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(54) **APPARATUS AND METHODS OF OPERATING A COMBUSTION ENGINE**

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(57) **ABSTRACT**

The present invention generally relates to dual chamber combustion engines. The invention particularly relates to apparatus and methods for ignition of ultra-lean fuel/air mixtures with fuel/air mixture streams traveling at supersonic velocities. Present invention will be impactful in emission reduction as well as improving fuel economy and thermal efficiency in engines.

APPARATUS AND METHODS OF OPERATING A COMBUSTION ENGINE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present U.S. patent application is related to and claims the priority benefit of U.S. Provisional Patent Application Ser. No. 62/414,854, filed Oct. 31, 2016, the contents of which are hereby incorporated by reference in their entirety into the present disclosure.

TECHNICAL FIELD

[0002] The present invention generally relates to dual chamber combustion engines. The invention particularly relates to apparatus and methods for ignition of ultra-lean fuel/air mixtures with fuel/air mixture streams traveling at supersonic velocities.

BACKGROUND

[0003] This section introduces aspects that may help facilitate a better understanding of the disclosure. Accordingly, these statements are to be read in this light and are not to be understood as admissions about what is or is not prior art.

[0004] Combustion of lean fuel mixtures, that is, mixtures having a relatively low fuel-to-air mixing ratio, may provide for reductions in emissions from internal combustion engines of the types used in the engine and power generation industries. Dual chamber engines, for example, of types that may be used in turbine engines, utilize a pre-chamber and a main chamber. In general, a small quantity of stoichiometric fuel/air is initially burned in the pre-chamber. The resulting combustion products are then discharged in the form of a hot turbulent fuel/air mixture stream (jet) through a small diameter nozzle into the main chamber, which is filled with leaner fuel/air mixture. Compared to a conventional spark plug, the turbulent jet has a much larger effective "surface area" leading to multiple ignition sites on its surface that can enhance the probability of successful ignition. The turbulence brought by the hot jet can cause faster flame propagation and heat release. A non-limiting example of a type of a dual chamber power turbine engine is described in U.S. Pat. No. 4,292,801 to Wilkes et al.

[0005] Decreasing the fuel-to-air mixing ratio of a fuel mixture used in engines can reduce emissions, for example, NOx, unburned hydrocarbon (UHC), particulate matters, and improve thermal efficiency. However, ignition of ultra-lean fuel/air mixtures can be challenging and may cause engine misfires. As used herein, ultra-lean fuel/air mixtures are defined as having a fuel/air equivalence ratio that is lower than the typical values used in current combustion engines, wherein the equivalence ratio is the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio.

[0006] Despite advances in lean burn combustion, there is an ongoing desire to reduce emissions from engines. In particular, there is a desire for an engine capable of reliably combusting ultra-lean fuel mixtures.

SUMMARY

[0007] The present invention provides apparatus and methods suitable for reliably combusting ultra-lean fuel mixtures in combustion engines.

[0008] In one embodiment, the present disclosure provides a supersonic ignition device comprising a supersonic nozzle, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, and the length of the supersonic nozzle is 10-30 mm, and the supersonic nozzle is configured to be capable of igniting an ultra-lean fuel-air mixture.

[0009] In one embodiment, the present disclosure provides a supersonic jet combustion engine comprising a pre-chamber, a supersonic nozzle with a length between 10-30 mm, and a main chamber, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio (defined as the value of the exit area of the nozzle divided by the throat area of the nozzle) between four and nine, wherein the supersonic jet combustion engine is configured to generate a jet of combustion products from a first fuel/air mixture in the pre-chamber, through the supersonic nozzle, and into the main chamber with at least supersonic velocity (at least Mach 1) to ignite a second fuel/air mixture in the main chamber, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4.

[0010] In one embodiment, the present disclosure provides a method of operating a supersonic jet combustion engine, wherein the method comprises: a) igniting a first fuel/air mixture in a pre-chamber; b) introducing a jet of combustion products from the first fuel/air mixture from the pre-chamber, through a supersonic nozzle with a length between 10-30 mm, and into a main chamber with at least supersonic velocity (at least MACH 1), wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine; wherein the jet with supersonic velocity causes combustion of a second fuel/air mixture in the main chamber, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4.

[0011] Technical aspects of the method described above preferably include the capability of reliably combusting ultra-lean fuel mixtures, thereby improving fuel economy and combustion efficiency and potentially reducing NOx emissions in combustion engines.

[0012] Other aspects and advantages of this invention will be further appreciated from the following detailed description.

DETAILED DESCRIPTION

[0013] For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to the embodiments illustrated in the drawings, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of this disclosure is thereby intended.

[0014] In the present disclosure the term "about" can allow for a degree of variability in a value or range, for example, within 10%, within 5%, or within 1% of a stated value or of a stated limit of a range.

[0015] In the present disclosure the term "substantially" can allow for a degree of variability in a value or range, for example, within 90%, within 95%, or within 99% of a stated value or of a stated limit of a range.

[0016] In present disclosure the term "ultra-lean fuel mixtures" may refer to a fuel mixtures that has a fuel/air equivalence ratio that is lower than the typical values used in current combustion engines. In some aspect, the ratio is

below 0.40, 0.35, 0.30, 0.29, 0.28, 0.27, 0.26, 0.25, 0.24, 0.23, or 0.22. In some aspect, the ratio may even approach the lean flammability limit of such fuel in air.

[0017] In the present disclosure, the term "area ratio" may refer to the value of the exit area (A_e) of the nozzle divided by the throat area (A_t) of the nozzle. For the purpose of the present disclosure, the area ratio is required to be in the range of 4-9. The throat is the joint section of the converging part and the diverging part of a converging-diverging supersonic nozzle.

[0018] If not specifically defined, other terms such as pre-chamber, main chamber, and other terms should be interpreted as meanings generally accepted by a person with ordinary skill in the art.

[0019] Conventional combustion engines that utilize a dual chamber system, such as but not limited to power turbines of the type, generally introduce a fuel/air mixture stream (jet) through a fuel nozzle from the pre-chamber into the main chamber at subsonic speeds, that is, at a rate of travel that is below the speed of sound. In addition, the traditional convergent-divergent nozzle (also referred as DeLaval nozzle) used in space application normally has an area ratio of about 20-160 due to need to use a vigorously high-speed (typically a few thousand meters per second) jet to produce thrust. Disclosed herein are apparatus and methods of operating dual chamber engines which include a fuel convergent-divergent supersonic nozzle that introduces the jet from the pre-chamber into the main chamber at supersonic speeds, that is, at a rate of travel that is at or above the speed of sound (Mach 1). Surprisingly, the area ratio for the convergent-divergent supersonic nozzle is required to be in the range of 4-9 to generate a supersonic jet capable of igniting ultra-lean fuel mixtures within the main chamber. Such engines are then capable of combustion of ultra-lean fuel mixtures within the main chamber. Although the engines and fuel nozzles disclosed herein will be described in reference to the combustion of hydrogen/air fuel mixtures, it should be understood that the teachings disclosed herein are applicable to various other fuel/air mixtures, such as but not limited to natural gas/air fuel mixtures, and are therefore also within the scope of the invention.

[0020] According to one aspect of the invention, by introducing a jet into a main chamber at supersonic speeds, the lean flammability limit of hydrogen/air in comparison to subsonic jets may be extended, that is, an engine is capable of combusting fuel mixtures having relatively lower fuel-to-air mixing ratios. For example, under conditions present during investigations leading to the present invention, a hydrogen/air lean limit of a main chamber mixture achieved by introducing jets at subsonic speeds resulted in an equivalence ratio of 0.31. In comparison, introducing jets at supersonic speeds extended (reduced) this limit to an equivalence ratio of 0.22 without any significant increase in ignition delay time. These results indicated that the main chamber mixture can be leaner (that is, have a relatively lower fuel-to-air mixing ratio) with the use of supersonic jets. Therefore, hydrogen/air engines that introduce jets into their main chamber at supersonic speeds can achieve a hydrogen/air lean limit of their main chamber mixture of equal to or less than 0.4, and preferably equal to or less than 0.22.

[0021] The design of converging-diverging (C-D) nozzle plays a crucial role to generate hot supersonic jet that could ignite a ultra-lean hydrogen/air mixture. Since the dimension of the nozzle is very small, the heat transfer through the nozzle wall becomes severe. If the heat transfer is too much, the enough heat may get lost through the nozzle wall and would fail to ignite the lean mixture in the main chamber. Therefore, the total length of the C-D nozzle should not be more than 25 mm. For optimized operation, the C-D nozzle should not be more than 15 mm. However, the length of the nozzle cannot be shorter than 10 mm since to generate a fully developed supersonic jet without any boundary layer separation, 10 mm is the least required length. Nozzle entrance and throat have been smoothened by providing chamfer. Further, the diameter of the throat is also critical. One requirement for the present disclosure is to generate a jet that can sustain for a reasonably long time. Since pre-chamber has a constant amount of mass after combustion, the flow rate depends on the nozzle diameter. Bigger diameter means larger flow. This means the jet lifetime would be short. Also the jet velocity will be small. In short, the jet will be ineffective. A smaller diameter also means area to volume ratio will be too large. The jet will lose too much heat to make the ignition ineffective. The diameter of the throat should be within a range of about 0.5 mm-3.0 mm. A preferred range is about 1.0 mm-2.0 mm. A more preferred range is about 1.25 mm-1.75 mm.

[0022] In general, the introduction of subsonic jets into the main chamber results in a monotonic decrease in the static temperature in a downstream location. In contrast, supersonic jets cause shock structures that result in the static temperature fluctuating and then increasing at the downstream location. The increase in the static temperature behind the shock structures escalates ignition probability, which leads to a reduction in the lean flammability limit.

[0023] This reduction in the lean flammability limit was counterintuitive. Since supersonic jets have relatively higher velocities, it was considered possible that they could result in rapid mixing at a rate that is too high for ignition to occur. However, investigations leading to the invention determined that ultra-lean supersonic jets can result in fast and reliable ignition.

[0024] Various nozzle geometries were evaluated during the investigations leading to the present invention. Nozzles having converging-diverging (C-D) geometries were observed to outperform nozzles having straight or converging geometries. Intuitively, with regard to C-D nozzles, since temperature rise increases with an increase in the area ratio of a nozzle, it was expected that performance would improve with an increase in the area ratio of the nozzles. However, the investigations indicated that the highest tested area ratio nozzles did not substantially extend the lean flammability limit. Rather, a range of nozzle area ratios between about four and nine resulted in an extension of the lean flammability limit, that is, the lowest equivalence ratios, and showed improved performance relative to higher area ratio nozzles.

[0025] In one embodiment, the present disclosure provides a supersonic ignition device comprising a supersonic nozzle, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, and the length of the supersonic nozzle is at least 10 mm.

[0026] In one embodiment, the present disclosure provides a supersonic ignition device comprising a supersonic nozzle, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, and the

length of the supersonic nozzle is 10 mm-30 mm. In one aspect, the length is 10 mm-20 mm, or 10 mm-15 mm.

[0027] In one aspect of the supersonic ignition device, the length of the diverging section is longer than converging section.

[0028] In one aspect of the supersonic ignition device, the diameter of the throat is about 0.5 mm-3.0 mm. In one aspect, the diameter of the throat is about 1.0 mm-2.0 mm. In one aspect, the diameter of the throat is about 1.25 mm-1.75 mm.

[0029] In one embodiment, the present disclosure provides a method of igniting a fuel-air mixture by a supersonic ignition device comprising a supersonic nozzle, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, and the length of the supersonic nozzle is at least 10 mm, wherein the velocity of the jet released from the supersonic nozzle is at least supersonic speed (Mach 1). In one aspect, the length of the supersonic nozzle is 10 mm-30 mm, 10 mm-20 mm, or 10 mm-15 mm. In one aspect, the length of the diverging section is longer than converging section. In one aspect, the fuel-air mixture is an ultra-lean mixture with fuel-air ratio of equal to or less than 0.4. In one aspect, fuel-air mixture is an ultra-lean mixture with fuel-air ratio is 0.22-0.29. In one aspect, fuel-air mixture is an ultra-lean mixture with fuel-air ratio is 0.22-0.23.

[0030] In one embodiment, the present disclosure provides a supersonic jet combustion engine comprising a pre-chamber, a supersonic nozzle with a length between 10-30 mm, and a main chamber, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio range between four and nine, wherein the supersonic jet combustion engine is configured to generate a jet of combustion products from a first fuel/air mixture in the pre-chamber, through the supersonic nozzle, and into the main chamber with at least supersonic velocity (at least Mach 1) to ignite a second fuel/air mixture in the main chamber. In one aspect, the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4, 0.35, 0.30, 0.29, 0.28, 0.27, 0.26, 0.25, 0.24, 0.23, or 0.22. In one aspect, fuel-air mixture is an ultra-lean mixture with fuel-air ratio is 0.22-0.40, 0.22-0.35, 0.22-0.30, 0.22-0.29, 0.22-0.28, 0.22-0.27, 0.22-0.26, 0.22-0.25, 0.22-0.24, or 0.22-0.23. In one aspect, the length of the supersonic nozzle is 10 mm-30 mm, 10 mm-20 mm, or 10 mm-15 mm. In one aspect, the diameter of the throat is about 0.5 mm-3.0 mm, 1.0 mm-2.0 mm, or 1.25 mm-1.75 mm.

[0031] In one embodiment, the present disclosure provides a method of operating a supersonic jet combustion engine, wherein the method comprises: a) igniting a first fuel/air mixture in a pre-chamber; b) introducing a jet of combustion products from the first fuel/air mixture from the pre-chamber, through a supersonic nozzle with a length between 10-30 mm, and into a main chamber with at least supersonic velocity (at least Mach 1), wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine; wherein the jet with supersonic velocity causes combustion of a second fuel/air mixture in the main chamber, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4. In one aspect, the second fuel/air mixture has a fuel/air equivalence ratio of equal to or less than 0.35, 0.30, 0.29, 0.28, 0.27, 0.26, 0.25, 0.24, 0.23, or 0.22. In one aspect, the second fuel/air mixture has a fuel/air equivalence ratio of 0.22-0.40, 0.22-0.35, 0.22-0.30, 0.22-0.29, 0.22-0.28, 0.22-0.27, 0.22-0.26, 0.22-0.25, 0.22-0.24, or 0.22-0.23. In one aspect, the length of the supersonic nozzle is 10 mm-30 mm, 10 mm-20 mm, or 10 mm-15 mm. In one aspect, the length of the supersonic nozzle is 10 mm-30 mm, 10 mm-20 mm, or 10 mm-15 mm. In one aspect, the diameter of the throat is about 0.5 mm-3.0 mm, 1.0 mm-2.0 mm, or 1.25 mm-1.75 mm.

[0032] Experimental Setup

[0033] A small volume, 100 cc cylindrical stainless steel (SS316) pre-chamber was attached to the rectangular (10"× 6"×6") carbon steel (C-1144) main chamber. The main chamber to pre-chamber volume ratio was 100:1.

[0034] A stainless steel orifice plate with various nozzle designs separated both chambers. Jet ignition characteristics of hydrogen/air for six different nozzle designs (straight, convergent and convergent-divergent (C-D)) were studied. Nozzle dimensions are tabulated in Table 1.

[0035] A thin, 0.001" thick aluminum diaphragm isolated both chambers with dissimilar equivalence ratios from mixing. A provision was made to heat up the fuel/air mixture in both chambers up to 600 K using built-in heating cartridges (Thermal Devices, FR-E4A30TD) inserted into the main chamber side and bottom walls. For the present disclosure, all tests were done at room temperature 300 K. The mixture in the pre-chamber was ignited by an electric spark created by a 0-40 kV capacitor discharge ignition (CDI) system. An industrial grade double Iridium Bosch spark plug was attached at the top of the pre-chamber. The transient pressure histories of both chambers were recorded using high resolution ~5 kHz Kulite (XTEL-190) pressure transducers combined with NI-9237 signal conditioning and pressure acquisition module via by LabVIEW software. Two K-type thermocouples were positioned at the top and bottom of the main chamber to ensure uniform temperature lengthwise thus avoiding natural convection or buoyancy effect. A 1 inch thick polymer insulation jacket was wrapped around the pre-chamber and main chamber to minimize heat loss. Fuel (industrial grade hydrogen) and air were introduced separately to the main chamber using the partial pressure method. Unlike the main chamber where fuel and air mixed in the chamber itself, fuel/air in the pre-chamber was premixed in a small stainless steel mixing chamber (2.5 cm diameter, 10 cm long) prior going into pre-chamber.

[0036] Diaphragm Assessment

[0037] After an electric spark ignites the fuel/air mixture in the pre-chamber, pre-chamber pressure starts to rise. Because the volume of the pre-chamber is very small and the initial flow field is quiescent, combustion in it is very likely to occur through the propagation of a laminar flame. Once pre-chamber pressure reaches the rupture pressure of aluminum diaphragm, the diaphragm bursts and the pressure difference between pre and main chamber results in a transient compressible jet with large density ratio with respect to the relatively cold fuel/air mixture in the main chamber. The jet further penetrates into the main chamber and could possibly ignite the mixture in the main chamber under favorable conditions. The jet properties, such as temperature, mean and fluctuating velocities are largely influenced by the pre-chamber combustion process, orifice geometry.

[0038] An accurate assessment of diaphragm rupture time is required in order to calculate precise ignition delay. Ignition delay is defined as the time required from the time

of diaphragm rupture to the instant of main chamber ignition. A series of tests were conducted to find out when and at what conditions the thin aluminum diaphragm will rupture. A potential difference of 5V was applied using National Instrument DAQ module (NI-9263) to the aluminum diaphragm via two thin copper wires touching the diaphragm. As the diaphragm ruptured, copper wires lost contact with aluminum. As a result, voltage dropped sharply marking the event of rupture. The rupture time is defined as the time interval between the completion of the electric spark in the pre-chamber and the rupture of the diaphragm. It was found the rupture time for hydrogen/air mixtures to be 2.6±0.1 milliseconds, consistent for all test conditions.

[0039] High-Speed Schlieren and OH* Chemiluminescence Imaging

[0040] A customized trigger box synchronized with the CDI spark ignition system sent a master trigger to two high-speed cameras for simultaneous Schlieren and OH* chemiluminescence imaging. The main chamber was installed with four rectangular (5.5"×3.5"×0.75") quartz windows (type GE124) on its sides for optical access. High quality UV transparent (85% UV transmission at 240 nm) quartz windows were used. One pair of the windows was used for ztype Schlieren system. Z-type Schlieren system positions light source, mirrors, test section and camera in a "Z" shape. Another pair was selected for simultaneous OH* chemiluminescence measurement. The high-speed Schlieren technique was used to visualize the evolution of the hot jet as well as the ignition process in the main chamber. The system consisted of a 100W (ARC HAS-150 HP) mercury lamp light source with a condensing lens, two concave parabolic mirrors (6" diameter, focal length 1.2 m), and a high-speed digital camera (Vision Research Phantom v7). Schlieren images were captured with a resolution of 800×720 pixels with a framing rate up to 12000 fps.

[0041] The simultaneous high-speed OH* chemiluminescence measurement provided a better view of the ignition and flame propagation processes. A high-speed camera (Vision Research Phantom v640) camera, along with videoscope gated image intensifier (VS4-1845HS) with 105 mm UV lens, were utilized to detect OH* signals at very narrow band 386 ±10 nm detection limit. The intensifier was externally synced with the camera via high-speed relay and acquired images at the same frame rate (up to 12,000 fps) with the Phantom camera. A fixed intensifier setting (gain 65,000 and gate width 20 microseconds, aperture f8) was used all through.

[0042] Hot Wire Pyrometry (HWP) and Infrared (IR) Imaging

[0043] The Hot Wire Pyrometry (HWP) technique provides a time resolved temperature field along a line during jet propagation. Planar time-dependent radiation intensity measurements of the flame were acquired using an infrared camera (FLIR SC6100) with an InSb detector. The view angle of the camera was aligned perpendicular to the flame axis (50 cm from the burner center to the camera lens) such that the half view angle of the camera is less than 10 deg. The radiation intensity detected by each pixel of the camera focal plane array can be approximated by a parallel line-of-sight because of the small view angle. The spatial resolution is 0.2×0.2 mm^2 for each pixel. The band pass filter was used to measure the radiation intensity of water vapor at the wavelength of 2.58±0.03 μm.

[0044] Schlieren Particle Image Velocimetry (SPIV)

[0045] In Schlieren PIV (SPIV) method a turbulent flow field containing turbulent eddies serve as PIV particles. These self-seeded successive Schlieren images with short time delay, Δt can be correlated to find instantaneous velocity field information. Due to path integrated nature of Schlieren an inverse Abel transformation is required to find true velocity field. A z-type Herschellian high-speed Schlieren system was used for Schlieren PIV. The Schlieren system consisted of a 100 Watt mercury arc lamp (Q series, 60064-100MC-Q1, Newport Corporation, Model 6281) light source with a condensing lens assembly (Q Series, F/1, Fused Silica, Collimated, 200-2500 nm), two concave parabolic mirrors (6" diameter, aperture f/8, effective focal length 1219.2 mm), a knife-edge, an achromatic lens (f=300 mm) to collimate the light, a beam splitter (1" cube, Thorlabs PBS251) and two identical high speed CCD cameras (v711, Vision Research Phantom). Utilization of two high speed cameras lie in precise controlling of the inter-frame delay, Δt. A small Δt is essential in order to resolve high exit jet velocity, U_0.

[0046] The ultra-lean fuel air ignition results for the different type of nozzles were obtained and presented in Table 1.

TABLE 1

Nozzle type, dimension, and the measured lean ϕ_{limit} for the different nozzles

Nozzle #	Type	d_{inlet} mm	d_{throat} mm	d_{exit} mm	$\frac{A_e}{A_t}$	ϕ_{limit}*
1	Straight	1.5	1.5	1.5	NA	0.34
2	Straight	3	3	3	NA	0.31
3	Convergent	3	NA	1.5	NA	0.29
4	C-D	3	1.5	3	4	0.22
5	C-D	3	1.5	4.5	9	0.23
6	C-D	3	1.5	6	16	0.29
7	C-D	3	1.5	3.75	6.25	0.22
8	C-D	3	1.5	7.5	25	0.32

[0047] From the data presented in Table 1, it was surprisingly found that the converging-diverging type supersonic nozzles 4, 5, and 7 with the area ration range of 4-9 provided the best ignition result that led to the lowest lean fuel-air ratios of 0.22-0.23. Intuitively, with regard to C-D nozzles, since temperature rise increases with an increase in the area ratio of a nozzle, it was expected that performance would improve with an increase in the area ratio of the nozzles. Hot Wire Pyrometry (HWP) technique was used to measure the jet temperature at a location that is 4 mm downstream of the nozzle exit. The results surprisingly showed that nozzle 4 and nozzle 5 (i.e., nozzles with area ratio 4 and 9) exhibit higher temperatures at the centerline than the other nozzles.

[0048] Radiation intensity (radiation intensity measurement is equivalent to temperature, higher the temperature, higher is radiation intensity) along the jet centerline in axial (i.e., jet propagation) direction was also measured for each nozzles. For straight nozzles (nozzle 1 and 2), the radiation intensity drops in a monotonic fashion, indicating the temperature of the jet keep decreasing as a result of mixing between the hot jet and the cold ambient mixture. However, for nozzles 3, 4 and 5, the measured radiation intensity first fluctuates near the nozzle exit due to the presence of shocks, for which the static temperature increases downstream of the shock. It then increases rapidly at a location further down-

stream, indicating the establishment of a higher temperature zone at that location. Resulted ignition of the main chamber lean mixture was observed to take place at this 'high-temperature zone' for nozzles 3, 4 and 5. In other words, this 'high-temperature zone' downstream of the nozzle exit is responsible for reducing the lean limit of the main chamber mixture by using a supersonic nozzle.

[0049] Radiation intensity along the jet centerline in axial explains why supersonic jets may ignite a lean mixture. Supersonic jets contain shock structure. The property of the hot gas changes across a shock. The static temperature rises across the shock. In the presence of a series of shock structures, the static temperature keeps on rising, and at the end of final shock the increases static temperature creates a 'high-temperature zone.' Since velocity near this zone is smaller compared to jet exit, and the mixing is enhanced; the hot supersonic jet gets time to mix with lean fuel/air mixture and has sufficient time for the chemistry to occur. Thus, the ignition occurs due to a favorable condition of two properties, 1) high-temperature zone, 2) reduced velocity/turbulence. C-D nozzles with area ratio between 4 to 9 achieve both the conditions. Thus, these nozzles can extend the flammability limit. However, the C-D nozzles with higher area ratio create a vigorously supersonic jet. Thus, even though they too create a high-temperature zone, due to a strong velocity/turbulent field the high-temperature zone failed to ignite unburned charge in the main chamber. Excessive turbulence extinguishes all the ignition kernels. Thus, a moderate turbulence created by C-D nozzles with area ratio between 4 to 9 could extend the lean flammability limit of hydrogen-air.

[0050] Since ignition delay generally increases with a decrease in the equivalence ratio, it was further expected that extension of the lean flammability limit would result in an increase in the ignition delay time. However, the investigations indicated that the increase in ignition delay time when using supersonic jets relative to subsonic jets was extremely small, and for practical purposes may be considered negligible.

[0051] Based on observations during the investigations, an ignition Damkohler number was determined below which ignition was unlikely to occur and above which the ignition probability was high. The Damkohler number is used herein as the ratio of the characteristic flow timescale to the characteristic chemical reaction timescale, which represents the competition between the turbulent mixing and chemical reactions. For example, if the temperature of a jet drops too rapidly, it may not be capable of igniting the main chamber mixture. Concurrently, if the velocity of the jet is too high, the chemical reaction may not have enough time to occur. The Damkohler number is independent of pre-chamber configuration and operating condition, such as chamber pressure and temperature, orifice size, pre-chamber volume, and geometry. This non-dimensional parameter can be used to promote successful ignition in the main chamber and therefore is believed to be beneficial for the design and optimization of pre-chambers for combustion engines. In the investigations leading to the present invention, a minimum Damkohler number of eleven was determined to be required to result in main chamber ignition.

[0052] By incorporating supersonic fuel nozzles into dual chamber engines, improvements to combustion efficiency and reductions to NOx emissions may be achieved.

[0053] In summary, a vital finding of the present disclosure is the extension of lean limit, ϕ_{limit} and lower ignition delay of the lean hydrogen/air mixture in the main chamber by using a supersonic nozzle than a straight nozzle. Ignition in the main chamber was achieved for ϕ=0.22 using a supersonic nozzle. Simultaneous Schlieren and OH* Chemiluminescence results show ignition initiates from the side surface of the hot jet. Due to the presence of shock structures at the exit of supersonic jet, supersonic jet exit temperature is higher than straight nozzles. Increase in the static temperature behind the shocks thus escalates ignition probability, which is the main reason that the lean limit can be further reduced. Moreover, converging and C-D nozzles with a unique area ratio range of 4-9 created a high temperature zone downstream of shocks responsible for initiation of ignition. This may help better controlling of the ignition location and ignition delays and design a better pre-chamber for lean combustion,

[0054] Those skilled in the art will recognize that numerous modifications can be made to the specific implementations described above. The implementations should not be limited to the particular limitations described. Other implementations may be possible.

1. A supersonic ignition device comprising a supersonic nozzle, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, and the length of the supersonic nozzle is 10-30 mm, and the supersonic nozzle is configured to be capable of igniting an ultra-lean fuel-air mixture.

2. The supersonic ignition device of claim **1**, wherein the length of the supersonic nozzle is 10-20 mm.

3. The supersonic ignition device of claim **1**, wherein the supersonic nozzle has a throat, wherein the throat has a diameter of 1.0-2.0 mm.

4. A supersonic jet combustion engine comprising a pre-chamber, a supersonic nozzle with a length between 10-30 mm, and a main chamber, wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine, wherein the supersonic jet combustion engine is configured to generate a jet of combustion products from a first fuel/air mixture in the pre-chamber, through the supersonic nozzle, and into the main chamber with at least supersonic velocity (at least Mach 1) to ignite a second fuel/air mixture in the main chamber.

5. The supersonic jet combustion engine of claim **4**, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4.

6. The supersonic jet combustion engine of claim **4**, wherein the second fuel/air mixture has a fuel/air equivalence ratio of 0.22-0.29.

7. The supersonic jet combustion engine of claim **4**, wherein the second fuel/air mixture has a fuel/air equivalence ratio of 0.22-0.23.

8. The supersonic jet combustion engine of claim **4**, wherein the supersonic nozzle has a length between 10-20 mm.

9. The supersonic jet combustion engine of claim **4**, wherein the supersonic nozzle has a throat, wherein the throat has a diameter of 1.0-2.0 mm.

10. A method of operating a supersonic jet combustion engine, wherein the method comprises: a) igniting a first fuel/air mixture in a pre-chamber; b) introducing a jet of combustion products from the first fuel/air mixture from the

pre-chamber, through a supersonic nozzle with a length between 10-30 mm, and into a main chamber with at least supersonic velocity (at least Mach 1), wherein the supersonic nozzle has a converging-diverging geometry and an area ratio between four and nine; wherein the jet with supersonic velocity causes combustion of a second fuel/air mixture in the main chamber, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of equal to or less than 0.4.

11. The method of claim **10**, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of 0.22-0.29.

12. The method of claim **10**, wherein the second fuel/air mixture is an ultra-lean fuel mixture with a fuel/air equivalence ratio of 0.22-0.23.

13. The method of claim **10**, wherein the supersonic nozzle has a length between 10-20 mm.

14. The method of claim **10**, wherein the fuel is hydrogen, gasoline or natural gas.

15. The method of claim **10**, wherein the fuel is hydrogen

16. The method of claim **10**, wherein the jet results in a Damkohler number of equal to or greater than 11.

17. The method of claim **10**, wherein the supersonic nozzle has a throat, wherein the throat has a diameter of 1.0-2.0 mm.

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