduced diameter extending into the threaded portion **50** and connecting with a restricted orifice **54** that connects prechamber **52** with the main combustion chamber **24.**

At the other end from the orifice **54,** adapter **48** includes an internally threaded portion **55** in which there is received a special spark plug **56.** Plug **56** has an electrical connection portion **58** extending outwardly of the adapter and a long central electrode **60** extending across the precombustion chamber to a point within the end of the orifice **54** immediately adjacent the prechamber **52.**

The engine of FIGS. **1** and **2** includes four cylinders, each having displacement of 28.95 cubic inches and a compression ratio of 7.4. The design parameters for the blind precombustion chamber cavity of each cylinder include volume equal to 3.6% of the top dead center clearance volume of its cylinder; a ratio of 7.5 cubic inches of prechamber volume per square inch of orifice area; and a ratio of 1.0 for the length of the orifice with respect to its diameter. It is noted that these parameters are within the preferred ranges previously noted.

In operation the blind cavity precombustion chamber **52** is charged with fresh air-fuel mixture from the main chamber **24** during the compression stroke of each cycle. The mixture is ignited before the piston reaches top dead center by a high energy arc having an energy level of 50 millijoules or more and a minimum peak current on the order of 150 milliamps passing between the



spark plug electrode **60** and the inner edge of the orifice **54** and caused by operation of the high energy ignition system. The specified energy level and peak current have been found to represent a practical minimum for minimizing arc blowout and consequent erratic combustion when the spark gap is located in the turbulent zone between the orifice and the center of the prechamber. The arc is continued for a minimum time interval of about 0.5 milliseconds to assure ignition and flame propagation in the lean turbulent air-fuel mixture which, during this time, burns toward the far end of the precombustion chamber and expands, expelling a jet of burning products through the orifice **54** into the main combustion chamber. The energy in the jet is increased by ionization of burned and burning gases passed through the electric arc upon entrance into and expulsion from the cavity, and this effect is increased by the use of higher energy ignition systems with greater peak current capability and extended arc periods.

The energy of the hot jet extending across the main combustion chamber is about 1 joule or 25 times a conventional spark. It permits successful burning of lean mixtures up to about 20 to 1 air-fuel ratio and substantially increases the rate of combustion of these mixtures. This is indicated by FIG. **4** which shows comparative curves of spark advance versus intake manifold vacuum for conventional and cavity ignition arrangements or otherwise comparable engines. These results were obtained at constant operating conditions of 2,000 RPM engine speed, 32.5 ft.-lbs. of torque output and 19:1 air-fuel ratio. A comparable high energy ignition system was used in both instances so the comparison indicates the effect of adding the cavity only. The curves show that at intake manifold vacuum of **11** inches of mercury for example, which indicates constant throttle opening and fuel rate, the spark advance of 33° for the conventional arrangement compares with only 14° for cavity ignition under the given conditions.

Further test results are given in Table I which presents a comparison of the optimum spark advance settings at various speeds and comparative steady state hydrocarbon and oxides of nitrogen emissions for an engine having the conventional production type spark plug and a high energy ignition system (conventional ignition) as compared to a high energy cavity ignition system (cavity ignition), according to the present invention. The comparison shows that the optimum spark advance for cavity ignition according to this invention is less than half that required for the conventional system at normal road loads and speeds, thus indicating the substantial increase in the rate of combustion by cavity ignition.

Table I

COMPARISON OF OPTIMUM SPARK ADVANCE*
AND STEADY STATE EMISSIONS
FOR VARIOUS ROAD LOAD SPEEDS
AT 18.5 AFR

| | Conventional Ignition | | | Cavity Ignition | | |
|---|---|---|---|---|---|---|
| Speed MPH | 25 | 40 | 60 | 25 | 40 | 60 |
| Optimum Spark Deg | 27° | 32° | 40° | 13° | 14° | 15° |
| HC gm per mile | 0.87 | 0.56 | 0.35 | 0.62 | 0.51 | 0.18 |
| $NO_x$ gm per mile | 0.88 | 1.32 | 4.2 | 0.40 | 1.12 | 2.10 |

*3% Power Loss Spark Setting

Table II

| TYPICAL COLD START 1975 FTP EMISSIONS | | | | | | | |
|---|---|---|---|---|---|---|---|
| VEHICLE OPERTATED IN THREE MODES: I CAVITY IGNITION WITH OPTIMUM SPARK AND AFR; II PRODUCTION IGNITION WITH ECONOMY EQUAL TO CAVITY IGNITION; III PRODUCTION IGNITION WITH SPARK EQUAL TO CAVITY IGNITION | | | | | | | |
| Mode | System | AFR | HC | CO | $NO_x$ | MPG | SA |
| I | Cavity Ignition | 19.5 | 1.2 | 6.4 | 1.8 | 18.3 | 15° |
| II | Production Ignition | 19.5 | 1.3 | 5.3 | 2.7 | 18.4 | 30° |
| III | Production Ignition | 19.5 | 0.9 | 6.7 | 1.8 | 15.3 | 15° |

Table II indicates the results of some comparative emissions tests of conventional type and cavity type spark ignition engines, both with high energy ignition, in a vehicle with a 3,000 pound inertia dynamometer setting. Three modes were tested which are described as follows:

Mode I — Blind cavity with high energy arc restrike ignition, optimum mixture preparation, lean carburetion, and optimum spark. Emission data shown is comparable to average of 10 repeat tests.

Mode II — Same as Mode I except production spark plug replaced blind cavity assembly and spark were advanced to match the fuel economy of Mode I.

Mode III — Identical to Mode I except production spark plug replaced blind cavity assembly.

Table II shows, for example, cold start emissions for the engine with cavity ignition, an air-fuel ratio of 19.5:1 and spark advance of 15° BTC to be: hydrocarbons (HC) — 1.2 grams per mile, carbon monoxide (CO) — 6.4 grams per mile, and nitrogen oxides ($NO_x$) — 1.8 grams per mile, all with a measured fuel economy of 18.3 miles per gallon operating on the Federal test procedure. Drivability of the vehicle equipped with cavity ignition and operating at 19.5 air-fuel ratio was considered acceptable and it was capable of following the 1975 Federal schedule for emission tests. This table shows the blind cavity ignition tested has the following benefits over the tested conventional ignition:

1. At the same spark advance of 15° the cavity ignition engine shows a gain in fuel economy from 15.3 MPG to 18.3 MPG.

2. At spark advances for equal economy, the cavity ignition engine shows a reduction in $NO_x$ emissions from 2.7 to 1.8 grams per mile.

FIG. **3** of the drawings shows application of a cavity ignition arrangement according to the present invention to an alternative engine embodiment, generally indicated by numeral **60.** Engine **60** includes a cylinder block **62** with cylinders **64** and pistons **66,** with the ends of the cylinders being closed by a cylinder head **68** forming a dome shaped combustion chamber **70.** Inlet and outlet valves **72** control adjoining inlet and outlet ports, not shown, disposed near the center of the combustion chamber.

An opening **74** at one side of each combustion chamber **70** connects with an auxiliary combustion chamber or blind cavity prechamber **76** formed within an insert **78** and having a restricted orifice **80** separating the prechamber **76** from the main combustion chamber **70.** Insert **78** is held in place within the cylinder head by a separate adapter **82** which extends the length of the head and receives a plurality of spark plugs **84,** one for each cylinder.

Each spark plug has a long centeral electrode **86** and a body mounted anode **87** extending through the associated prechamber **76** to form a spark gap at a point between the center of the prechamber and the orifice but preferably near the end of the orifice **80** adjacent to the prechamber. A spark gap at the orifice is best located to increase jet energy by ionizing gases passing cut through the orifice. However, electrode temperatures are reduced and durability increased by moving the gap away from the orifice toward the center of the cavity. At this location, the plasma effect is reduced but is still significant. If desired, the spark gap may be formed between the electrode **86** and the edge of the orifice **80** as in the previously described embodiment. Cylindrical shield elements **88** are sealingly retained around each spark plug and define, with the adapter **82,** surrounding passages **90** through which engine coolant may flow for cooling the metal surrounding the bodies of the spark plugs **84.**

The operation of the embodiment of FIG. **3** is essentially the same as that indicated for the first described embodiment.

An alternative form of ignition system for use with the cavity ignition arrangement of the present invention may be of the type disclosed in U.S. pat. application Ser. No. 487,238 Neuman, filed July 10, 1974 and assigned to the assignee of the present invention. This system includes a coil of high current capacity incorporated into a high energy system of the type first mentioned. The alternative system causes a surge of high current peaking between about 5 to 15 amperes and preferably about 10 amperes to be dumped across the spark gap at a predetermined interval after striking of the arc, at a time when a substantial gas flow out of the prechamber orifice has been established by combustion in the prechamber. This causes burned and burning products jetting through the orifice into the main chamber to be further ionized to a higher energy plasma resulting in a plasma jet of ionized products being forced into the main chamber. This highly active jet has an energy of about 2 joules or 50 times a conventional electric spark. It quickly ignites and causes rapid burning of lean mixtures in the main combustion chamber and is particularly suitable for carrying out the purposes of the invention as previously described.

FIG. **5** illustrates the relative timing of some of the steps in the ignition processes described herein. Before reaching point **1,** the engine cylinder has been charged with a suitable lean air-fuel mixture which has been compressed into the main and auxiliary combustion chamber cavities. At point **1** the high energy ignition system applies up to about 30,000 volts across the spark gap, causing a high energy arc which provides an ionized path for current flow. The arc is continued by extended application of a lower voltage in the neighborhood of about 2,000 volts and is effective to ignite the lean mixture in the area, as well as additional mixture which moves through the arc due to gas movement through the orifice. This occurs during interval **2** which may extend for 0.5 to 2 milliseconds.

If the arc is continued at the same level of energy for an extended period without further change, the system operates as a plasma jet ignition system as originally described in conjunction with the engine arrangement of FIGS. **1** and **2**. FIG. **5**, however, illustrates the application of further measures causing operation as a higher energy plasma jet ignition system. Thus, at point **3** a high current, peaking in this instance at 10 amperes, is dumped across the previously ionized spark gap. This current is maintained at a high level for about 1 or 2 milliseconds, extending through the period when the peak gas flow passes from the prechamber cavity to the main combustion chamber as a result of combustion of the mixture in the prchamber. This occurs during interval **4**. The high current flow causes formation of an electrically ionized gas plasma which is expelled into the main chamber in the manner previously described, and results in a high energy plasma jet for ignition of the main chamber charge. At point **5**, the electrical portion of the ignition process is complete, and combustion in the main chamber is in process.

The disclosure of certain specific features and the manner of operation of certain preferred embodiments of the present invention is for purposes of explanation only and is not intended to limit the use of other forms or modifications of the invention, many of which will be obvious to those skilled in the art from the present disclosure. Accordingly, the invention is intended to be limited only by the language of the following claims:

What is claimed is:

**1.** The combination in an internal combustion engine of

main combustion chamber defining means including a closed chamber and a member movable therein to vary the volume of said chamber, said movable member being connected with an output shaft for delivery of power thereto,

means for cyclically admitting to said combustion chamber combustible air-fuel mixtures having controlled air-fuel ratios substantially leaner than stoichiometric,

means for cyclically discharging burned gases from said combustion chamber, and

plasma jet ignition means including

a closed auxiliary chamber adjacent said main chamber and connected therewith by a restricted orifice at least when the main chamber is near its smallest volume,

spark ignition means mounted in a wall of said auxiliary chamber and having an electrode extending therein and forming a spark gap at a pont between the orifice and the center of the auxiliary chamber, said spark gap being in the flow path for highly turbulent gases being forced into or discharging from said auxiliary chamber through said restricted orifice, and

electrical ignition means connected with said spark ignition means and cyclically operable to cause an arc at said spark gap having a minimum energy level on the order of 50 millijoules and a minimum peak current on the order of 150 milliamps to ignite and propagate flame combustion within the turbulent lean air-fuel mixtures in and adjacent to the spark gap in said auxiliary chamber.

**2.** The combination in an internal combustion engine of

main combustion chamber defining means including a closed chamber and a member moveable therein to vary the volume of said chamber, said movable member being connected with an output shaft for delivery of power thereto,

means for cyclically admitting to said combustion chamber combustible air-fuel mixtures having controlled air-fuel ratios substantially leaner than stoichiometric,

means for cyclically discharging burned gases from said combustion chamber, and

plasma jet ignition means including

a closed auxiliary chamber adjacent said main chamber and connected therewith by a restricted orifice at least when said main chamber is near its smallest volume,

spark ignition means mounted in a wall of said auxiliary chamber and having an electrode extending therein and forming a spark gap at a point between the orifice and the center of the auxiliary chamber, said spark gap being in the flow path for highly turbulent gases being forced into or discharging from said auxiliary chamber through said restricted orifice and into said main chamber, and

electrical ignition means connected with said spark ignition means and cyclically operable to cause a sustained high energy arc at said spark gap, said arc having sufficient energy to ignite and propagate flame combustion within the turbulent lean air-fuel mixtures in and adjacent the spark gap in said auxiliary chamber, said ignition means being further capable to discharge a high current of at least 5 amperes across said spark gap during the existance of said arc and coincidentally with the expulsion of burning gases from said auxiliary chamber due to combustion therein, whereby the burned and burning gases are ionized to a high energy plasma which is expelled into the main combustion chamber for ignition of the lean air-fuel mixture therein.

**3.** The method of operating an internal combustion engine of the type having a main combustion chamber connected by a restricted orifice with a small auxiliary combustion chamber having a spark gap between the center of the auxiliary chamber and the orifice and means for admitting a lean homogeneous air-fuel mixture into said main chamber and compressing said mixture into said main and auxiliary combustion chambers, said method comprising the steps of

providing a homogeneous lean air-fuel mixture to the main combustion chamber,

compressing said mixture in the main chamber whereby a portion thereof is forced through the orifice into the auxiliary combustion chamber moving with high turbulence past and around the spark gap, and

impressing a high voltage across the spark gap to break down the resistance of the gap and sufficient to create an arc across the gap having a minimum energy level on the order of 50 millijoules and a minimum peak current on the order of 150 milliamps to ignite the air-fuel mixture passing through and adjacent to the spark gap,

whereby flame combustion is propagated within the auxiliary chamber, causing expansion of the gases therein and forcing burning gases through the orifice to form a flame plasma jet in the main chamber, thereby igniting the lean mixture in the main combustion chamber.

**4.** The method of operating an internal combustion engine of the type having a main combustion chamber connected by a restricted orifice with a small auxiliary combustion chamber having a spark gap between the center of the auxiliary chamber and the orifice and means for admitting a lean homogeneous air-fuel mixture into said main chamber and compressing said mixture into said main and auxiliary combustion chambers, said method comprising the steps of

providing a homogeneous lean air-fuel mixture to the main combustion chamber,

compressing said mixture in the main chamber whereby a portion thereof is forced through the orifice into the auxiliary combustion chamber moving with high turbulence past and around the spark gap,

impressing a high voltage across the spark gap to break down the resistance of the gap and create an arc across the gap having a current and energy level sufficiently high to dependably ignite the air-fuel mixture passing through and acjacent to the orifice, whereby flame combustion is propagated within the auxiliary chamber, causing expansion of the gases therein and forcing burning gases through the orifice to form a flame torch in the main chamber, and

dumping a high current of between 5 and 15 amperes across the pre-ionized spark gap at a predetermined interval after the initiation of the arc, thereby further ionizing the burned and burning gases in the arc and forming a high energy plasma, said high current flow being timed to coincide with the expulsion of gases from the auxiliary chamber into the main chamber so that the high energy plasma is forced in torch like fashion into the main chamber increasing the energy of the flaming gases and resulting in ignition and burning of the lean air-fuel mixture in the main combustion chamber.

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UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 3,921,605

DATED : November 25, 1975

INVENTOR(S) : Floyd A. Wyczalek

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, line 54, after "combustion" insert --provide--.

Column 9, line 57, "pont" should read --point--.

Column 10, line 36, "capable" should read --operable--.

Signed and Sealed this

*second* Day of *March 1976*

[SEAL]

*Attest:*

**RUTH C. MASON**
*Attesting Officer*

**C. MARSHALL DANN**
*Commissioner of Patents and Trademarks*