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(54) **An ignition method, an ignition plug and an engine using an ignition plug**

(57) The invention relates to a method of igniting a spark in an electrical plug provided in a circuit and having a discharge gap for yielding a plurality of consecutive spatially distributed sparks per single ignition event, wherein the method comprises the steps of: applying a breakdown voltage pulses U to the discharge gap with a period of maximally 1 millisecond, said discharge voltage pulses having a leading edge; limiting conductivity current over the discharge gap to below of about 10 mA

during an interval corresponding to the said leading edge or ensuring that a conductivity current across the discharge gap is substantially zero during an interval of at least 5% of the said period. The invention further relates to an ignition system comprising a power generator connected to a spark plug using an optional transmission line, preferably comprising coaxial cable. The invention still further relates to an internal combustion engine and a vehicle.

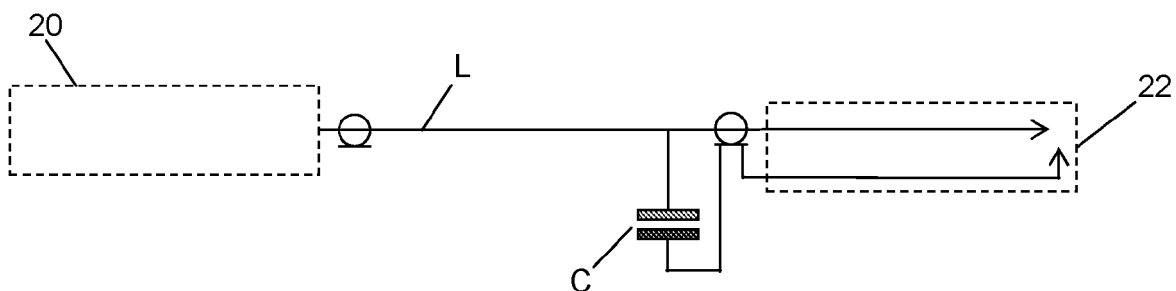


Fig. 5

Description

FIELD OF THE INVENTION

[0001] The invention relates to a method of igniting a spark.

[0002] The invention further relates to an ignition system comprising an electrical plug having a discharge gap, a voltage source adapted to apply a series of voltage pulses to the discharge gap.

[0003] The invention still further relates to an internal combustion engine.

[0004] The invention still further relates to a vehicle.

BACKGROUND OF THE INVENTION

[0005] An ignition spark is used to ignite a mixture, notably in an internal combustion engine, such as an engine of an automobile. A conventional ignition spark operates as follows: upon an application of a discharge voltage which is in excess of a breakdown voltage a spark develops between two electrodes of the ignition plug. The discharge voltage may be changing in time to allow three sequential types of discharge with substantially different energy and physical properties of the thus formed plasma.

[0006] First, a voltage at the plug may rise until it reaches the breakdown threshold, which may be followed by a breakdown, usually within less than about 10 microseconds. Then, the impedance of the discharge gap may fall drastically and the current may rise from about several hundred milliamperes up to a several hundred amperes within a few nanoseconds. The capacitance of the plug empties through the discharge gap of the plug. Peak current phase in the conventional systems takes less than 100 nanoseconds. The spark then transits into the arc phase in which the current is mainly determined by the output impedance of the pulsed power source and the transmission line. Often, it is limited by an optional resistance connected in series with the discharge gap.

[0007] At the cathode of the plug one or many hot spots may arise because of strong emission of electrons that may lead to vaporization of the cathode material and the cathode erosion as a consequence. This operational phase in the conventional ignition systems takes about 1 to 20 microseconds. At currents below 100 mA the discharge process may transit to a glow phase. Multiple transitions may occur between an arc and a glow discharge depending on changes and displacement of the mixture between the electrodes. In the conventional systems this phase may last up to several milliseconds.

[0008] It is a disadvantage of the known ignition system that that the energy supplied to the mixture is limited. The limitation occurs due to the fact that arc channel once formed possesses high conductivity, thus confining power dissipated in gas channel due to flowing current. Said limitation of conventional system restricts ignitibility of diluted mixtures, that are combustible mixtures with high

content of exhaust gas recirculated (EGR) or lean mixtures or a composition of lean mixture and EGR.

[0009] It is a further disadvantage of the known ignition system that the electrode erosion may be quite substantial deteriorating the operational characteristics of the plug and possibly leading to a malfunction of a plug-based apparatus.

SUMMARY OF THE INVENTION

[0010] It is an object of the invention to provide a method of igniting a spatially distributed spark in a spark plug, wherein ignition of a mixture in the discharge gap of the plug has an increased efficiency and the range of ignitability is extended towards diluted and/or lean mixtures.

[0011] It is a further object of the invention to provide a method of igniting a spark in a plug wherein electrode erosion is substantially reduced.

[0012] In addition, it is a further objective of the invention to provide a method to power a spark plug capable to deliver more energy to a mixture in a discharge gap than conventional methods.

[0013] To this end the method, according to the invention, for igniting a spark in an electrical plug provided in a circuit and having a discharge gap for yielding a plurality of consecutive spatially distributed sparks per single ignition event, wherein the method comprises the steps of:

- applying discharge voltage pulses U to the discharge gap with a period of maximally 1 millisecond, said discharge voltage pulses having leading edge and an amplitude sufficient to cause breakdown;
- limiting a conductivity current across the discharge gap to maximum of about 10 mA during an interval corresponding to the said leading edge or
- ensuring that a conductivity current across the discharge gap is substantially zero during an interval of at least 5% of the said period.

[0014] The technical measure of the invention is based on the following insights.

[0015] It is found that an energy portion inputted by a voltage pulse into a gas phase, a maximum temperature in the discharge channel and a total energy for a conventional ignition system may be about:

breakdown - energy share about 94%, temperature about 60 000 C, 1 mJ;

arc - energy share about 50%, temperature about 6 000 C, 1 mJ;

glow - energy share about 30%, temperature about 3 000 C, 30 mJ; as stated, for example, in Internal Combustion Engine Handbook, Richard van Basshuysen and Fred Schäfer, SAE International, 2004, ISBN 0-7680-1139-6, pages 417-421.

[0016] Accordingly, the breakdown phase has the greatest ignition efficiency and causes faster energy con-

version in the initial phase of the combustion process. By enlarging the volume and/or duration of the spark it is possible to improve reliability of the ignition process as well as to extend the range of ignition towards more diluted and/or leaner mixtures. Partially, this may be explained by inhomogeneities of air-fuel mixture composition thus aiming at large spark volume and/or extended discharge time leads to better chances of spark affecting mixture having best air-fuel ratio available. See, for example, J. Warnatz, U. Maas, R. W. Dibble, Combustion, 4th ed., Springer, 2006, ISBN 978-3540677512.

[0017] One of the known methods uses multiple sparks within one event of ignition. The multiple sparks method is capable to provide several breakdowns of the discharge gap and thus may lead to substantially increased ignition efficiency. In order to create several consecutive sparks per ignition event one can break and close a primary circuit, for example using a current switch introduced into the primary circuit of ignition coil. A secondary circuit may be connected to a spark plug. An open/closed condition of the switch may be controlled with suitable threshold levels for the electrical current flowing through the secondary circuit. It is appreciated that consecutive discharge channels in the known multiple-spark device repeat the trajectory of previous channels or are stochastically distributed in discharge gap. They typically create a localized spark in contrast to spatially distributed spark in accordance with the current invention.

[0018] It is found that using the method of the invention a broader range of stoichiometric ratios may be used for the ignitable medium to run, for example, an internal combustion engine or a gas turbine. In addition, it is found that with the method of the invention higher energies may be injected per ignition event with less electrode wear. Still in particular, the method according to the invention is found to substantially reduce fouling of the plug.

[0019] It will be understood that in the context of the present invention the term 'discharge voltage' will be interpreted as a voltage in excess of the breakdown voltage of the plug under consideration. It will be understood that in the context of the present invention the term 'leading edge' will be interpreted as a rising edge of the voltage pulse prior to the breakdown voltage, and correspond, for example, to 10% to 90% of breakdown voltage rise. Those skilled in the art would readily appreciate that the breakdown voltage is a pre-determined parameter for any particular plug operable with a known mixture composition, density, temperature, etc.

[0020] It will be further appreciated that the term 'spatially distributed spark' or 'travelling spark' will be interpreted as a sequence of adjacent sparks across a discharge gap, wherein individual paths of the sparks substantially do not overlap and that the individual sparks are sequential in time.

[0021] It is found that with the method of the invention it is possible to generate a plurality of adjacent flame kernels formed by independent sparks. The spatially distributed sparks according to the invention excite the me-

dium multiple times during a single ignition event. It will be appreciated that the ignition event may correspond to a burst of discharge voltage pulses. This feature advantageously increases ignition reliability and extends ignition limits towards leaner and/or more diluted mixtures.

[0022] It is further found that the method of the invention is capable to generate the spatially distributed sparks across the discharge gap within a relatively small time so that a relatively large volume is filled with plasma during one ignition event, while shortening arc and glow phases duration as compared to conventional systems; said phases eroding electrodes faster than the breakdown or spark phase. This feature advantageously reduces electrode wear.

[0023] It will be further appreciated that the method of the invention may be practiced on various types of the plugs having different geometry; it is preferable to use a plug wherein at least one electrode is extended. It will be appreciated that the term 'extended electrode' relates to an electrode having an extended surface area.

[0024] It will be further appreciated that although the invention may be explained with reference to the internal combustion engine, the method of igniting the travelling spark as recited in the appended claims may be applicable to other areas. For example, the method as is recited in claim 1 may be applied in the field of turbines.

[0025] The ignition system according to the invention comprises an electrical plug having a discharge gap provided in an electrical circuit, a voltage source adapted to apply a series of discharge voltage pulses U to the discharge gap, wherein the application of the discharge voltage pulses U results in a generation of a plurality of spatially distributed adjacent sparks across the discharge gap for a single ignition event.

[0026] A suitable spark plug for practicing the invention may comprise two or more electrodes partially separated by a heat resistant and electrically insulating material, preferably ceramic, or ceramic-like. The plug may be part of a suitable transmission line connecting the spark plug to an output of a voltage pulse generator. Optionally, the plug may be shunted by a capacitor. The voltage pulse generator may be a solid-state pulser based on electronic switches and/or flyback transformer, arranged to provide voltage pulses to the transmission line. However, the generator may be connected to the spark plug directly.

[0027] Such ignition system may be used in an automotive industry. It will be appreciated that the ignition system may form a part of an engine. It will be further appreciated that the engine may comprise a plurality of cylinders, wherein at least one cylinder may be provided with a plug being energized in accordance to the method of the invention for producing the travelling spark.

[0028] Alternatively, the ignition system may be used in an energy production device, for example for lean flame stabilization, launch/relaunch of a turbine, boiler acoustic noise control. Still alternatively, the discharge device according to the invention may be used in a clean powder production, for example in processes of powder

production from a gas phase.

[0029] In an embodiment of the ignition system, the discharge voltage pulses have a period and the electrical circuit is adapted to ensure that a conductivity current across the discharge gap is substantially absent during an interval of at least 5% of the said period or that the conductivity current across the discharge gap does not exceed 10 mA during an interval corresponding to a leading edge of the discharge voltage.

[0030] It is found advantageous to generate the burst of the discharge voltage pulses with a period of about 1 microsecond - 1 millisecond. Accordingly, the electric circuit of the ignition system of the invention is adapted to ensure that the conductivity current across the discharge gap is substantially absent at least during 0.05 microsecond - 0.05 millisecond. Those skilled in the art would readily appreciate which measures have to be undertaken for a known spark plug and a known voltage pulse generator. Alternatively, the same effect may be reached when the conductivity current across the discharge gap does not exceed 10 mA during an interval corresponding to the leading edge of the discharge voltage. In a still further embodiment of the ignition system according to the invention the electrical circuit comprises a coaxial cable at least on a path connecting the voltage source and the plug. An exemplary embodiment of a pulse shape of the discharge voltage pulse will be discussed with reference to Figures 3-4.

[0031] In a still further embodiment of the ignition system according to the invention the plug comprises a dielectric material having a dielectric strength of at least 1 kV. An embodiment of the plug will be discussed in more detail with reference to Figure 1.

[0032] In a still further embodiment of the ignition system according to the invention the coaxial cable has impedance in the range of 10 - 300 Ohm. Preferably, the power source is a solid-state switch device.

[0033] In a still further embodiment of the ignition system according to the invention the electrical circuit further comprises a capacitance connected in parallel with respect to the plug, said capacitance having a value of less than 3 nF. This feature is found to be advantageous for reducing secondary post-breakdown currents in the electrical circuit connecting the voltage source and the plug. Alternatively, the electrical circuit may comprise a capacitance that temporarily shunts voltage source after discharge in the discharge gap occurs: closing the circuit with said capacitance and said voltage/current source shortly after breakdown of the discharge gap to direct power off the arc channel in order to subsequently dissipate the power in reactive elements, and breaking the circuit connecting said capacitance to said generator prior to charging the spark plug to breakdown voltage in order to save energy per spark. An embodiment of the ignition system will be discussed in more detail with reference to Figure 5.

[0034] In a still further embodiment of the ignition system according to the invention the discharge gap has a

variable thickness and/or is partially covered by an insulator.

[0035] It is found that even for non-regularly shaped discharge gaps the method of the invention is capable of generating spatially distributed sparks. Preferably, the variable thickness may be ranging up to 2 times of the shortest distance between the electrodes forming the discharge gap and not covered by insulator for meeting the working conditions for generation of the spatially distributed sparks.

[0036] In a still further embodiment of the ignition system according to the invention the plug is additionally energized using a burst of discharge voltage pulses either in advance of a desired ignition event or post the ignition. An embodiment of the ignition system will be discussed in more detail with reference to Figure 6.

[0037] It is found to be particularly advantageous to allow a pre-treatment of the discharge gap with a series of voltage pulses prior to actual ignition event. Such voltage pulses may advantageously pre-treat the mixture in the discharge gap, for example by converting a small part of a mixture containing hydrocarbons and air into peroxides, aldehydes, ketones, alcohols as well as H₂, CO, CH₄, etc. Those skilled in the art will readily appreciate that CO and CH₄ will comprise products of partial oxidation of ultra-lean hydrocarbon-air mixtures that may be initiated by a plurality of distributed sparks. Thus, the ignition delay, the flame propagation velocity, etc. may be suitably tuned.

[0038] An application of a burst of voltage pulses in advance or post of a mixture ignition event may also remove fouling film if occurred and might be advantageous for cold engine start or rich combustion conditions. It will be appreciated that these examples are not limitative.

[0039] It is found advantageous to apply a burst of discharge voltage pulses after an ignition event (post-treatment) in order to discover knocking. Travelling spark breakdown voltage is substantially constant for fixed density, temperature and mixture composition in the discharge gap. Shortly after ignition, the products of combustion surround spark plug gap, thus composition is fixed while temperature and pressure continue to change gradually in case of a knock-free combustion. If knocking occurred, highpressure waves propagate inside combustion chamber thus alternating breakdown voltage stochastically, which can be monitored for repetitive pulses applied to the discharge gap of said plug causing a travelling spark.

[0040] The internal combustion engine according to the invention comprises the ignition system as is set forth in the foregoing. Preferably, the internal combustion engine comprises a plurality of cylinders, wherein the application of the discharge voltage pulses is synchronized with a compression phase within at least one of the said cylinders.

[0041] It is found advantageous for a cylinder to comprise several spark plugs according to the invention to provide ignition in several points. For example, for the

conditions with slow flame propagation in lean and/or diluted mixtures.

[0042] The vehicle according to the invention comprises the engine as is set forth in the foregoing.

[0043] These and other aspects of the invention will be discussed in more detail with reference to the figures. It will be appreciated that the figures are illustrative, not limiting.

BRIEF DESCRIPTION

[0044]

Figure 1 presents a schematic view of an embodiment of a spark plug for practicing the invention.

Figure 2 presents pictures corresponding to top and side view of a plurality of distributed sparks formed over spark plug as in Figure 1 and obtained with the method of the invention.

Figure 3 presents in a schematic way an embodiment of a suitable voltage shape according to an aspect of the invention.

Figure 4 presents oscillograms of current through a plug (top curve) and voltage over discharge gap of the plug (bottom curve) obtained when practicing the embodiment of the invention.

Figure 5 presents in a schematic way an embodiment of an ignition system according to the invention.

Figure 6 presents in a schematic way an embodiment of voltage bursts according to a further aspect of the invention.

Figure 7 presents pressure profiles inside of a cylinder of an IC engine obtained using conventional ignition system and ignition system based on the invention for identical engine load and revolution rate.

Figure 8 presents pressure profiles in the cylinder of an engine operating in uniform lean-burn regime using ignition system based on the invention for identical engine load and revolution rate for air excess factor λ in the range 1.0 - 4.5.

Figure 9 presents nitric oxide concentration in exhaust reduction and exhaust temperature decrease for an engine operating in a uniform lean-burn regime using ignition system based on the invention for air excess factor λ in the range 1.0 - 6.0.

DETAILED DESCRIPTION

[0045] Figure 1 presents a schematic view of an embodiment of a spark plug for practicing the invention. Although it will be appreciated that any geometry of a spark plug may be used an embodiment of a suitable spark plug will be explained using a cylindrically symmetrical plug. It will be appreciated that, alternatively, the gap may have a variable dimension or may be partially covered by an insulator.

[0046] A cylindrically symmetrical spark plug suitable for practicing the invention comprises an outer shell of

the main axis A formed in a first conducting material 4, with one end facing a combustion chamber preferably having a circular cross-sectional surface. An electrical insulator 2 is provided in a cavity of the shell 4. At a combustion chamber end of the insulator 2, the insulator forms a sheath around the central electrode tip 9 for electrically insulating from the shell 4. The combustion chamber end of the shell 4 is welded through at least one contact pin, a ground electrode 8 is provided. The ground electrode may be shaped as a coil. Preferably, a gap having a constant dimension is provided between the electrode 9 and the ground electrode 8. A terminal nut 1 provides an electrical contact for the central electrode 3 to an external power supply of voltage pulses. A conductive sealant may be located between the central electrode 3 and the central electrode tip 9. The conductive sealant may be manufactured from an electrically conductive glass, which may mechanically anchor the components of the central electrode and may provide a gas-tight seal against the combustion pressure. Another sealing 7 may be provided for enabling a gas-tight seal for the interior of the shell 4. A yet another seal 6 may be provided for isolating the combustion chamber from ambient atmosphere. Thread 10 carved in the shell 4 may be used to fix the spark plug inside the engine. Shell 4 may have a hexagon-like outer shape 11, for example for screwing the plug inside the engine.

[0047] Shell 4 may form a part of coaxial fitting from transmission line or directly from voltage generator to the discharge gap. Optionally, it may be provided with additional thread (11, not shown) to connect directly voltage generator or transmission line to said spark plug. Seal 6 may be a part of coaxial fitting connecting directly voltage generator or transmission line to said spark plug.

[0048] Yet other possible geometries for the combustion chamber end of the spark plug are presented in the cross-sectional views AP and LP.

[0049] Figure 2 presents pictures of an embodiment of a distributed spark obtainable with the method of the invention in a combustion chamber end view for a spark plug depicted in view AP in Figure 1. In this figure, view "a" item 1 denotes the electrode tip (item 9 in Figure 1), item 2 denotes the insulator 2 (item 2 in Figure 1) and item 3 denotes the shell (item 4 in Figure 1). It will be appreciated that the sparks corresponding to the consecutive time moments $i-3$, $i-2$, $i-1$ and i start spatially next to each other and the direction of spark propagation tends to maintain. Accordingly, the hot spots produced by each spark at places where it contacts the electrodes are both spatially and temporally distributed. The corresponding discharge channels are distributed over the discharge gap. The discharge gap may have a variable thickness. The variable thickness is preferably 100% - 200% of the shortest distance between the electrodes forming the discharge gap.

[0050] View "b" presents an image of plurality of the spatially distributed sparks; those skilled in the art will appreciate a uniform distribution of said sparks. View "c"

presents a front view of a plug having a travelling spark. It will be appreciated that the view "c" is acquired with a camera adapted to register temporally consequent events, i.e. in the view "c" an imaginary X-axis represents time. View "d" presents a side view of plurality of distributed adjacent sparks. It is seen that a substantially volumetric travelling spark is produced in the region S. This has an advantage that substantially no degradation of the dielectric surface occurs, in contrast to the static non-travelling surface sparks known from the art. It is further found that such volumetric dynamic spark is more effective for igniting a suitable mixture than a static surface spark.

[0051] Figure 3 presents in a schematic way an embodiment of a suitable voltage pulse shape when measured across the gap according to an aspect of the invention. It will be appreciated that for clarity reasons a single discharge voltage pulse U from a series of voltage pulses corresponding to an ignition burst is presented.

[0052] The voltage pulse is characterized by a maximum amplitude U_{br} , which is the discharge voltage, at least, equals to a breakdown voltage for a given plug. It will be appreciated that it is possible to apply voltages to the gap having the same or different polarities. Those skilled in the art will appreciate that in case of short duration voltage pulses fed to said spark plug through transmission line, preferably comprising coaxial cable, it is possible to use voltage pulses with an amplitude differs from the breakdown voltage of the gap. These pulses increase their amplitude when reflect from high-impedance load, limit peak discharge current, and favour distributed spark development. It is found that for the leading edge of the voltage pulse, defined as T_f being, for example, a time period between a 10% value and a 90% value of the breakdown voltage, the conductivity current across the discharge gap should not exceed of about 10 mA for favouring development of the distributed sparks. Alternatively, conductivity current across the discharge gap should be substantially zero during an interval of at least 5% of a period between the consecutive breakdown voltage pulses of the ignition burst. After-breakdown S oscillations of voltage over the discharge gap typically occur after formation of high-conductivity channel in the gap. The shape of oscillations can differ from the presented in the figure and is intended to be illustrative here.

[0053] It should be appreciated that presented voltage pulse shape is indicative and not limiting, admixed AC and DC voltages are allowed as long as they do not substantially change distributed spark development.

[0054] Figure 4 presents oscillograms of voltage and current that correspond to a single spark from a plurality of distributed sparks over a spark plug depicted in Figure 2. The plug is powered with a generator of nanosecond voltage pulses through a coaxial cable. Top curve depicts current through the plug. The scope of current oscillations is about 100 A, base level is 0 A. First peak corresponds to the breakdown and subsequent current oscillations are due to short-circuiting of the gap. Bottom curve cor-

responds to the voltage over the gap of said plug. First high amplitude peak corresponds to a pulse formed by generator until breakdown threshold is reached. Shortly after a spark channel is formed in the discharge gap, the voltage over the gap drops because a high conductivity channel is formed. Subsequent oscillations of voltage and current are due to voltage pulse reflections from the generator end and the plug end of the cable. At this time interval, the energy stored in the pulse dissipates and the generator does not supply more energy into the circuit. The key issue is an almost zero current through the plug at the period of time immediately preceding the voltage peak that ensures no conductive channel exists when new spark starts to form. This in combination with energy release from spark formed with the previous voltage pulse provides that consecutive voltage pulses applied to the discharge gap form adjacent sparks rather than overlapping sparks.

[0055] Figure 5 presents in a schematic way an embodiment of an ignition system according to an aspect of the invention. According to an aspect of the invention the voltage pulse generator 20, such as a suitable solid-state switch device, is connected to the spark plug 22 using a transmission line L, preferably a coaxial cable. Accordingly, the duration of the leading edge of the voltage across the gap is smaller than the time of the voltage pulse propagation along said transmission line. In order to reduce undesirable secondary effects occurring in the electrical circuit connecting the generator 20 and the plug 22, such as oscillations, a shunt capacitance C may be provided. Preferably, said capacitance has a value of less than 3 nF. Preferably, the coaxial cable L has impedance in the range of 10 - 300 Ohm. Another aspect of the invention is the power source 20 is directly connected to the plug 22.

[0056] Figure 6 presents in a schematic way an embodiment of voltage bursts A, B, C according to a further aspect of the invention. Shown pulses amplitude and period relations and burst durations are indicative and do not limit present application, pulses amplitude within burst may change as long as considerable part of pulses provide distributed sparks. The bursts A, B and C are presented as a function of the crank angle (X-axis).

[0057] The burst B corresponds to the ignition, the burst causes a plurality of distributed sparks to develop over the discharge gap of a spark plug which is installed inside combustion chamber of a spark ignition engine. In the upper section of the figure, two curves are presented characterizing the physical phenomena which take place over the discharge gap. The curve P represents the pressure development over the discharge gap while the curve T represents the temperature in the combustion chamber. In accordance with an aspect of the invention, the beginning of the ignition burst B is synchronized with a particular and regulatable crank angle, which is typically between -30 and -20 degrees of the crank. It will be appreciated that other synchronizations are possible depending on the type, geometry of the combustion cham-

ber as well as the engine current load and revolution rate.

[0058] In accordance with a further aspect of the invention the ignition burst of pulses B may be preceded by a burst of voltage pulses A, having an amplitude that may differ from that for burst B. Said burst A provides pre-treatment that is useful for tuning ignition properties of the mixture and can eliminate fouling film if occurred. Pulses A are preferably applied during compression. Said burst A application strategy may also be advantageous for engines running in HCCI mode when fine tuning of temperature and composition of mixture prior to main ignition is needed. It is possible to provide additional heating with combustion of very lean mixture provided by direct injection of small amount of fuel at early stage of compression cycle.

[0059] Likewise, it is found to be advantageous to provide a suitable burst of pulses C for a post treatment of discharge gap, preferably between +5 and +25 degrees of the crank, in order to remove fouling film if occurred, for example, during cold engine start or rich combustion conditions.

[0060] As an example, Figure 7 presents two pressure profiles (Y-axis) obtained with a conventional ignition system 17a and with an ignition system based on the invention 19a in a cylinder of an engine operating with a fixed load and revolution rate. Standard deviation of cycle-to-cycle pressure profiles is also presented in the Figure for both systems, 17b for the conventional system and 19b for the system operating according to the method of the invention. As it follows from this Figure, use of ignition system based upon invention leads to remarkably lower cyclic variations and eliminates misfiring. Under the conditions of presented test, misfiring regularly happens with an ordinary system between +80 and +190 degrees of the crank (X-axis). For this particular case, about of 30% lower fuel consumption is obtained when practicing the invention due to a higher overall efficiency.

[0061] Figure 8 presents pressure development in a cylinder (Y-axis) of an engine on the crank angle (X-axis) for the uniform lean-burn combustion for a fixed load and revolution rate with different levels of excess air ratio λ . The engines designed for lean burning provide better performance, more efficient fuel use and lower exhaust emissions than those found in conventional engines.

[0062] Figure 9 presents nitric oxide concentration in exhaust reduction (Y-axis, left) and exhaust temperature decrease (Y-axis, right) as a function of the crank angle (X-axis) for an engine operating in a uniform lean-burn regime using ignition system based on the invention for air excess factor λ in the range 1.0 - 6.0. According to the results presented in Figure 9 an ignition system based upon the invention provides reliable ignition for such conditions as well as significant exhaust emission reduction and gas temperature decrease. These results are intended to be illustrative, not limiting.

[0063] While specific embodiments have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The de-

scriptions above are intended to be illustrative, not limiting. Thus, it will be apparent to one skilled in the art that modifications may be made to the invention as described in the foregoing without departing from the scope of the claims set out below.

Claims

1. A method of igniting a spark in an electrical plug provided in a circuit and having a discharge gap for yielding a plurality of consecutive spatially distributed sparks per single ignition event, wherein the method comprises the steps of:
 - applying discharge voltage pulses U to the discharge gap with a period of maximally 1 millisecond, said discharge voltage pulses having a leading edge and an amplitude sufficient to cause breakdown;
 - limiting a conductivity current across the discharge gap below of about 10 mA during an interval corresponding to the said leading edge or
 - ensuring that a conductivity current across the discharge gap is substantially zero during an interval of at least 5% of the said period.
2. The method according to claim 1, wherein the electrical plug comprises electrodes, at least one electrode being extended.
3. The method according to claim 1 or 2, wherein the application of the discharge voltage pulse is preceded by an application of a series of sub-breakdown voltage pulses and/or AC and/or DC admixed voltages.
4. The method according to claim 1, 2 or 3, wherein the electrical plug forms part of an ignition system of an engine.
5. An ignition system having an electrical circuit comprising an electrical plug having a discharge gap, a voltage source adapted to apply a series of discharge voltage pulses U to the discharge gap, wherein the application of the discharge voltage pulses U results in a generation of a plurality of spatially distributed adjacent sparks across the discharge gap for a single ignition event.
6. The ignition system according to claim 5, wherein the said discharge voltage pulses have a leading edge and a period, the electrical circuit being adapted to ensure that a conductivity current across the discharge gap is substantially absent during an interval of at least 5% of the said period or that the conductivity current across the discharge gap is less than 10 mA during an interval corresponding to the

leading edge of the discharge voltage.

7. The ignition system according to claim 6, wherein the said period is in the range of 1 microsecond - 1 millisecond. 5
8. The ignition system according to claim 5, 6 or 7, wherein the electrical circuit comprises a transmission line at least on a path connecting the voltage source and the plug, wherein said voltage source is capable to provide pulses with the total duration less than 1 microsecond and/or with the total energy less than 100 mJ per pulse. 10
9. The ignition system according to any one of the preceding claims 5 - 8, wherein the plug comprises a dielectric material having a dielectric strength of at least 1 kV. 15
10. The ignition system according to any one of the preceding claims 8 or 9, wherein the transmission line has impedance in the range of 10 - 300 Ohm. 20
11. The ignition system according to claim 8, 9 or 10, wherein the power source is a solid-state switch device. 25
12. The ignition system according to claim 11, wherein the power source is directly connected to the plug. 30
13. The ignition system according to any one of the preceding claims 5 - 12, wherein the electrical circuit further comprises a capacitance connected in parallel with respect to the plug, said capacitance having a value of less than 3 nF or wherein the capacitance is capable of shunting said voltage source after discharge of the discharge gap. 35
14. The ignition system according to any one of the preceding claims 5 - 13, wherein the discharge gap has a variable thickness. 40
15. The ignition system according to claim 14, wherein said variable thickness is ranging from 100% - 200% of the shortest distance between the electrodes forming the discharge gap. 45
16. The ignition system according to any one of the preceding claims 5 - 15, wherein the spark plug comprises several discharge gaps. 50
17. The ignition system according to any one of the preceding claims 5 - 16, wherein said plug is energized in advance of a desired ignition event using a burst of discharge voltage pulses. 55
18. The ignition system according to any one of the preceding claims 5 - 16, wherein said plug is energized after the ignition event using a burst of discharge voltage pulses.
19. An internal combustion engine, comprising the ignition system according to any one of the preceding claims 5 - 18.
20. The engine according to claim 19, comprising a plurality of cylinders provided with corresponding plugs, wherein the application of the discharge voltage pulses to said plugs is synchronized with a compression phase within at least one of the said cylinders.
21. A vehicle comprising an engine according to claim 20.

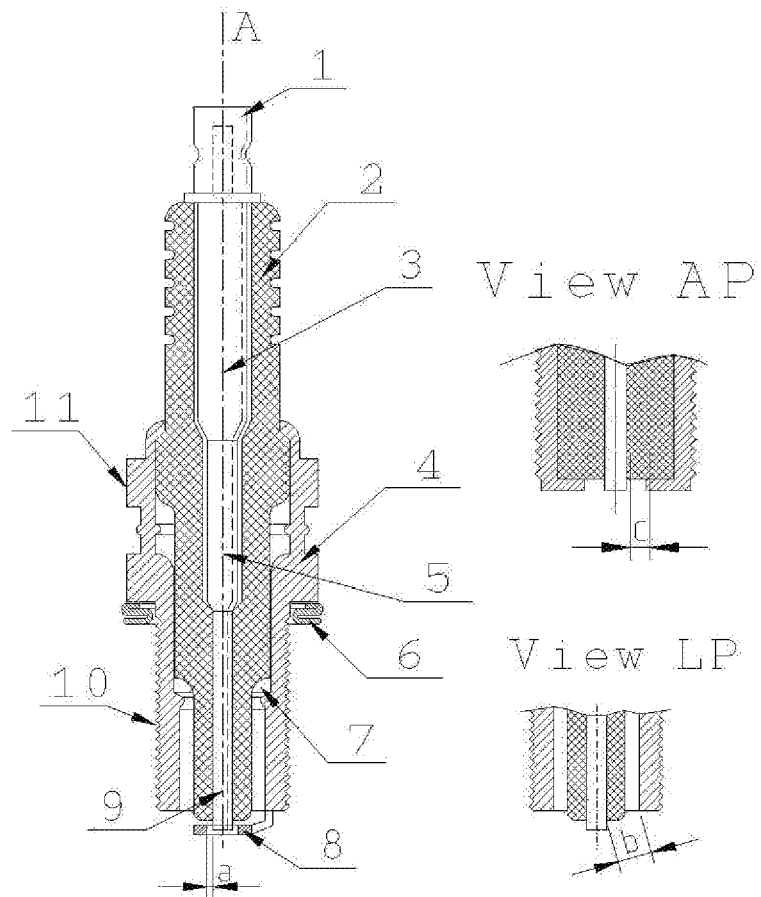


Fig. 1

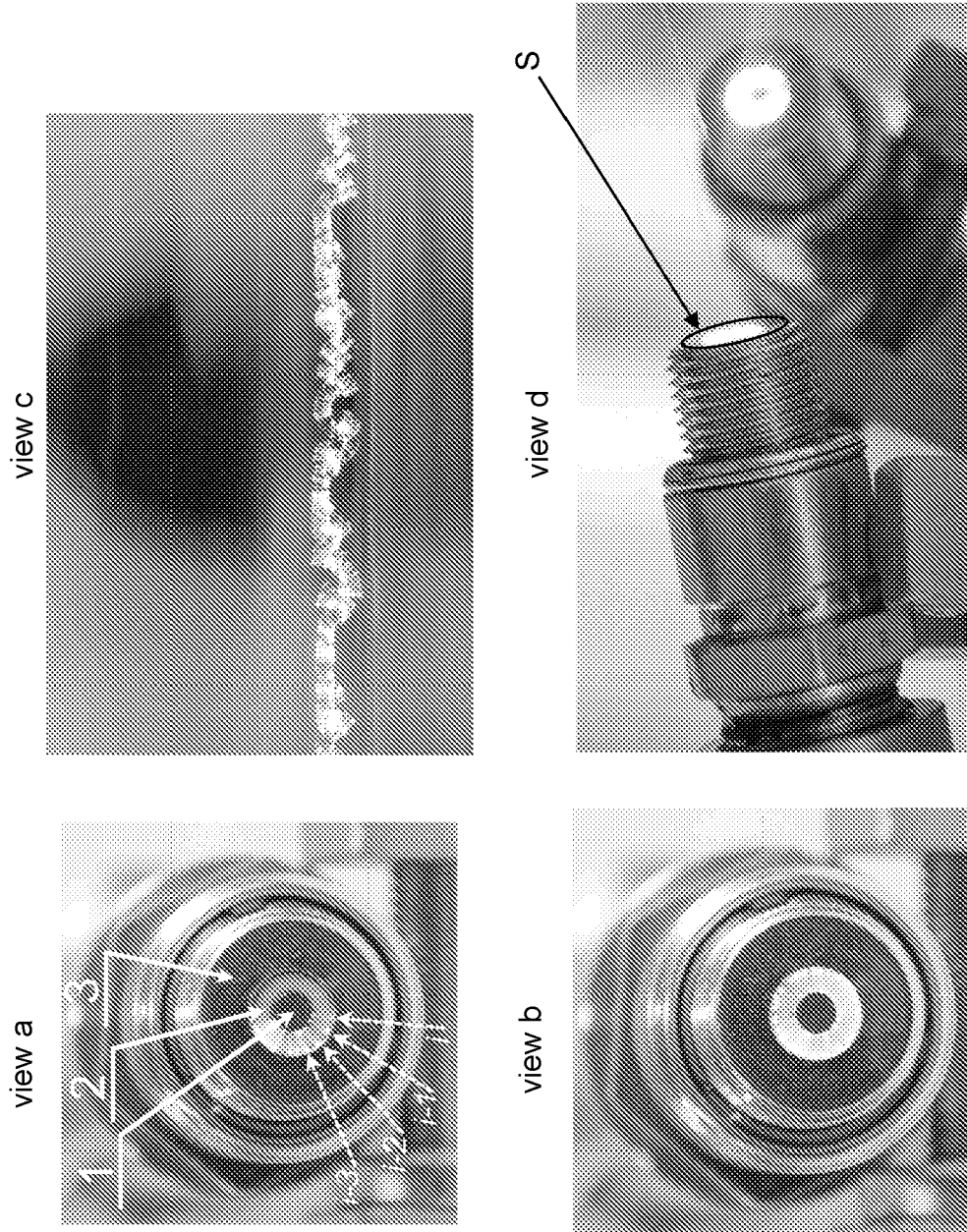


Fig. 2

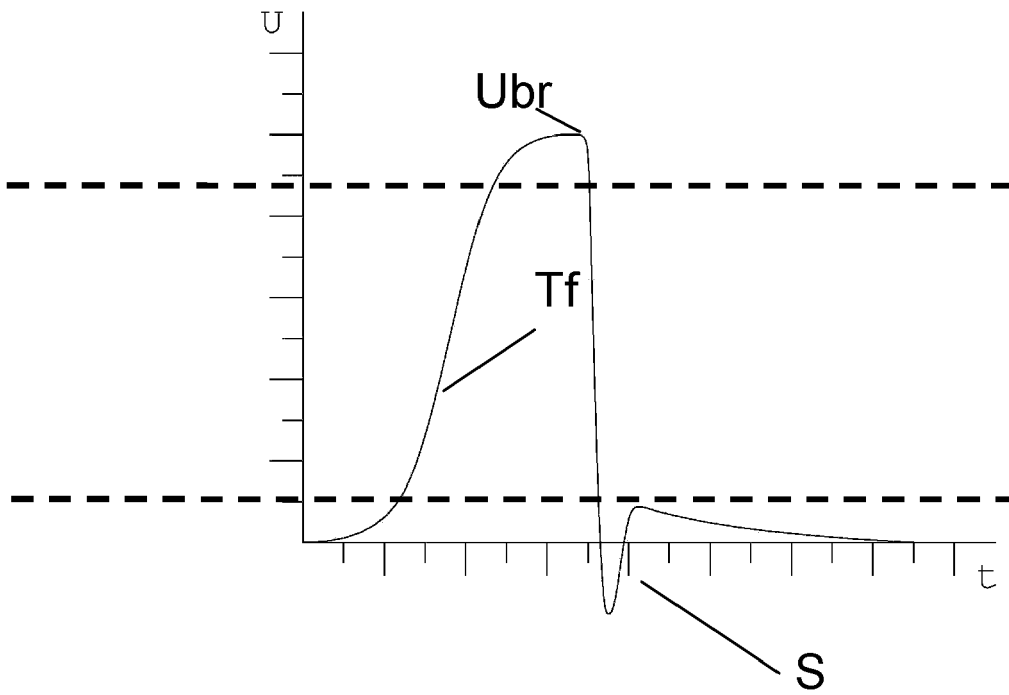


Fig. 3

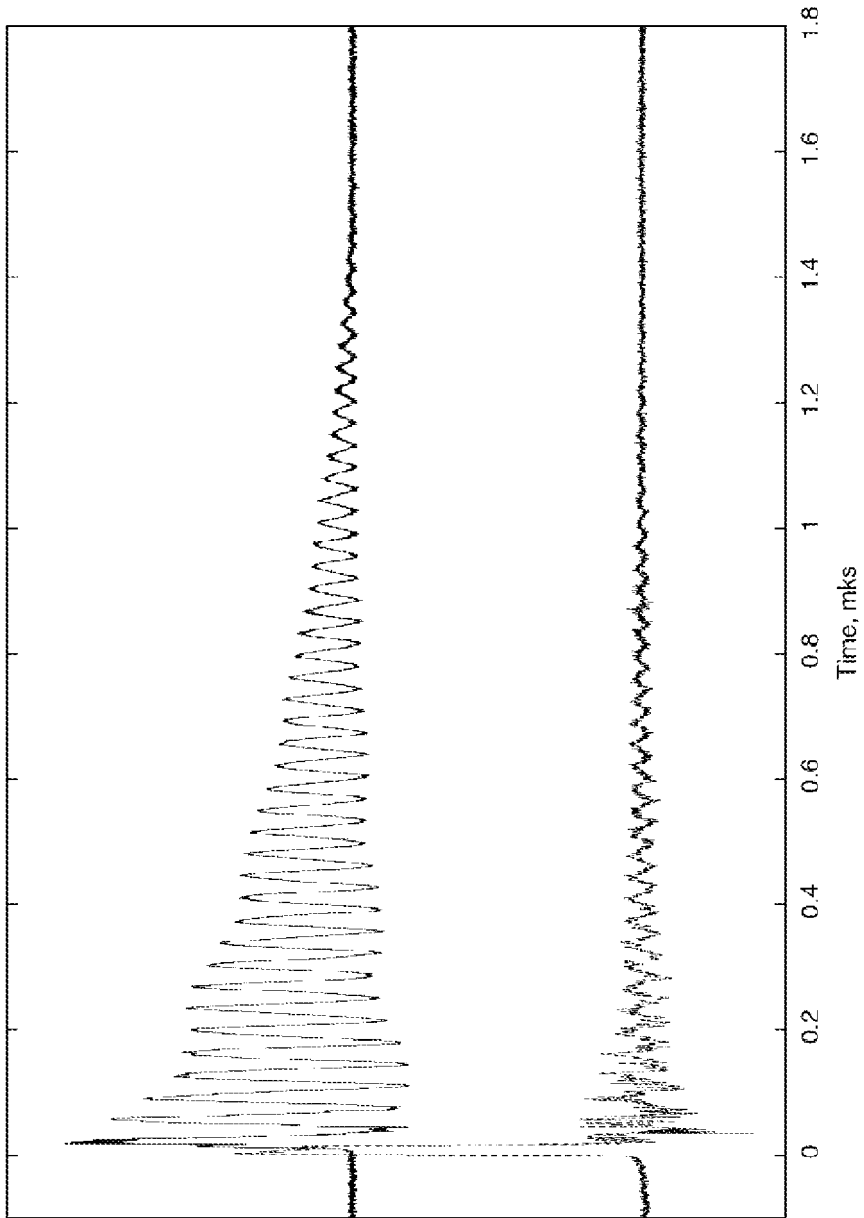


Fig. 4

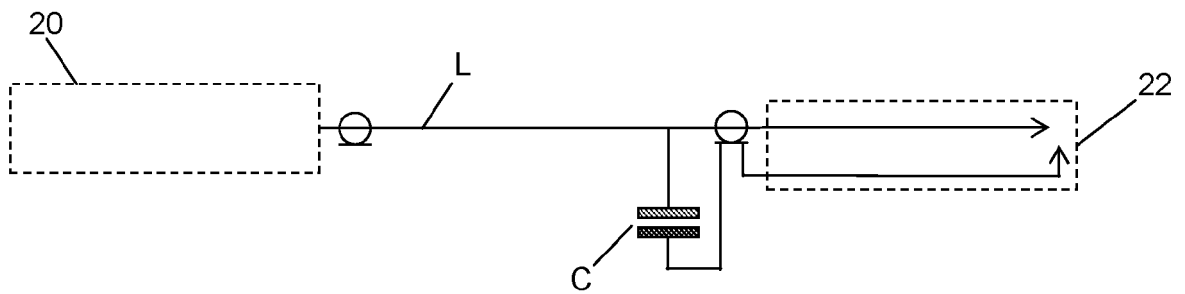


Fig. 5

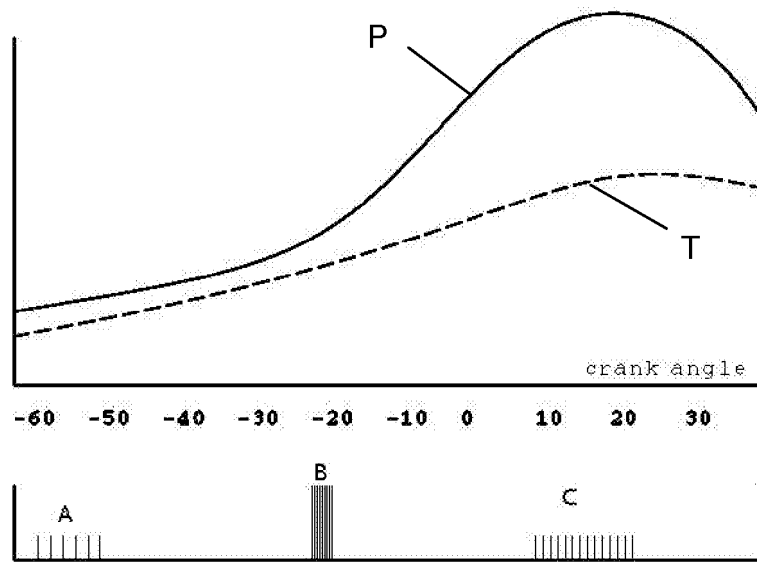


Fig. 6

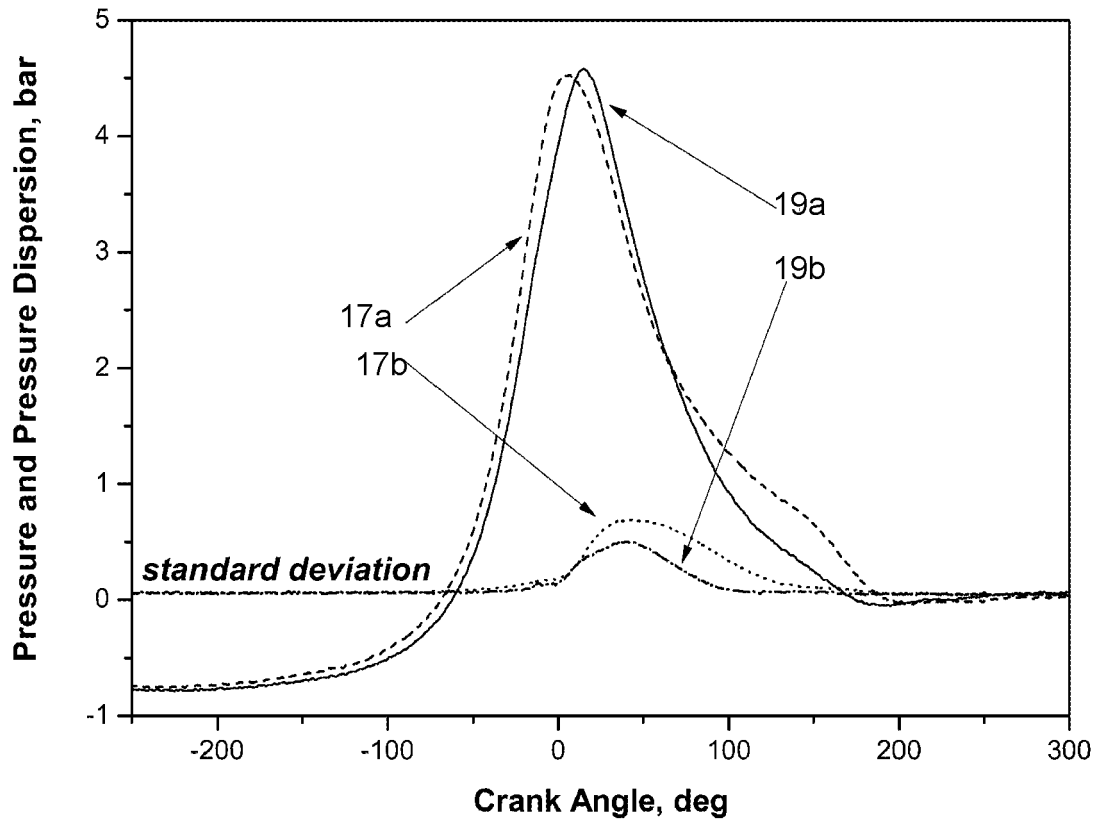


Fig. 7

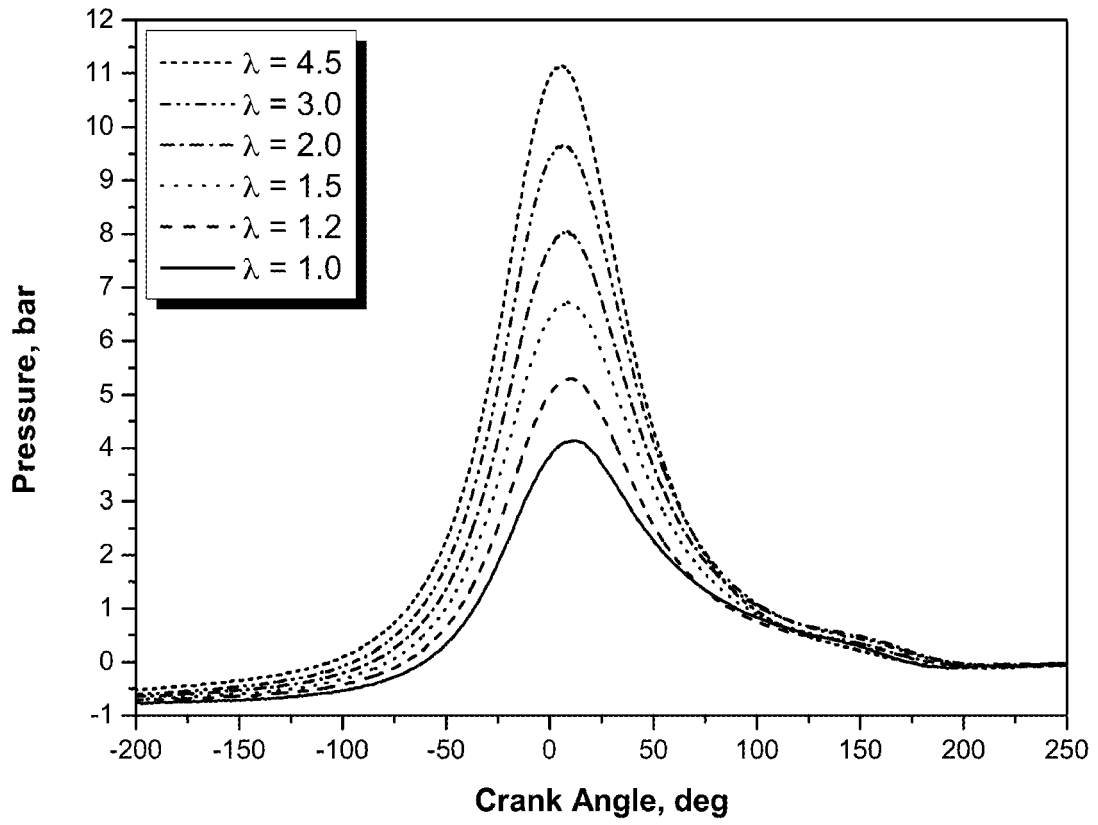


Fig. 8

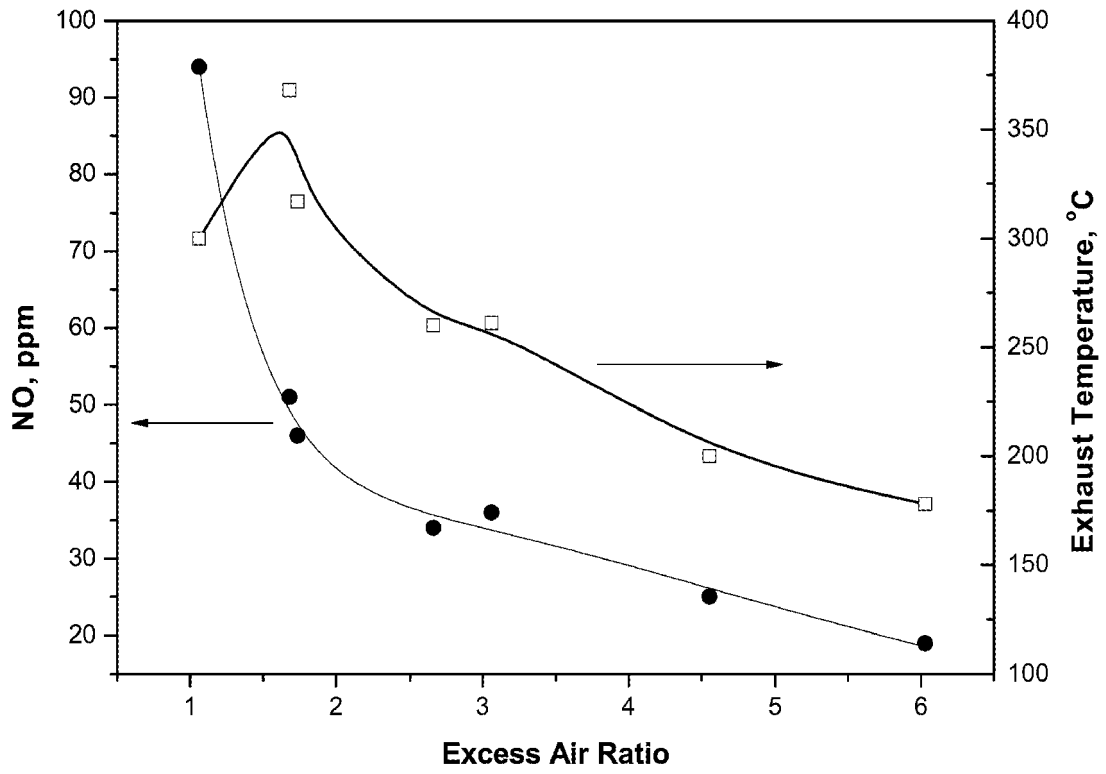


Fig. 9



EUROPEAN SEARCH REPORT

Application Number
EP 11 17 6514

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	FR 1 327 226 A (RENAULT) 17 May 1963 (1963-05-17) * page 1, column 1st; figure 3 * * page 2, column 1st; figures 1,2 * -----	1,2,5-7, 19-21	INV. F02P15/08 H01T13/28 H01T13/38 H01T13/44 H01T13/52
X	FR 2 904 155 A1 (PEUGEOT CITROEN AUTOMOBILES SA [FR]; ECOLE CENTRALE PARIS [FR]) 25 January 2008 (2008-01-25) * paragraphs [0007], [0005], [0024], [0028], [0038]; figures * -----	1-16, 18-21	
X	EP 0 763 759 A2 (SUMITOMO ELECTRIC INDUSTRIES [JP]; SUMIDEN OPCOM LTD [JP]) 19 March 1997 (1997-03-19) * figures * -----	1-7,13, 19-21	
X	WO 2010/090545 A1 (NEQ LAB HOLDING INC; STARIKOVSKY ANDREY YURIEVICH [RU]) 12 August 2010 (2010-08-12) * pages 12,15; figures * -----	1-4	
A		5-21	TECHNICAL FIELDS SEARCHED (IPC)
A	US 6 131 555 A (TOZZI LUIGI P [US] ET AL) 17 October 2000 (2000-10-17) * column 7; figures * -----	1-21	F02P H01T
A	US 4 774 914 A (WARD MICHAEL A V [US]) 4 October 1988 (1988-10-04) * column 7; figures * -----	1-21	
A	EP 2 020 503 A2 (NISSAN MOTOR [JP]) 4 February 2009 (2009-02-04) * paragraph [0051] - paragraph [0056]; figures * -----	1-21	
A	US 5 947 093 A (WARD MICHAEL A V [US]) 7 September 1999 (1999-09-07) * column 3; figures * -----	1-21	
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 16 December 2011	Examiner Olivieri, Enrico
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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EPO FORM 1503 03.82 (P04C01)

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 11 17 6514

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

16-12-2011

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
FR 1327226	A	17-05-1963	NONE		

FR 2904155	A1	25-01-2008	NONE		

EP 0763759	A2	19-03-1997	CA	2183840 A1	15-03-1997
			EP	0763759 A2	19-03-1997
			US	5777867 A	07-07-1998

WO 2010090545	A1	12-08-2010	NONE		

US 6131555	A	17-10-2000	DE	19917889 A1	21-10-1999
			FR	2777607 A1	22-10-1999
			GB	2336629 A	27-10-1999
			JP	3249488 B2	21-01-2002
			JP	11324880 A	26-11-1999
			US	6035838 A	14-03-2000
			US	6131555 A	17-10-2000

US 4774914	A	04-10-1988	AU	591528 B2	07-12-1989
			AU	6471686 A	07-04-1987
			EP	0239617 A1	07-10-1987
			US	4774914 A	04-10-1988
			WO	8701767 A1	26-03-1987

EP 2020503	A2	04-02-2009	EP	2020503 A2	04-02-2009
			JP	2009036123 A	19-02-2009
			US	2009031984 A1	05-02-2009

US 5947093	A	07-09-1999	NONE		

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **RICHARD VAN BASSHUYSEN ; FRED SHÄFER.** Internal Combustion Engine Handbook. SAE International, 2004, 417-421 **[0015]**
- **J. WARNATZ ; U. MAAS ; R. W. DIBBLE.** Combustion. Springer, 2006 **[0016]**