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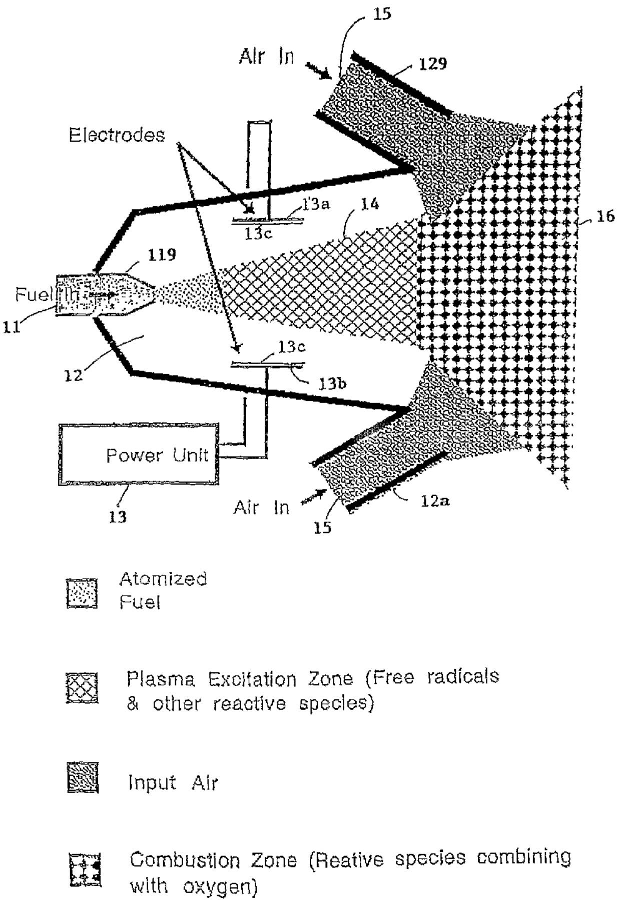
(54) Title: PLASMA CATALYTIC FUEL INJECTOR FOR ENHANCED COMBUSTION



(57) Abstract: Apparatus and method for enhancing combustion comprises an enclosure defining an opening for introduction of a gas and openings for the introduction of air, with a nozzle in the opening for introduction of a fuel gas into the enclosure. First and second electrodes are located in the enclosure, the first and second electrodes being coated with dielectric material, and being connected to an electrical power supply. With electrical power applied to the first and second electrodes and with the fuel gas sprayed into the enclosure, an atmospheric pressure plasma created by a dielectric barrier discharge is produced in the enclosure that cracks the fuel gas prior to its mixing with air introduced through the openings for the introduction of air.

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PLASMA CATALYTIC FUEL INJECTOR FOR ENHANCED COMBUSTION

The present invention generally relates to combustion processes, and, more specifically, to processes that enhance the efficiency of combustion processes. This invention was made with Government support under Contract No. W-7405-ENG-36 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Combustion processes are involved in many aspects of modern life, and are, in large part, responsible for our current standard of living. Combustion provides the propulsion of our automobiles and airplanes, generates virtually all our electrical power, heats most of our homes and buildings, and provides much of our hot water. In this age of increasing energy costs, it is vitally important to assure that these combustion processes are carried out in the most efficient way possible, and to assure that fuel is conserved and that pollution is reduced.

All combustion processes involve the breakdown of the fuel being burned into free radicals and other reactive species. It is this breakdown into reactive species that initiates a combustion process. In many applications, a spark plug produces a momentary high voltage spark discharge that breaks down an air/fuel mixture into the requisite free radical/ion reactive species so that combination with oxygen and/or fuel can occur. Combustion then continues by the propagation of the reactive species generated by the heat of the reaction itself.

Thus, the overall combustion reaction rate usually is determined by the efficiency of generation of the new reactive species in the spreading flame front. As the reaction rate and temperature of the combustion process are increased, a related increase in detonations and pressure will occur.

Since the efficiency of combustion processes largely is determined by usual thermodynamic considerations, namely, the higher the temperature, the more thorough and efficient the combustion process becomes, and the greater the energy that can be extracted -and the higher the Carnot efficiency. This is the reason behind the thrust of engine makers, either of internal combustion engines or jet engines, to seek ever-higher temperature combustion processes. However, this increase in temperature places increasing demands on material scientists to provide materials that can withstand such high temperatures.

The objects, advantages and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

SUMMARY OF THE INVENTION

In accordance with the objects and purposes of the present invention, as embodied and broadly described herein, apparatus for enhancing combustion comprises an enclosure defining an opening for introduction of a gas and openings for the introduction of air, with a nozzle in the opening for introduction of a fuel gas into the enclosure. First and second electrodes are located in the enclosure, the first and second electrodes being coated with dielectric material and being connected to an electrical power supply. Wherein, with electrical power applied to the first and second electrodes and with fuel gas sprayed into the enclosure, an atmospheric pressure plasma created by a dielectric barrier discharge is produced in the enclosure that cracks the fuel gas prior to its mixing with air introduced through the openings for the introduction of air.

In another aspect of the present invention, and in accordance with its purposes and objects, a method of increasing the efficiency of combustion processes comprises the steps of producing an atmospheric pressure plasma created by dielectric barrier discharge; and spraying a fuel gas into the atmospheric pressure plasma; wherein the atmospheric pressure plasma cracks the fuel gas.

In still another aspect of the present invention and in accordance with its purposes and objectives, apparatus for enhancing combustion comprises separate supplies of fuel and air, with valve means for controlling the flow of fuel and air. Plasma processing means receive the fuel and air for selectively pre-cracking the fuel and exciting the air and outputting the pre-cracked fuel and excited air to a combustor.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and forms a part of the specification, illustrate embodiments of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

FIGURE 1 is an illustration of an embodiment of the present invention in which an atmospheric pressure plasma is used to crack the fuel.

FIGURE 2 is an illustration of an embodiment of the present invention in which a combination of a plasma and heated electrodes are used to crack the fuel.

FIGURE 3 is an illustration of an embodiment of the present invention in which valves and individual plasma units are used to show some of the various ways that a plasma treatment could be applied to the combustion process.

DETAILED DESCRIPTION

The present invention converts liquid or gaseous fuels into reactive species on a continuous basis, so that the combustion process does not rely solely on the self-generation of reactive species. The understanding of the invention can be aided through reference to the drawings.

In Figure 1, a schematical illustration of one embodiment of the invention is shown where fuel gas 11 is introduced into volume 12 through fuel nozzle 11a. If fuel gas 11 is initially in liquid form, such as all hydrocarbon fuels, oxygenated hydrocarbon fuels and other functionalized fuels, fuel oils, diesel fuels, kerosene fuels including usual jet fuels such as Jet A, Jet B, JP-10, crude oil, and kerosene, it is atomized in the manner of conventional fuel injectors before being introduced into volume 12. If the fuel gas 11 is a gas, such as propane, natural gas, butane, propene, pure methane, ethylene, ethane and related fuels, it is passed directly through nozzle 11a to meter the flow. The present invention can use essentially any liquid or gas that burns as fuel gas 11.

Because the present invention can accommodate both liquid and gaseous fuels it useful in virtually all present combustion processes. In some circumstances, it will be beneficial to heat fuel gas 11 before it is passed through nozzle 11a to achieve an even higher level of enhancement.

Electrical power unit 13 produces a voltage at electrodes 13a and 13b inside volume 12. Each of electrodes 13a, 13b is coated with dielectric material 13c. The voltage at electrodes 13a, 13b produces an atmospheric pressure plasma created by dielectric barrier discharge in volume 12 that cracks fuel gas 11 into reactive species 14. Reactive species 14, now a highly reactive cracked fuel, is exhausted through volume 12 until it is mixed with air 15 incoming through ports 12a and combusts into flame front 16. Further ignition may not be needed as reactive species 14 are predisposed to immediate reaction with oxygen. Hence, this embodiment of the invention can serve as an ignition initiator device. To further enhance the cracking process, electrodes 13a, 13b could be coated with a dielectric material that has a catalytic material deposited at predetermined non-contiguous areas.

Electrical power unit 13 can supply a range of voltages to electrodes 13a, 13b. In a one embodiment, electrical power supply 13 provides a radio frequency voltage having a frequency of 13.56 MHz. Other possible outputs of electrical power supply 13 include pulsed direct current, alternating currents from low frequencies to radio frequency and even microwave. Each will be capable of creating the atmospheric pressure plasma created by a dielectric barrier discharge.

Fuel gas 11, whether atomized or gaseous, is cracked by passing through the atmospheric pressure plasma region in volume 12 in a process that can be adjusted to produce any desired level of molecular breakdown. For example, in the case of propane, the cracking could be limited to just cleaving hydrogen as shown in the following reaction:

$$CH_3\text{-}CH_2\text{-}CH_3 \rightarrow CH_3\text{-}CH_2\text{-}CH_2\bullet + H\bullet. \qquad 10$$

Should it be desired to cleave methylene fragments or carbene structures, the following reactions would occur:

$$CH_3\text{-}CH_2\text{-}CH_3 \rightarrow CH_3\text{-}CH2\bullet + CH_3\bullet \qquad 11$$

$$CH_3\text{-}CH_2\text{-}CH_3 \rightarrow 2CH_3\bullet + CH_2: \qquad 12$$

Another embodiment of the invention is illustrated schematically in Figure 2. In this embodiment, which is similar to that shown in Figure 1, electrical power unit <u>13</u> is connected to electrodes <u>21a</u>, <u>21b</u>, which may be fabricated from any metallic materials, and which are coated with a dielectric material having, in one embodiment, known transition elements, such as platinum, or alloys made of combinations of transition elements, deposited at predetermined non-contiguous areas. To achieve similar results, a catalyst such as platinum or other transition element, could be suspended inside volume 12.Electrodes <u>21a</u>, <u>21b</u> also can be resistance heated by power sources <u>22</u>, <u>23</u> to add thermal deposition to the cracking reactions to further accelerate the cleavage reactions.

Experiments using a configuration as shown in Figure 1 have shown the benefits of plasma-enhanced combustion. Propane was combusted in a coaxial tube with an atmospheric pressure plasma present showed significant differences when compared to combustion with the plasma not present. Among these differences are (1) an enhanced flame front <u>16</u> (Figure 1) that was more stable and less prone to "blow out;" (2) the physical character of flame front <u>16</u> was visually different; (3) and, most importantly, residual unburned propane was measurably reduced as shown by mass spectrometry. The amount of efficiency enhancement is still under investigation and optimization of the propane combustion process is progressing. In unoptimized experiments with activated propane mixed with air, an increase in propane utilization of approximately 88% was observed, with a concomitant increase of carbon dioxide and water production (indicators of better combustion) of approximately 130% and 67%, respectively, was observed.

Another embodiment of the invention that may provide improved pollutant emission performance and excellent control is illustrated in schematic form in Figure 3. Here, fuel supply 31 provides fuel as previously described to valves 32, 33, and 34. Air supply 36 provides air to valves 37, 38, and 39. With valves 32 and 37 open, fuel and air can mix in T-connection 35 and be provided to combustor 40 if valve 41 is open. This would be for conventional combustion. Alternatively, if only valves 34 and 39 are open, fuel and air would separately be provided to combustor 40.

However, to achieve the benefits of the present invention, valves 34, 39, and 41 would be closed and valves 32, 37, and 42 opened. In this arrangement, the mixed fuel and air flows through plasma unit 42 where fuel is cracked and air is excited, in a process previously described, before entering combustor 40. However, there is no present evidence indicating that subjecting the fuel-air mixture is superior to using the plasma to crack only the fuel prior to its mixing with air. If desired, the fuel and air could separately pass through plasma units 44 and 45 respectively if valves 33 and 38 are open and all other valves closed. According to the desired effect, any or all of the valves may be partly open with some of the fuel, the air, or a mixture of both undergoes treatment by the plasma.

From Figure 3, it is easy to understand how this embodiment of the present invention can provide the most efficient operation of combustor 40. Configurations ranging from no plasma pre-cracking to complete plasma pre-cracking of any stream of air and/or fuel can be easily obtained through control of the valves.

The foregoing description of the embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto.

What is claimed is:

1. Apparatus for enhancing combustion comprising:
   an enclosure defining an opening for introduction of a gas and openings for the introduction of air;
   a nozzle in said opening for introduction of a fuel gas into said enclosure;
   first and second electrodes located in said enclosure, said first and second electrodes being coated with dielectric material, and being connected to an electrical power supply;
   wherein, with electrical power applied to said first and second electrodes and with said fuel gas sprayed into said enclosure, an atmospheric pressure plasma created by a dielectric barrier discharge is produced in said enclosure that cracks said fuel gas prior to its mixing with air introduced through said openings for the introduction of air.

2. The apparatus as described in Claim 1 wherein said fuel gas is an atomized liquid fuel.

3. The apparatus as described in Claim 1 wherein said fuel gas is propane.

4. The apparatus as described in Claim 1 wherein said fuel gas is natural gas.

5. The apparatus as described in Claim 1 wherein said fuel gas is atomized Jet A fuel.

6. The apparatus as described in Claim 1 wherein said fuel gas is atomized Jet B fuel.

7. The apparatus as described in Claim 1 wherein said fuel gas is atomized JP-10 fuel.

8. The apparatus as described in Claim 1 wherein said dielectric material has a catalytic material deposited onto it at predetermined non-contiguous areas to enhance cracking of said fuel gas.

9. The apparatus as described in Claim 8 wherein said catalytic material is at least one transition element.

10. The apparatus as described in Claim 8 wherein said catalytic material is an alloy of two or more transition elements.

11. The apparatus as described in Claim 8 wherein said at least one transition element is platinum.

12. The apparatus as described in Claim 1, wherein said electrical power supply provides radio frequency power having a frequency of 13.56 MHz.

13. The apparatus as described in Claim 1, wherein said electrical power supply provides pulsed direct current power.

14. The apparatus as described in Claim 1 wherein said electrical power supply provides sub-radio frequency alternating current power.

15. A method of increasing the efficiency of combustion processes comprising the steps of: producing an atmospheric pressure plasma created by dielectric barrier discharge;

spraying a fuel gas into said atmospheric pressure plasma;

wherein said atmospheric pressure plasma cracks said fuel gas.

16.The method as described in Claim 15, wherein said fuel gas is an atomized liquid fuel.

17. The method as described in Claim 15, wherein said fuel gas is propane.

18. The method as described in Claim 15, wherein said fuel gas is natural gas.

19. The method as described in Claim 15, wherein said fuel gas is pure methane.

20. The method as described in Claim 15, wherein said fuel gas is atomized Jet A fuel.

21. The method as described in Claim 15, wherein said fuel gas is atomized Jet B fuel.

22. The method as described in Claim 15, wherein said fuel gas is atomized JP-10 fuel.

23. The method as described in Claim 15, further comprising the step of heating said fuel gas before said fuel gas is sprayed into said atmospheric pressure plasma.

24. The method as described in Claim 15, wherein said atmospheric pressure plasma is produced using an electrical power supply.

25. The method as described in Claim 24, wherein said electrical power supply provides radio frequency power.

26. The method as described in Claim 24, wherein said radio frequency power has a frequency of 13.56 MHz.

27. The method as described in Claim 24, wherein said electrical power supply provides pulsed direct current power.

28.The method as described in Claim 24, wherein said electrical power supply provides sub-radio frequency alternating current power.

29. Apparatus for enhancing combustion comprising:

separate supplies of fuel and air;

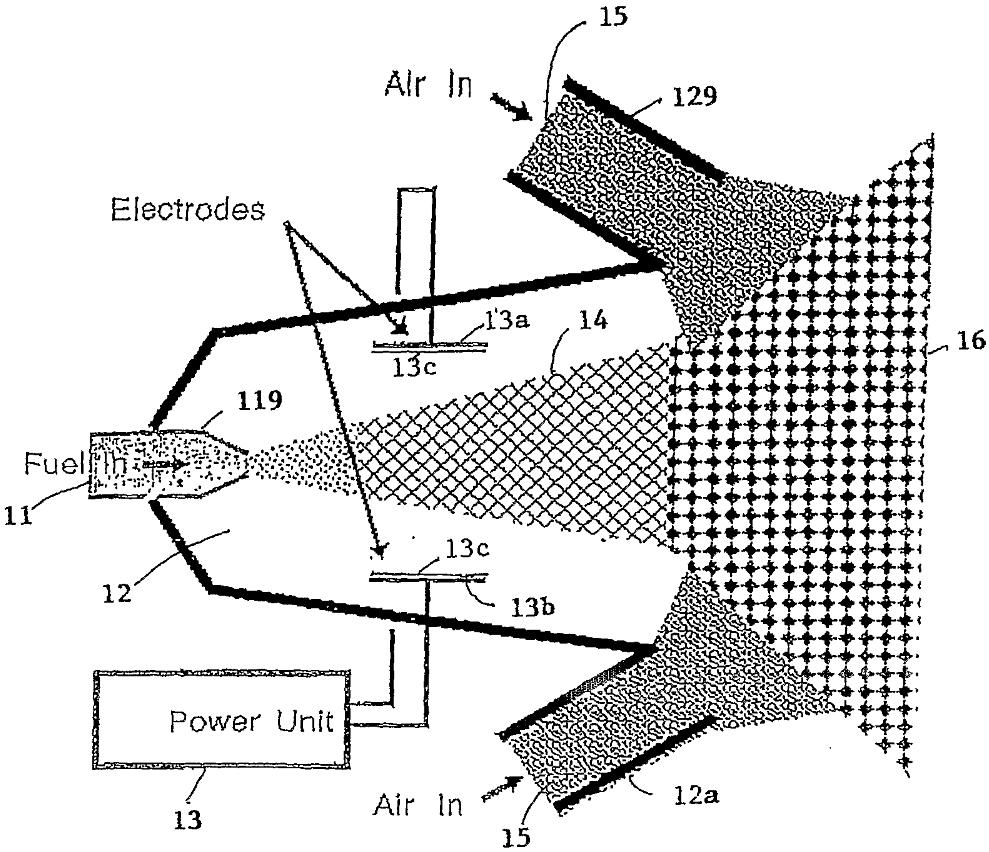
valve means for controlling the flow of fuel and air;

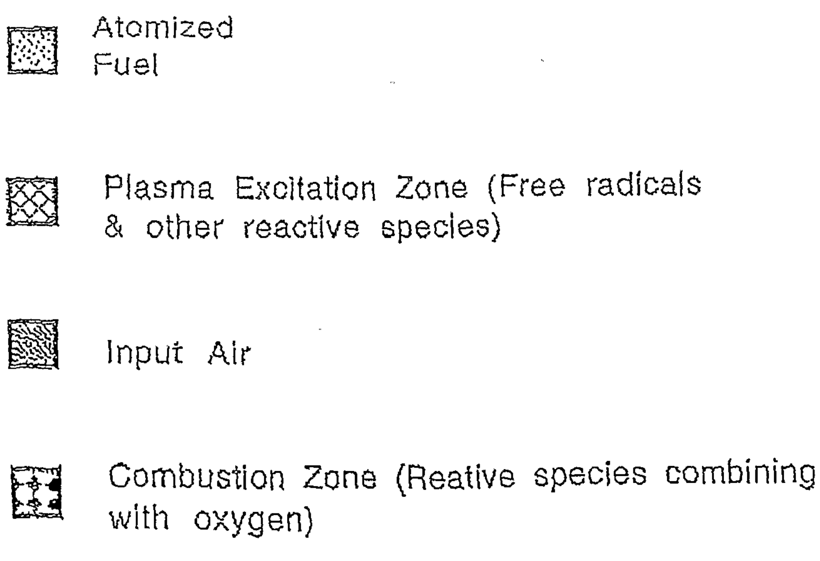
plasma processing means receiving said fuel and air for selectively pre-cracking said fuel and exciting said air and outputting said pre-cracked fuel and excited air to a combustor.

30. The apparatus as described in Claim 29, wherein said fuel is pre-cracked prior to being output to said combustor, and said air is output directly to said combustor.

31. The apparatus as described in Claim 29, wherein said air is excited prior to being output to said combustor, and said fuel is output directly to said combustor.

32. The apparatus as described in Claim 29, wherein said fuel is pre-cracked and said air is excited prior to being output to said combustor.

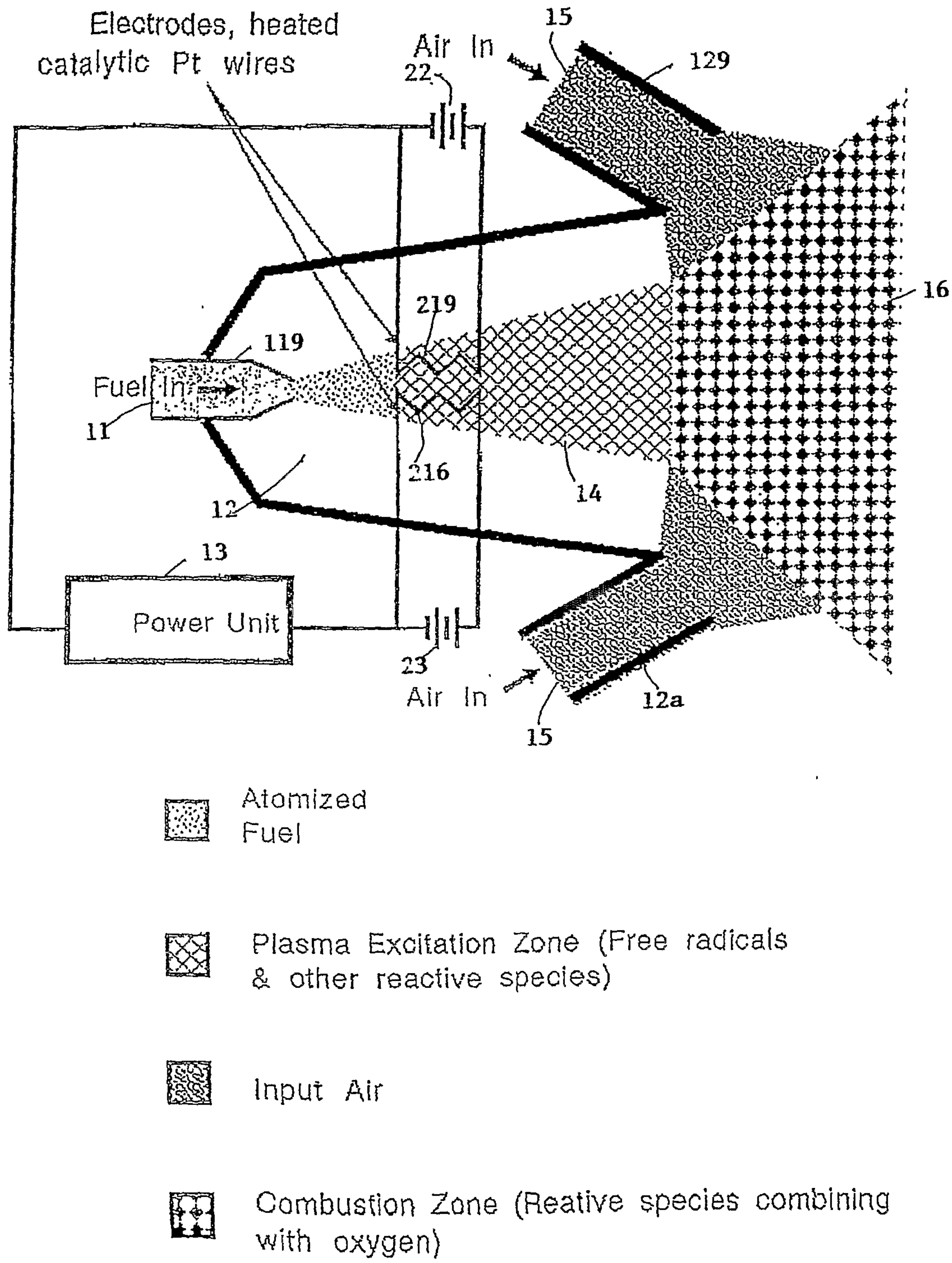

15
Air In
129
Electrodes
13a
14
13c
16
119
Fuel In
11
12
13c
13b
Power Unit
13
Air In
12a
15


Atomized
Fuel

Plasma Excitation Zone (Free radicals
& other reactive species)

Input Air

Combustion Zone (Reative species combining
with oxygen)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16
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Fuel In
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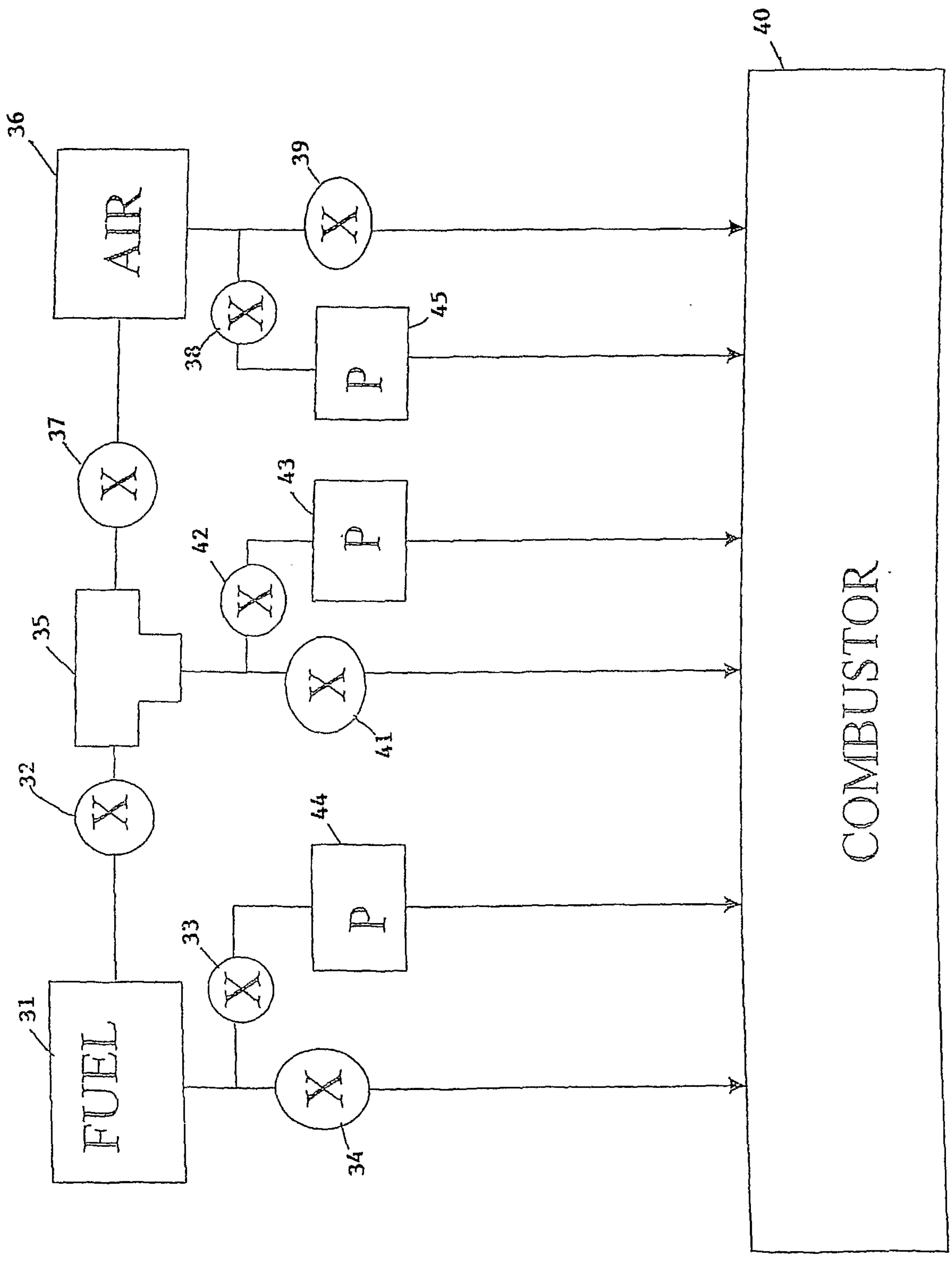
Atomized Fuel
Plasma Excitation Zone (Free radicals & other reactive species)
Input Air
Combustion Zone (Reative species combining with oxygen)


FUEL
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US04/22664

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : F23B 1/00
US CL : 431/002
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 431/002, 265, 258, 264, 266, 208; 60/723, 39.822

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB; USOCR; plasma, catalyst, fuel, combustion, burner, cracks

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	GB 972,302 A (YOUNG et al) 14 October 1964, see entire document	1-32
Y	WO 02/076884 A1 (CARLOW et al) 03 October 2002, see entire document	1-32

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search	Date of mailing of the international search report
04 December 2004 (04.12.2004)	09 DEC 2004

Name and mailing address of the ISA/US	Authorized officer
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