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Borissov

(54) **APPARATUS AND METHODS FOR PROVIDING UNIFORMLY VOLUME DISTRIBUTED COMBUSTION OF FUEL**

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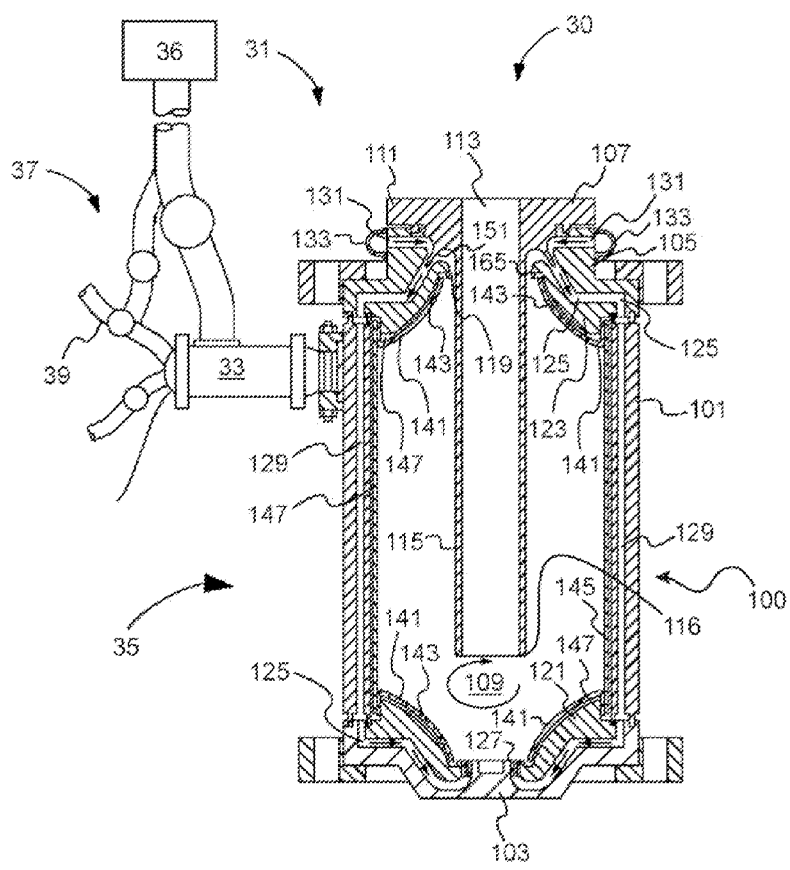
(57) **ABSTRACT**

A combustor apparatus and method for the combustion of viscous fuels are provided. The combustor apparatus can include a precombustion chamber particularly adapted to heat and at least partially combust a heavy primary fuel, and a main combustion chamber adapted to combust the primary fuel uniformly through the main combustion chamber (in flameless mode). The precombustion chamber can include at least one air injection inlet port positioned to induce a first stage vortex in the main body portion of the housing of the precombustion chamber. Further, the precombustion chamber can be interfaced with a main combustion chamber to induce a second stage vortex within the main combustion chamber. The main combustion chamber can have an extended axial length in order to accommodate heavier fuels that require additional time to sufficiently combust (oxidize) within the combustion chamber.



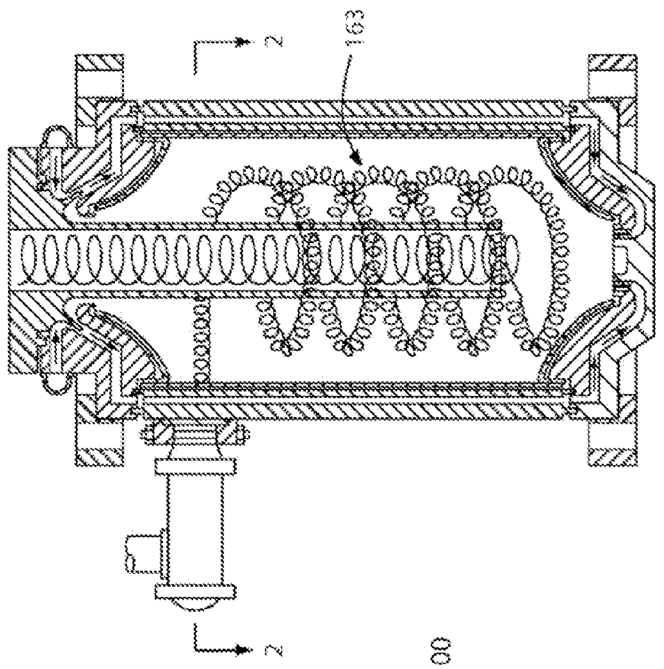

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Fig. 1B

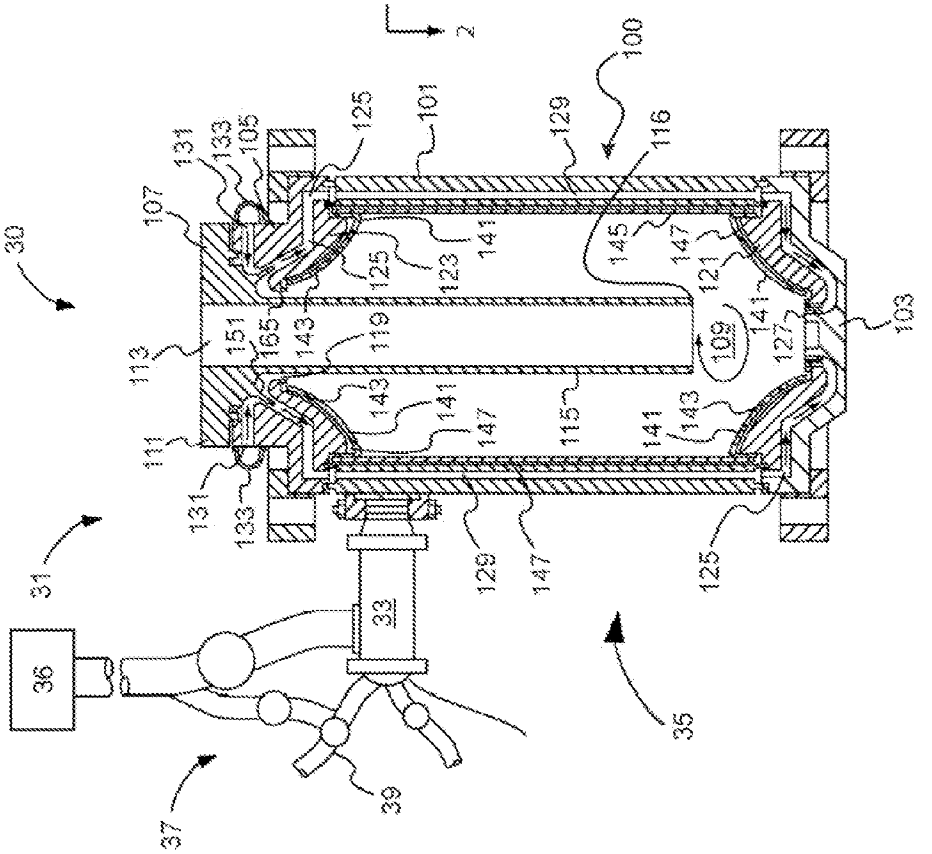
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Fig. 1A

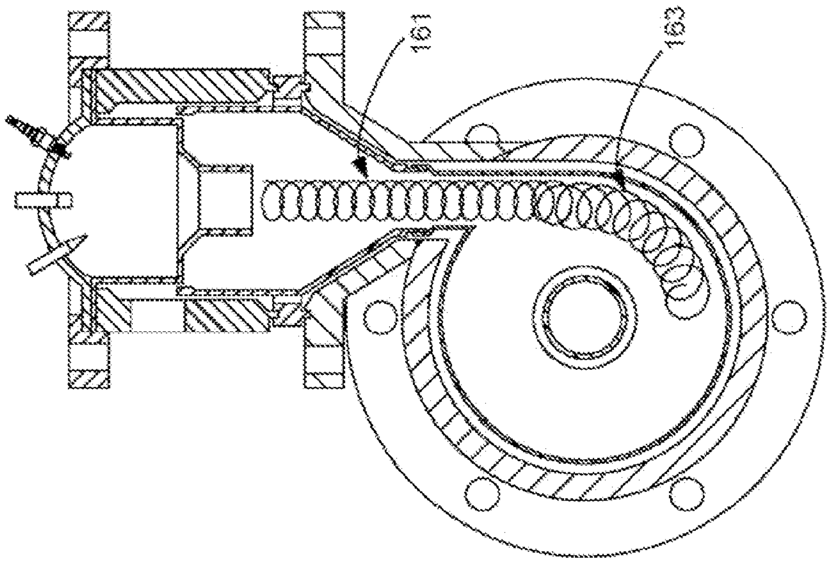
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Fig. 2B

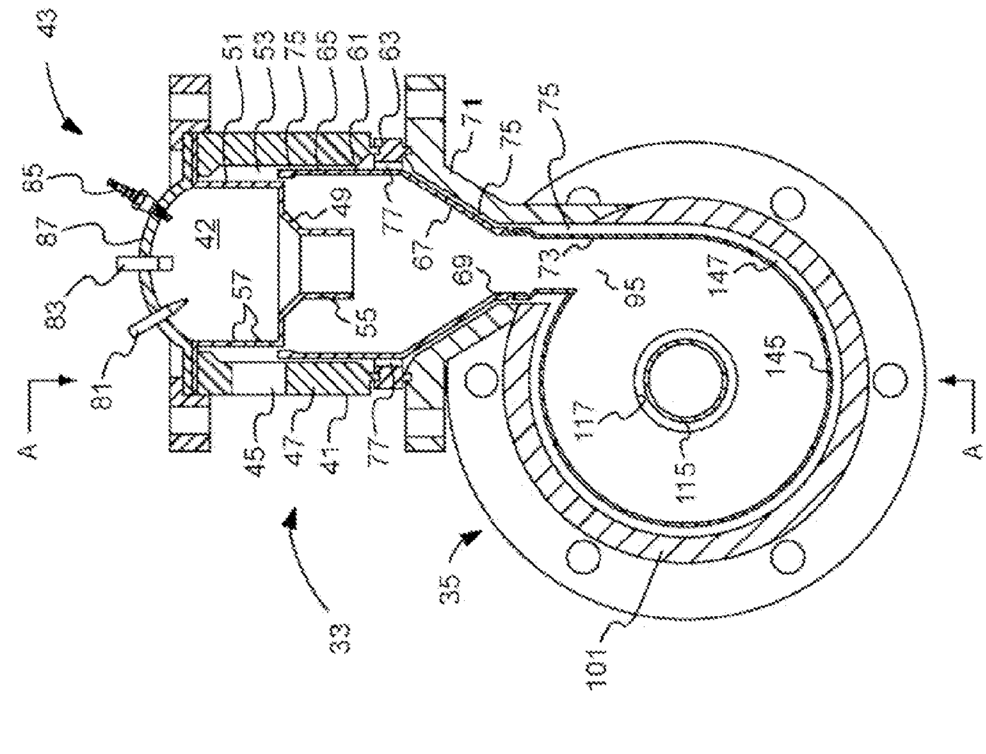
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Fig. 2A

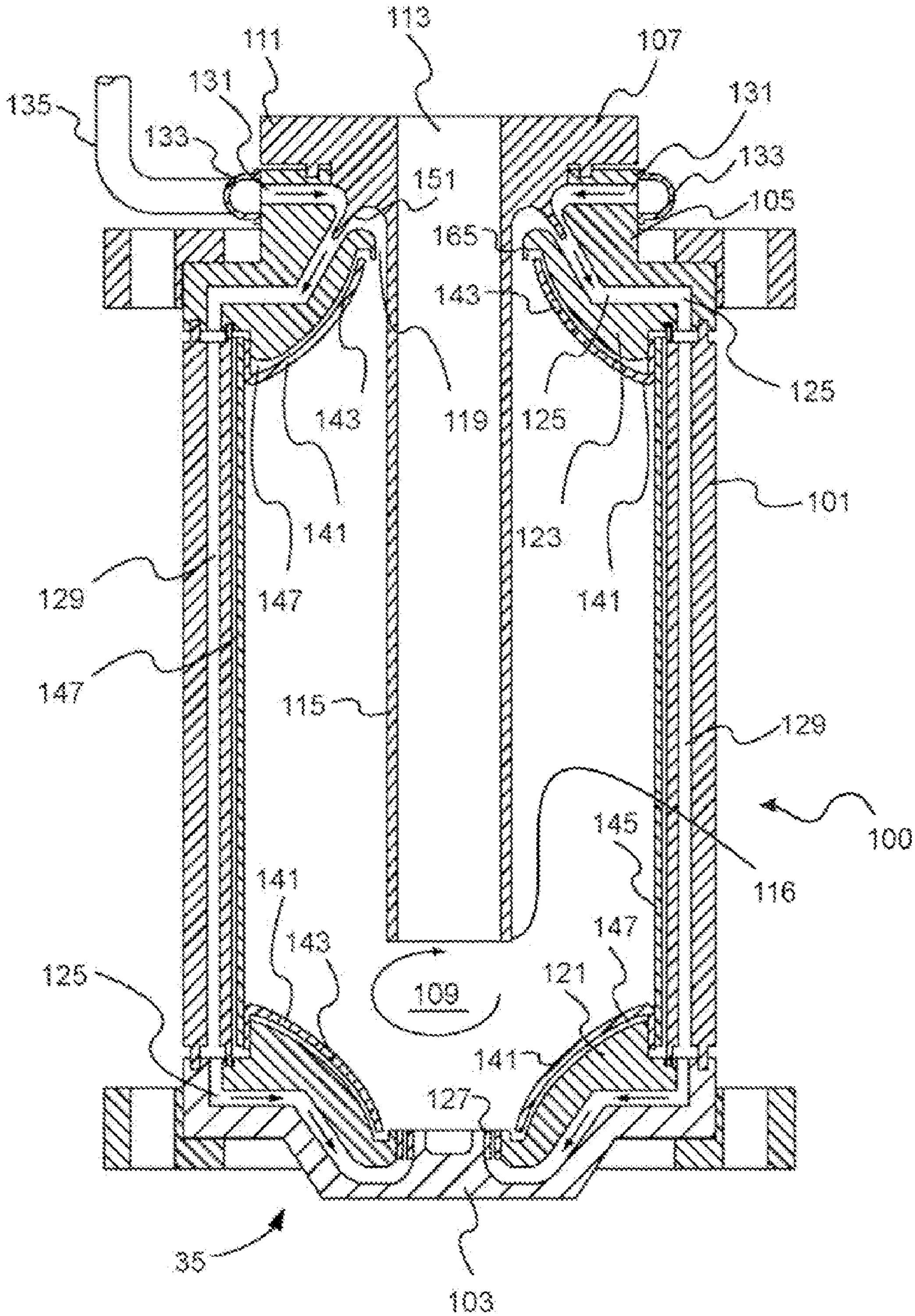
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Fig. 3A

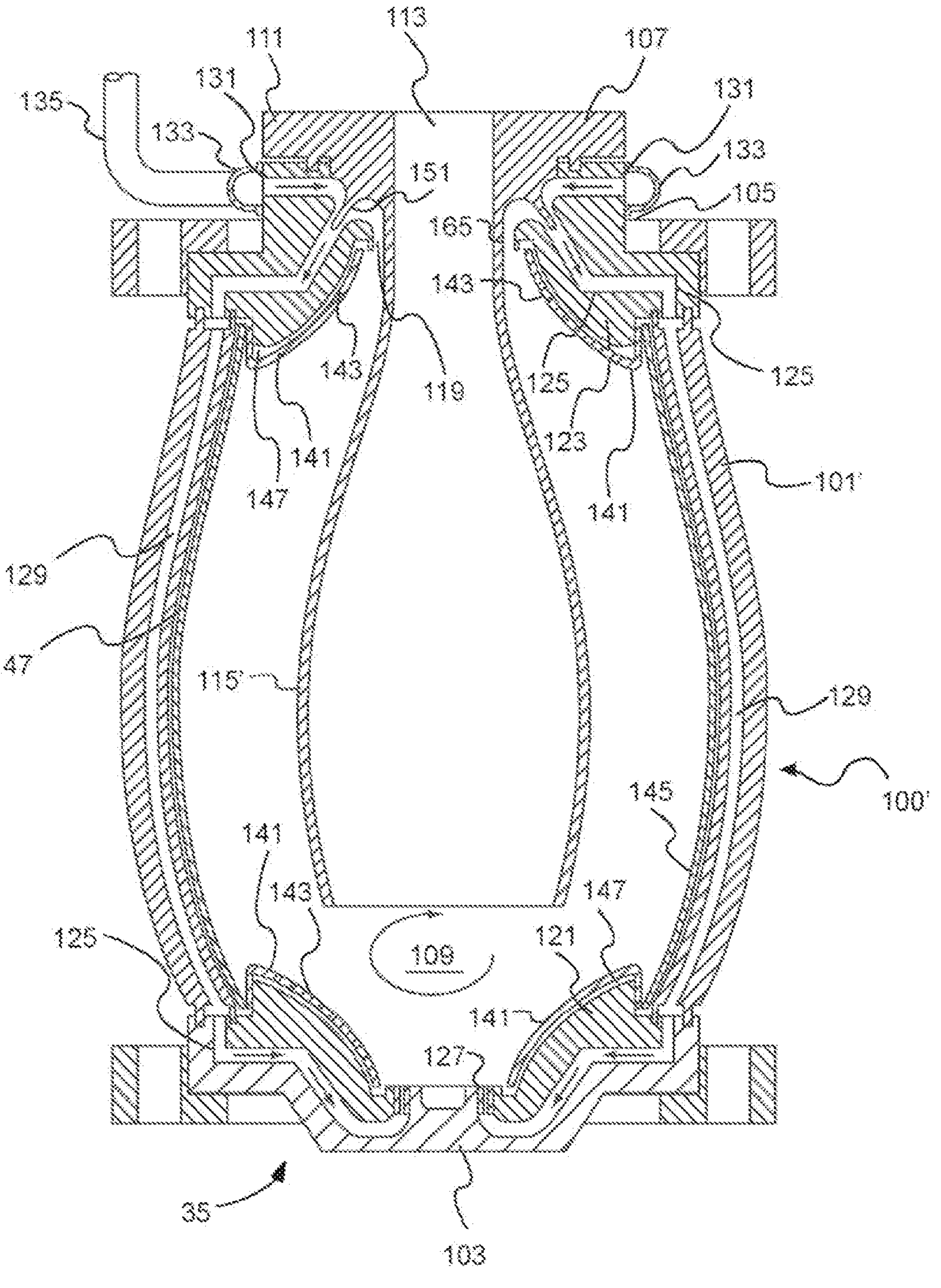
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Fig. 3B

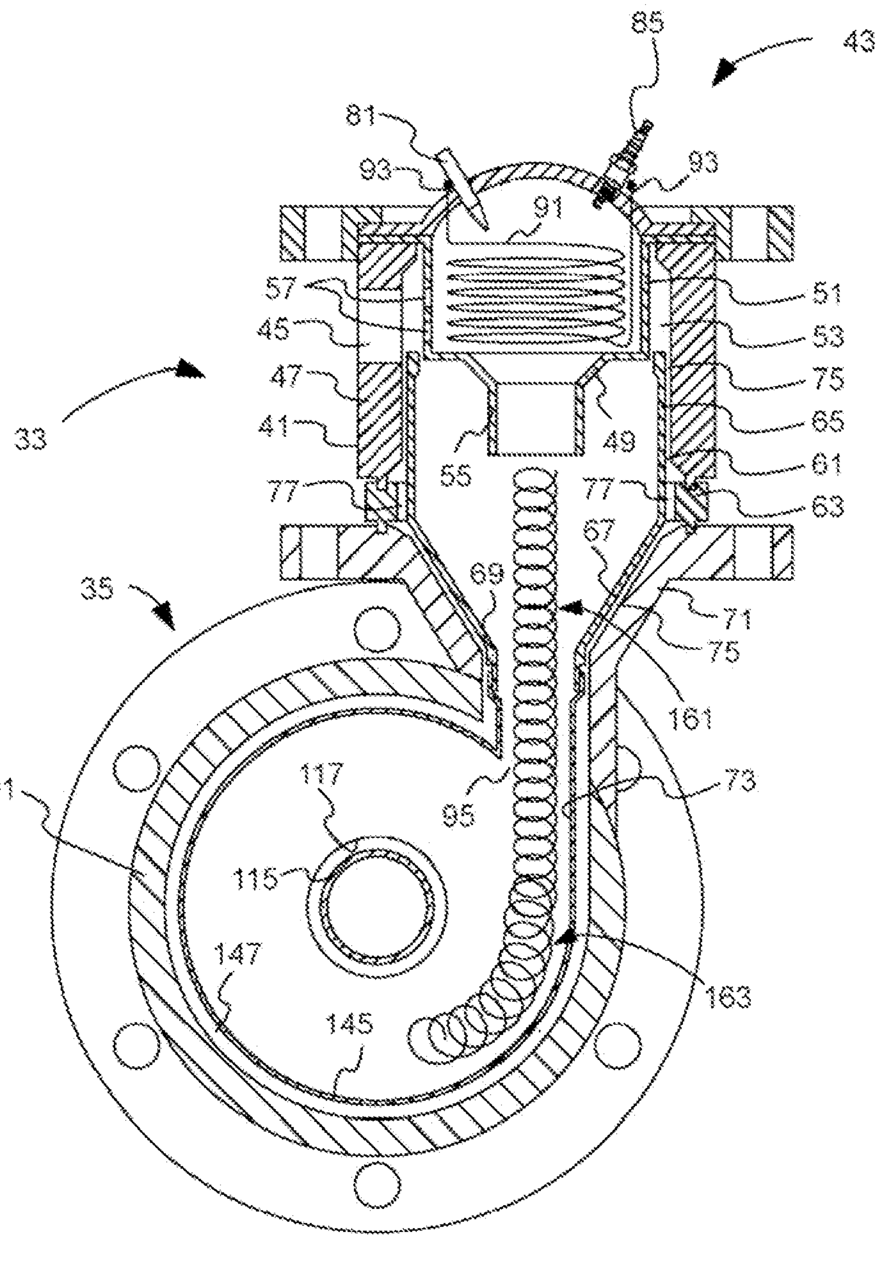
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Fig. 4

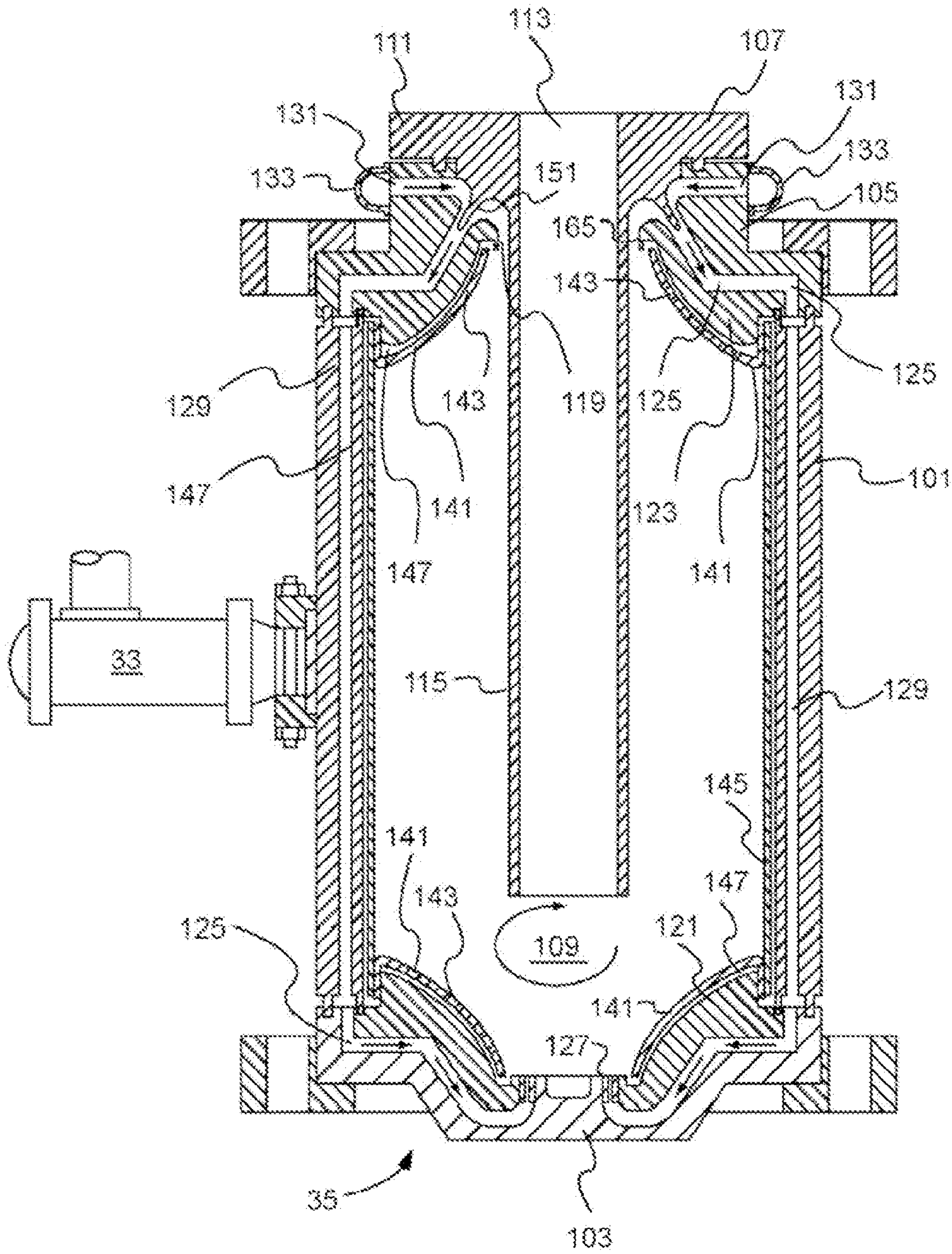
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Fig. 5

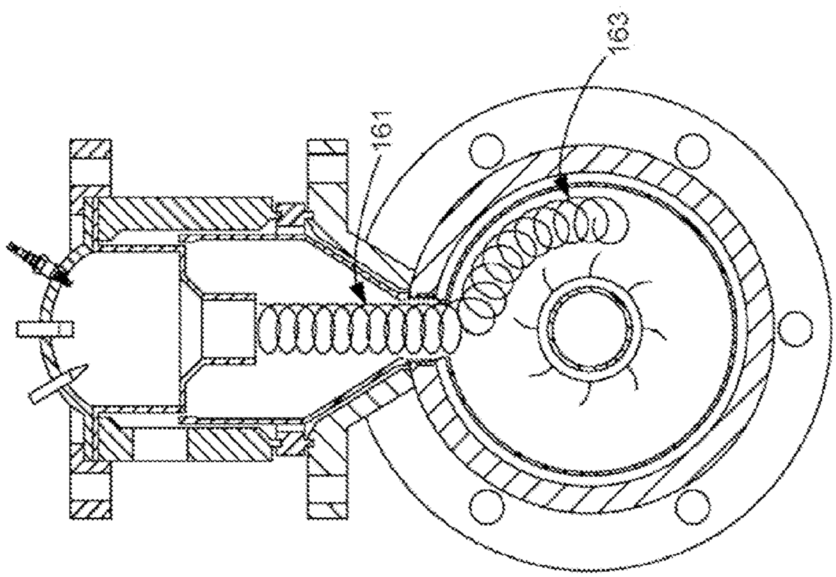
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Fig. 6B

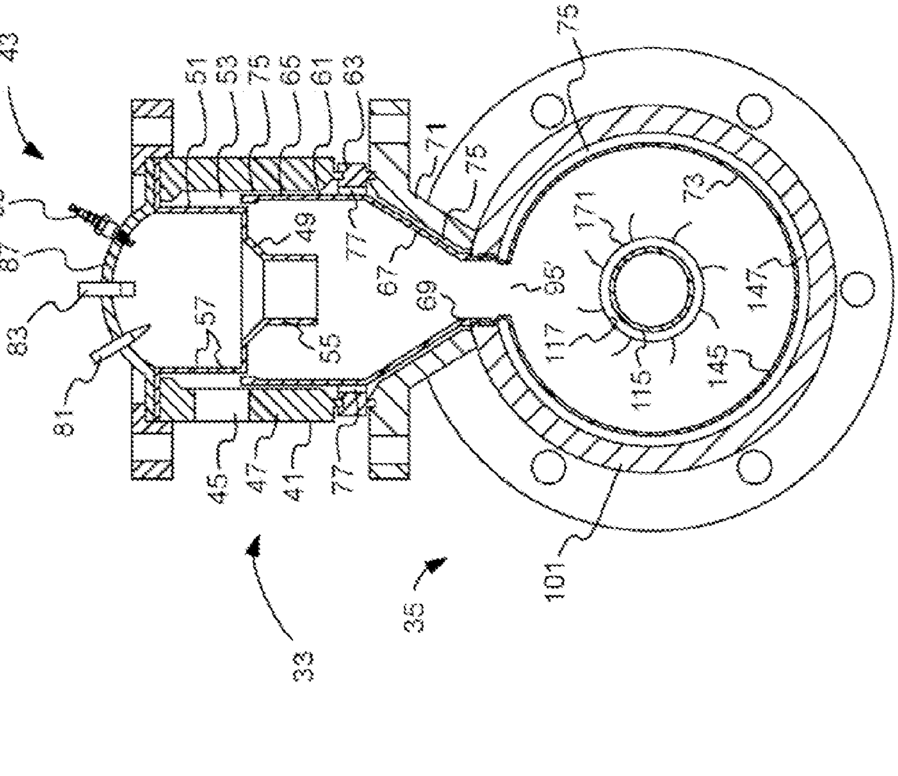
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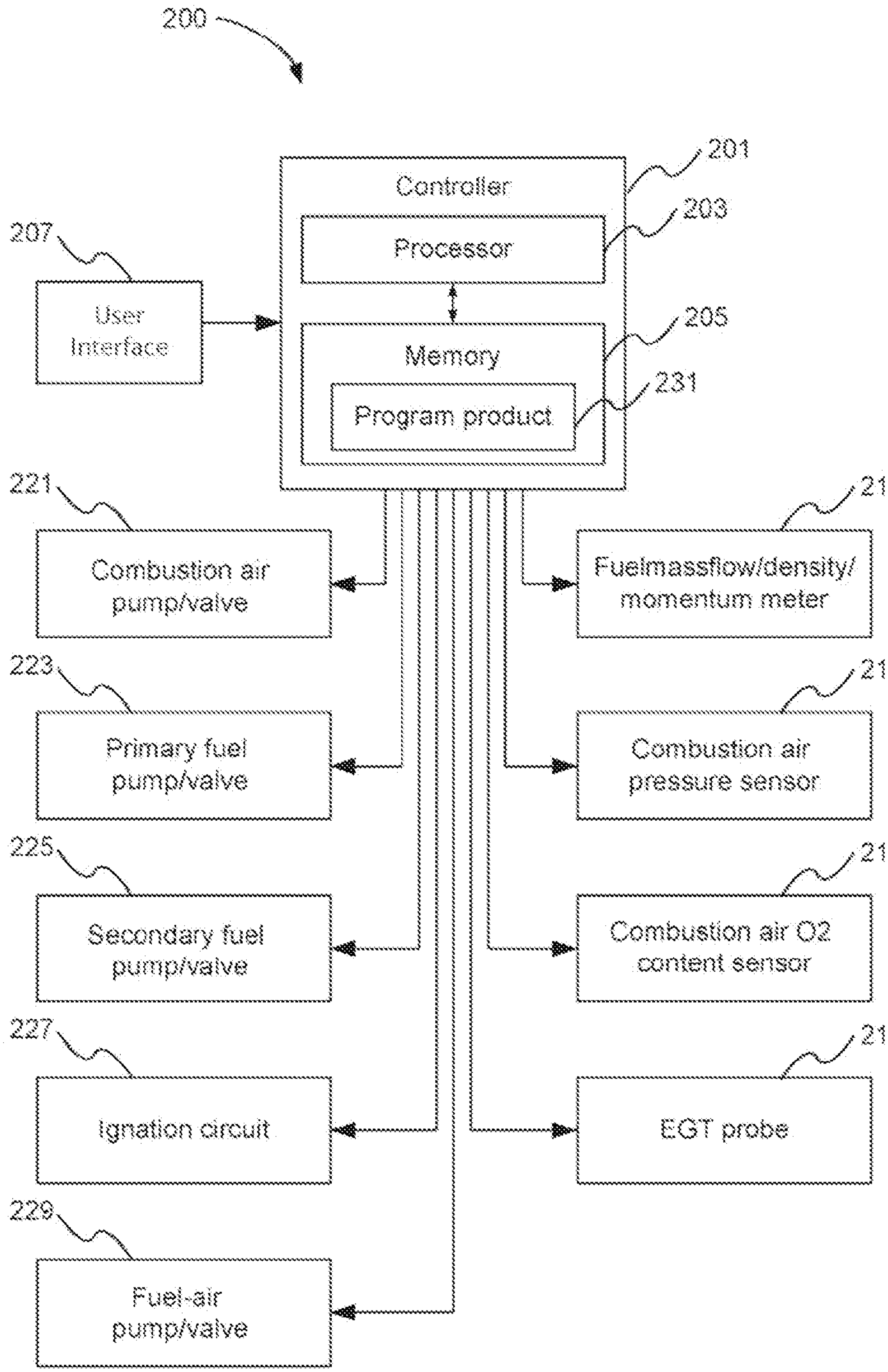
Fig. 6A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Controller
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Processor
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User Interface
Memory
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Program product
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221
Combustion air pump/valve
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Fuelmassflow/density/ momentum meter
223
Primary fuel pump/valve
21
Combustion air pressure sensor
225
Secondary fuel pump/valve
21
Combustion air O2 content sensor
227
Ignation circuit
21
EGT probe
229
Fuel-air pump/valve

Fig. 7

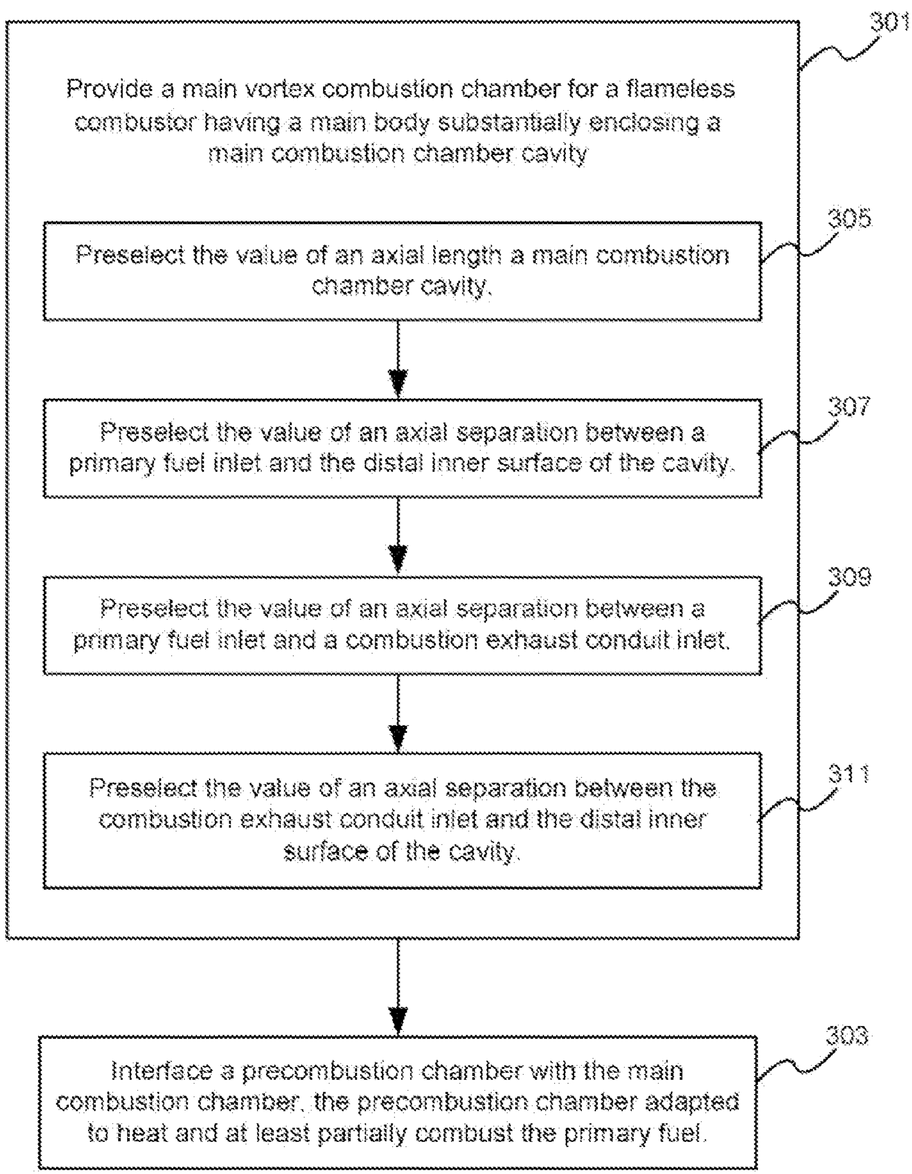

301
Provide a main vortex combustion chamber for a flameless combustor having a main body substantially enclosing a main combustion chamber cavity
305
Preselect the value of an axial length a main combustion chamber cavity.
307
Preselect the value of an axial separation between a primary fuel inlet and the distal inner surface of the cavity.
309
Preselect the value of an axial separation between a primary fuel inlet and a combustion exhaust conduit inlet.
311
Preselect the value of an axial separation between the combustion exhaust conduit inlet and the distal inner surface of the cavity.
303
Interface a precombustion chamber with the main combustion chamber, the precombustion chamber adapted to heat and at least partially combust the primary fuel.

Fig. 8

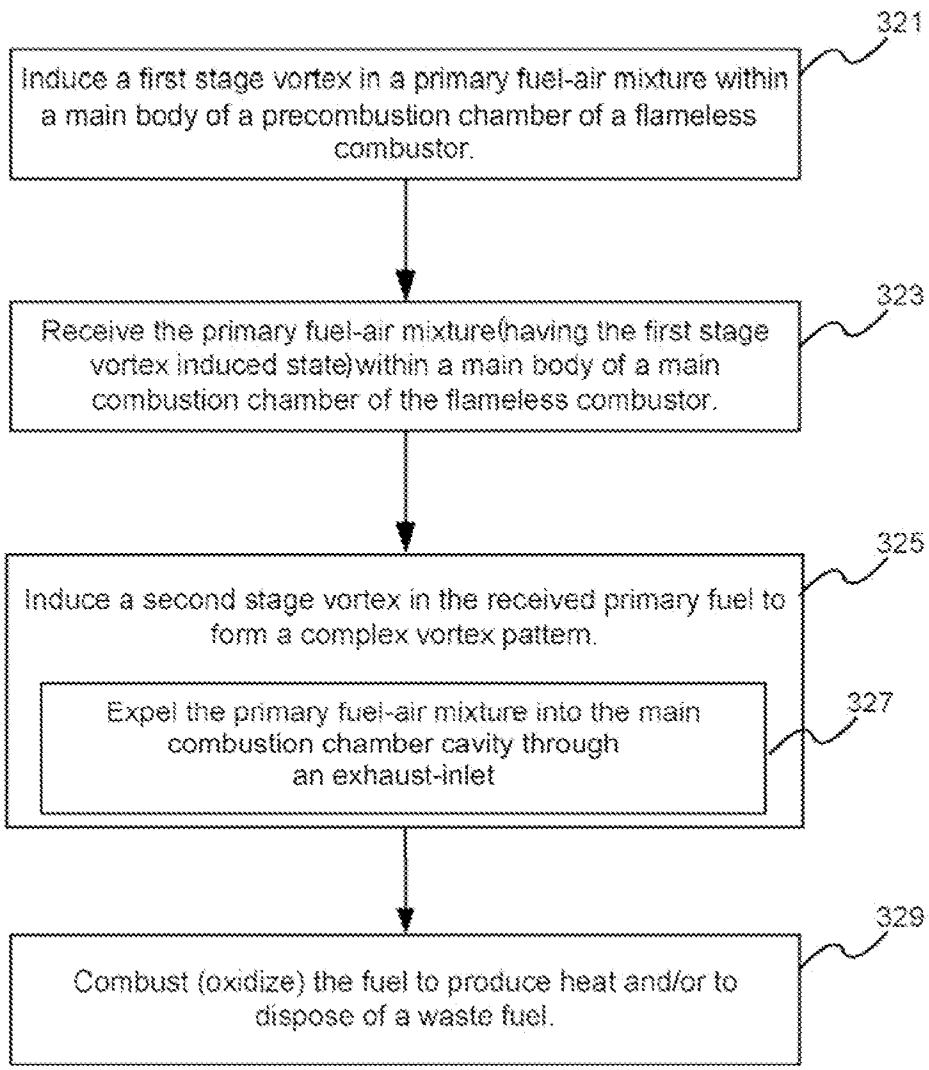

321
Induce a first stage vortex in a primary fuel-air mixture within a main body of a precombustion chamber of a flameless combustor.
323
Receive the primary fuel-air mixture(having the first stage vortex induced state)within a main body of a main combustion chamber of the flameless combustor.
325
Induce a second stage vortex in the received primary fuel to form a complex vortex pattern.
327
Expel the primary fuel-air mixture into the main combustion chamber cavity through an exhaust-inlet
329
Combust (oxidize) the fuel to produce heat and/or to dispose of a waste fuel.

Fig. 9

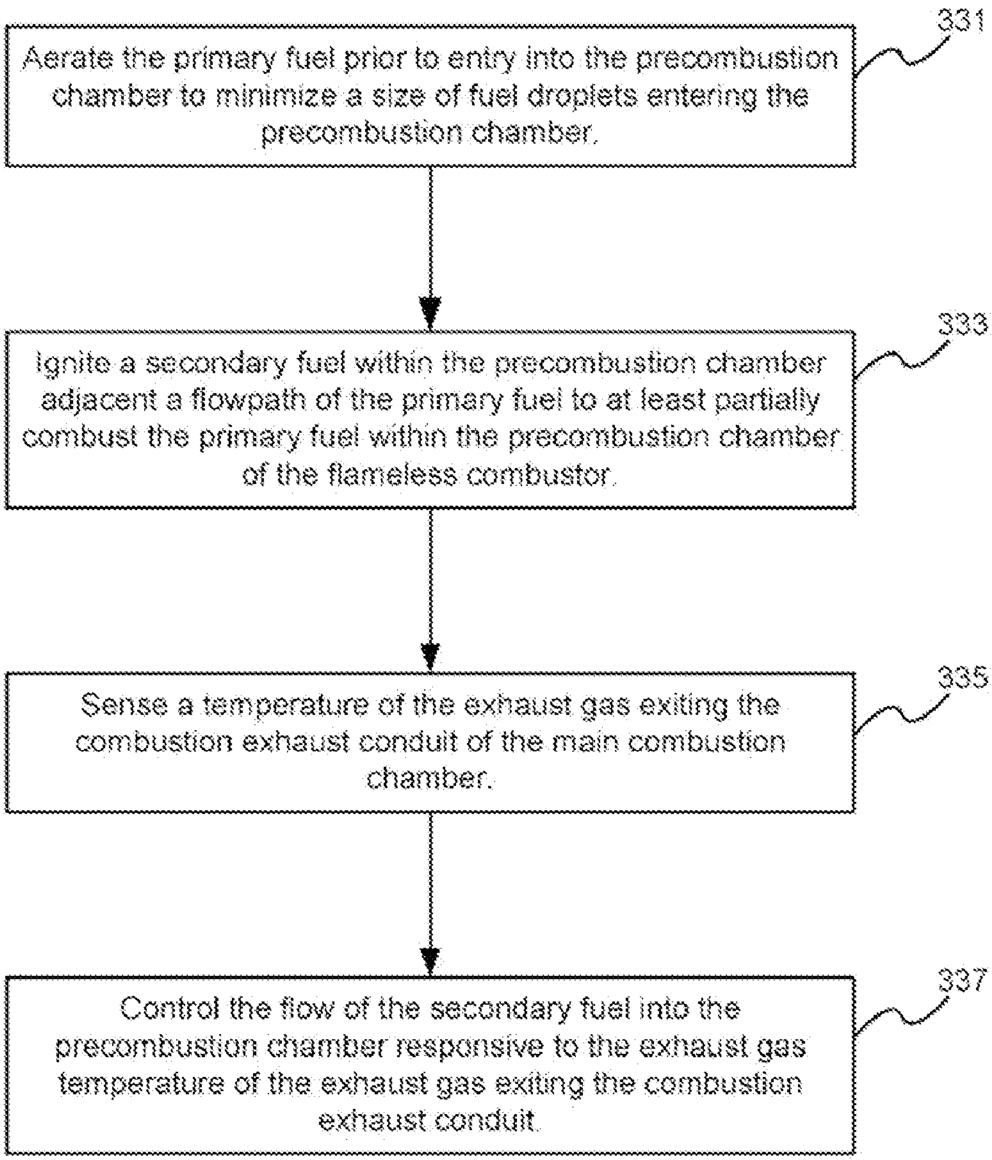
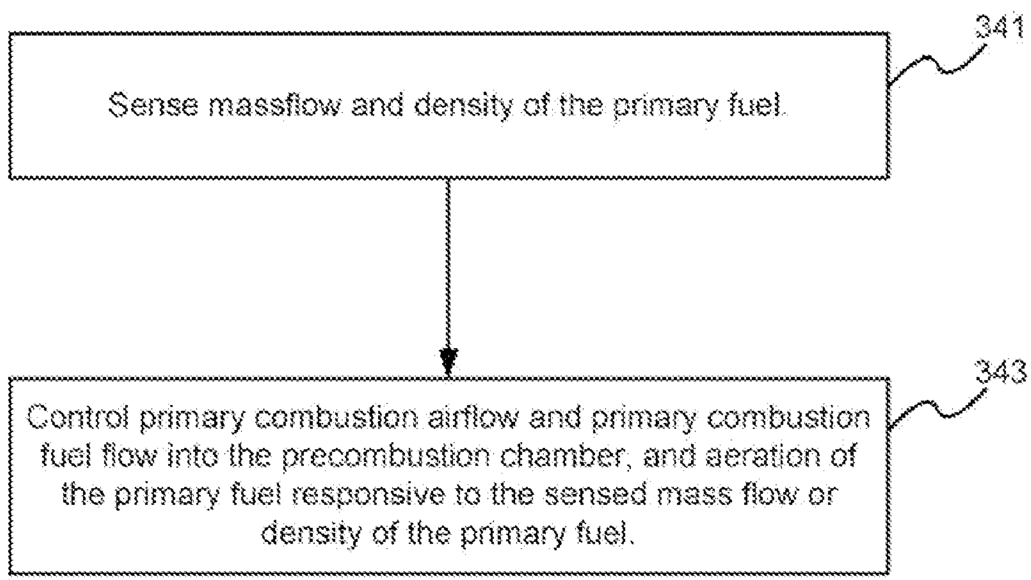

331
Aerate the primary fuel prior to entry into the precombustion chamber to minimize a size of fuel droplets entering the precombustion chamber.
333
Ignite a secondary fuel within the precombustion chamber adjacent a flowpath of the primary fuel to at least partially combust the primary fuel within the precombustion chamber of the flameless combustor.
335
Sense a temperature of the exhaust gas exiting the combustion exhaust conduit of the main combustion chamber.
337
Control the flow of the secondary fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit.

Fig. 10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Sense massflow and density of the primary fuel.
343
Control primary combustion airflow and primary combustion fuel flow into the precombustion chamber, and aeration of the primary fuel responsive to the sensed mass flow or density of the primary fuel.

Fig. 11

APPARATUS AND METHODS FOR PROVIDING UNIFORMLY VOLUME DISTRIBUTED COMBUSTION OF FUEL

RELATED APPLICATIONS

[0001] This non-provisional application claims priority to and the benefit of U.S. Patent Application No. 61/176,006, filed May 6, 2009, titled "Apparatus and Methods for Providing Uniformly Volume Distributed Combustion of Fuel," incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to fuel combustion processes and apparatus, and specifically to apparatus for providing uniformly volume distributed combustion and related methods.

[0004] 2. Description of Related Art

[0005] It was arguably not until the late 1970s and early 1980s, as a result of the first and the second energy crisis, that research and development activities began to seriously focus on improving energy efficiency. Similarly, it has only been since until after such time period that industry has truly recognized the need for eliminating noxious pollutants such as nitrogen oxides, mostly due to concerns over human health and concern for the environment. As a result, although uniformly distributed (flameless) combustion was discovered circa 1911, it was not until recently that uniformly distributed combustion (flameless oxidation) has become a focus of industrial research.

[0006] In flameless combustion, ignition occurs and progresses with generally no visible or audible signs of a flame usually associated with burning. As early as 1989, it was found that combustion in a furnace could be sustained even in an extremely low concentration of oxygen, if the combustion air was sufficiently preheated. Particularly, during experiments with a self-recuperative burner, it was observed that at furnace combustion temperatures of about 1000° C. and an air preheat temperature of about 650° C., no flame was visible and no ultraviolet signal was detected. Nevertheless, the fuel was substantially combusted "burnt," and the carbon monoxide content and nitric oxide of the exhaust was found to be extremely low.

[0007] Conventionally, to initiate flameless combustion, preheated oxidizing air and fuel gas is fed into a combustion chamber at relatively high injection speeds. The geometry of the combustion chamber, as well as the injection speed of the fuel-air mixture, create large internal recirculations of the combustion mixture. Once the recirculations are sufficient, the combustion becomes distributed throughout the volume of the combustion chamber and the flame will no longer be visible. Further, as an application of such principle, nitric oxide emission can be reduced by dilution of the combustion air with recirculated burned gas in the furnace. Dilution of the combustion air can reduce the oxygen content of the oxidizer, which decreases temperature fluctuations in the combustion chamber as well as the mean temperature, hence, a resultantly low amount of nitric oxide emission.

[0008] Recognizing the potential benefits of flameless combustion, the industry has attempted to develop various types of combustion chambers that support flameless combustion. For example, U.S. Pat. No. 6,796,789 by Gibson et al. titled Method to Facilitate Flameless Combustion Absent Catalyst or High-Temperature Oxidant" describes and oval-shaped combustion chamber configured to recirculate fuel gas with flue gas and combustible air. U.S. Pat. No. 5,340,020 by Manus et al. Titled "Method and Apparatus for Generating Heat by Flameless Combustion of a Fuel in a Gas Flow" describes a combustion apparatus, which utilizes a catalyst for producing the flameless combustion.

[0009] U.S. Pat. No. 5,839,270 by Jirnov et al., titled "Sliding-Blade Rotary Air-Heat Engine with Isothermal Compression of Air" describes a particularly effective combustion chamber originally configured for use with the sliding-blade rotary air-heat engine. The Jirnov "vortex" combustion combined with a straight-flow precombustion chamber successfully solved problems associated with operating on multi-fuels with a high completeness of combustion over the wide range of the coefficient of air redundance, while producing a substantial drop in toxicity of the exhaust gases. The combustor was also characterized by providing a simplified combustor design and ease of fabricating, high thermal and volumetric efficiency, while being able to employ a variety of types of combustible hydrocarbon gas or liquid fuels. The vortex combustor provided a vortex chamber positioned at the tube inlet and ejectors with feedback loops positioned along the length of the heat transfer section. This enabled the results to he increased by inducing a swirl flow and intensive recirculation of fluid all along the length of the heat transfer section. A precombustion chamber was provided to form a super-rich fuel and air mixture, ignition, partial combustion and pyrolyzation of heavy and low grade fuels. In operation with the Jirnov engine, prior to entering the precombustion chamber the combustion air was first preheated by exhaust gases. Upon entry, heating coils in the precombustion chamber then further heated the air and heated fuel also injected into the precombustion chamber prior to entry into the main vortex combustion chamber. The entry of the fuel-air mixture into the main vortex combustion chamber was such that a very large swirl was created which helped ensure proper mixture and a substantially uniform combustion within the combustion chamber.

[0010] In recent years, due to the cost of fuel and due to concern for the environment, there has been a high interest in the use of biofuels. Biofuels can include solid, liquid, or gas fuel derived from recently expired biological material. Biofuel can be produced from theoretically any biological carbon source, the most common of which include plants and plant-derived materials. The biofuel industry is expanding in Europe, Asia and the Americas. The most common use for biofuels is as liquid fuels for automotive transport. There is also, however, a desire in industry to use biofuel to generate steam at and/or electricity. Biodiesel is the most common biofuel in Europe, and is becoming more popular in Asia and America. Biodiesel can be produced from oils or fats, for example, using transesterification of vegetable oil, and forms into a liquid similar in composition to petroleum diesel.

[0011] Biodiesel production can result in glycerol (glycerin) as a by-product; for example, at one part glycerol for every 10 parts biodiesel. This has resulted in a glut in the market for glycerol. Accordingly, rather than being able to sell the glycerol, many companies have to pay for its disposal. Sources indicate that the 2006 levels of glycerol production were at about 350,000 tons per annum in the USA, and 600,000 tons per annum in Europe. Sources further indicate that such levels will only increase as biodiesel becomes more popular as a homegrown energy source and as Europe implements EU directive 2003/30/EC, which requires replacement of 5.75% of petroleum fuels with biofuel, across all member states by 2010. Recognized, therefore, by the inventor is the need for and apparatus and methods of economically disposing of glycerin or other in an environmentally friendly and energy efficient manner.

[0012] Also recognized by the inventor is that, although considered a waste product of biodiesel fuel production, waste fuels, such as glycerin, have significant energy delivery potential. Glycerin, however, along with some other forms of waste/biofuels, have characteristics which must be overcome in order to employ them as a fuel source. For example, various forms of glycerol remain a solid below approximately 18° C. (64.4° F.), have a flashpoint of 199° C. (390.2° F.), and have an autoignition point of 412° C. (773.6° F.). In contrast, petroleum diesel is a liquid at room temperature and has a typical flashpoint of between approximately 52° C. (126° F.) and 96° C. (204° F.) and an autoignition point of approximately 210° C. (410° F.)—nearly half that of glycerin. Recognized, therefore, by the inventor is the need for an apparatus and methods for economically and efficiently burning such heavily viscous waste/biofuels in a combustion chamber to produce an exhaust which can be utilized as an energy source. Further recognized by the inventor is the need for such apparatus and methods which can provide flameless combustion to thereby decrease nitric oxide emissions and increase energy efficiency.

SUMMARY OF THE INVENTION

[0013] In view of the foregoing, various embodiments of the present invention advantageously provide an apparatus and methods for economically and efficiently burning viscous biofuels in a combustion chamber to produce an exhaust which can be utilized as an energy source. Various embodiments of the present invention also advantageously provide an apparatus and methods which include a vortex combustion chamber configured to provide flameless combustion to thereby decrease nitric oxide emissions and increase energy efficiency. Various embodiments of the present invention provide an apparatus and methods which improve upon the Jirnov vortex combustion chamber and precombustion chamber described in U.S. Pat. No. 5,839,270 by Jirnov et al., titled "Sliding-Blade Rotary Air-Heat Engine with Isothermal Compression of Air," to more efficiently accommodate use of the more viscous fuels, such as glycerol.

[0014] Particularly, various embodiments of the present invention advantageously provide an apparatus for providing flameless combustion of a viscous fuel. According to an embodiment of the present invention, the apparatus includes a precombustion chamber adapted to heat and at least partially combust a primary fuel and a main combustion chamber adapted to combust the primary fuel. The precombustion chamber can include a cylindrical housing having an enclosed proximal end portion, an open distal end portion, and a substantially hollow main body extending therebetween and substantially enclosing a precombustion chamber cavity. The precombustion chamber can include at least one air injection inlet port extending through the body of the cylindrical outer housing and positioned to inject or otherwise deliver combustion air into the precombustion chamber and positioned to help induce a first stage vortex in the main body portion of the housing of the precombustion chamber. The precombustion chamber can also include at least one primary fuel nozzle positioned to inject primary fuel into the precombustion chamber, an igniter fuel nozzle positioned to inject ignition fuel into the precombustion chamber, an igniter positioned to ignite the igniter fuel, and a hollow cylindrical combustion stabilizer positioned within the precombustion chamber cavity to receive igniter fuel and primary fuel and to isolate the primary fuel from a portion of the combustion air when being heated with the igniter fuel.

[0015] The combustion stabilizer includes a proximal end portion, a distal end portion, and a main body portion extending between the proximal end portion and the distal end portion. The combustion stabilizer main body includes a large diameter sidewall spaced radially inward from the precombustion chamber housing to define an annulus therebetween and includes at least one air inlet aperture extending therethrough to receive a portion of the combustion air to thereby supply oxygen to the igniter fuel and to thereby initiate oxidation of the fuel within the combustion stabilizer. The distal end portion is in fluid communication with the combustion stabilizer main body and has a small diameter sidewall having a diameter substantially smaller than the large diameter sidewall of the main body. The distal end portion further includes an unobstructed distal end aperture for expelling heated primary fuel into the precombustion chamber cavity adjacent to the distal end portion of the precombustion chamber housing.

[0016] The main combustion chamber includes an, e.g., cylindrical or elliptical housing having an at least partially enclosed proximal end portion including an exhaust aperture, an enclosed distal end portion, and an elongate main body extending therebetween and substantially enclosing a main combustion chamber cavity. The main body can include an inner main body diameter and can have a main body axial length extending at least approximately twice the main body diameter. The main body axial length can have a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance within the main combustion chamber based upon one or more fuel performance characteristics of the primary fuel. The main combustion chamber can also include a combination precombustion chamber exhaust outlet and main combustion chamber fuel-air mixture inlet (hereinafter "exhaust-inlet) located adjacent the proximal end portion of the main combustion chamber housing and extending through the main body of the main combustion chamber housing. The exhaust-inlet is positioned to receive the at least partially combusted primary fuel from the precombustion chamber and positioned (e.g., tangentially) to induce a second stage vortex within the main body of the main combustion chamber housing.

[0017] The main combustion chamber also includes a combustion exhaust tube or other form of conduit (e.g., Venture form) extending from, and interfaced with, the proximal end portion of the main combustion chamber housing, and extending coaxially along a same longitudinal axis as the main combustion chamber housing. The combustion exhaust tube or conduit includes an open distal end portion and an elongate main body extending between the open distal end portion of the combustion exhaust tube and the proximal end portion of the main combustion chamber housing. The distal end portion of the combustion exhaust tube extends axially within the main combustion chamber cavity to a location between a position distally forward of an axial midpoint position of the elongate main body of the main combustion chamber housing and a position located axially a distance of at least one exhaust tube main body diameter from the distal end portion of the main combustion chamber housing.

[0018] According to another embodiment of the present invention, an apparatus for providing flameless combustion of a fuel includes a main combustion chamber adapted to combust a primary fuel. The main combustion chamber includes a housing having a proximal end portion including an exhaust aperture, a distal end portion, and an elongate main body extending therebetween and substantially enclosing a main combustion chamber cavity. The main body has an inner main body diameter and a main body axial length. An exhaust-inlet extends through the main body of the main combustion chamber housing at an inlet location. The exhaust-inlet is positioned to receive at least partially combusted primary fuel from a precombustion chamber and is positioned to help induce a vortex within the main body of the main combustion chamber housing. According to a preferred configuration, the main body axial length extends distally from the inlet location a distance value approximately equal to or greater than that of the inner main body diameter. Particularly, the main body axial length has a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance from the exhaust-inlet within the main combustion chamber cavity to exit based upon one or more fuel performance characteristics of the particular type/configuration of the primary fuel.

[0019] The main combustion chamber can further include a combustion exhaust conduit extending from and interfaced with the proximal end portion of the main combustion chamber housing and extending coaxially along a same longitudinal axis as the main combustion chamber housing. The combustion exhaust conduit can include an open distal end portion and an elongate main body extending between the open distal end portion of the combustion exhaust conduit and the proximal end portion of the main combustion chamber housing. Specifically, the distal end portion of the combustion exhaust tube can extend axially within the main combustion chamber cavity to a location between a position distally forward of an axial midpoint position of the elongate main body of the main combustion chamber housing and a position located axially a distance of at least one exhaust tube main body diameter from the distal end portion of the main combustion chamber housing. According to this configuration, the axial spacing of the distal end portion of the combustion exhaust conduit from the distal end portion of the main combustion chamber housing has a value approximately equal to or greater than that of at least one exhaust conduit main body diameter inner diameter.

[0020] Various embodiments of the present invention also provide methods of providing flameless combustion of a viscous fuel. According to an embodiment of the present invention, such a method can include the steps of inducing a first stage vortex in a primary fuel-air mixture within a main body of a precombustion chamber of a flameless combustor, receiving within a main body of a main combustion chamber of the flameless combustor the primary fuel-air mixture having a first stage vortex induced state, and inducing a second stage vortex in the received primary fuel-air mixture to form a complex vortex pattern to thereby enhance flameless oxidation of the primary fuel within the main body of the main combustion chamber. According to a preferred configuration, the step of inducing can include expelling the primary fuel-air mixture tangentially into the main combustion chamber cavity through a precombustion chamber exhaust outlet. According to this configuration, the diameter of the first stage vortex is substantially smaller than a diameter of the second stage vortex formed within the main combustion chamber.

[0021] The method can also include the steps of interfacing with the main combustion chamber, a precombustion chamber adapted to heat and at least partially combust the primary fuel, igniting a secondary fuel within the precombustion chamber adjacent a flowpath of the primary fuel to at least partially combust the primary fuel within the precombustion chamber, sensing a temperature of the exhaust gas exiting the combustion exhaust conduit of the main combustion chamber, and controlling a flow of the secondary fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit.

[0022] According to another embodiment of the present invention, a method of providing flameless combustion of a viscous fuel can include the steps of providing a main vortex combustion chamber of a flameless combustor having a main body substantially enclosing a main combustion chamber cavity having an axial length approximately equal to or greater than an inner diameter of the main combustion chamber cavity, and inducing a vortex within the main combustion chamber cavity to enhance flameless oxidation of a primary fuel. The method can also include the step of providing a combustion exhaust conduit within and axially coincident with the main combustion chamber cavity. The combustion exhaust conduit can have an inlet positioned at a location between an axial position distally forward of an axial midpoint position of the elongate main body of the main combustion chamber housing and an axial position within the main combustion chamber cavity adjacent the distal end portion of the main combustion chamber housing. The axial spacing of the distal end portion of the combustion exhaust conduit from an inner surface of the distal end portion of the main combustion chamber housing can further have a value approximately equal to or greater than that of at least one exhaust conduit main body inner diameter.

[0023] The method can further include the step of injecting the primary fuel into the main combustion chamber cavity through a combination precombustion chamber exhaust outlet-main combustion chamber inlet ("exhaust-inlet"). The exhaust-inlet is axially spaced apart from the combustion exhaust conduit inlet a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance from the exhaust-inlet within the main combustion chamber cavity based upon one or more fuel performance characteristics of the primary fuel to provide substantially complete pyrolization thereof. The method can further include the step of preselecting the value of the axial separation between the exhaust-inlet and the combustion exhaust conduit inlet to provide the sufficient pyrolyzed fuel travel distance from the exhaust-inlet within the main combustion chamber cavity responsive to one or more fuel performance characteristics of the glycerol fuel.

[0024] Various embodiments of the present invention also provide a precombustion chamber, and a vortex combustion chamber which is an improvement over the Jirnov vortex combustion chamber and precombustion chamber. Various embodiments of the present invention provide, for example, a vortex combustor including a main combustion chamber connected or otherwise interfaced with a precombustion chamber, which successfully solves problems associated with operating on highly viscous fuels with a high completeness of combustion over the wide range of the coefficient of air redundance and produces a substantial reduction in toxicity of exhaust gases. Various embodiments of the present invention provide high thermal and volumetric efficiency, may employ a variety of types of viscous and non-viscous combustible hydrocarbon fuels, have reduced quantities of environmentally damaging emissions, and have a simplified combustor design and ease of fabricating, which is economical to manufacture in mass production and is inexpensive to operate, service, and repair.

[0025] Various embodiments of the present invention provide a vortex chamber positioned at the tube inlet and provide feedback loops positioned along the length of the heat transfer section, which enable the resulting fuel combustion efficiency to be increased by inducing a swirl flow and intensive recirculation of fluid along the length of the heat transfer section. Such improved fuel efficiency can advantageously reduce environmentally damaging emissions. Further, such apparatus may be used in converting thermal energy into electric power, can be used in generating steam, and/or can be utilized as part of a transportation engine with high thermal efficiency.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] So that the manner in which the features and advantages of the invention, as well as others which will become apparent, may be understood in more detail, a more particular description of the invention briefly summarized above may be had by reference to the embodiments thereof which are illustrated in the appended drawings, which form a part of this specification. It is to be noted, however, that the drawings illustrate only various embodiments of the invention and are therefore not to be considered limiting of the invention's scope as it may include other effective embodiments as well.

[0027] FIG. **1**A is a partially perspective and partially sectional view of a combustor for providing flameless combustion of a viscous fuel according to an embodiment of the present invention;

[0028] FIG. **1**B is a partially prospective and partially sectional view of the combustor of FIG. **1**A illustrating vortex generation according to an embodiment of the present invention;

[0029] FIG. **2**A is a sectional view of the combustor taken along the **2-2** line of FIG. **1**B according to an embodiment of the present invention;

[0030] FIG. **2**B is a sectional view of the combustor of FIG. **2**A illustrating vortex generation according to an embodiment of the present invention;

[0031] FIG. **3**A is a sectional view of the main combustion chamber of FIG. **1**A according to an embodiment of the present invention;

[0032] FIG. **3**B is a sectional view of an alternate embodiment of the main combustion chamber of FIG. **1**A according to an embodiment of the present invention

[0033] FIG. **4** is a sectional view of an alternate embodiment of the combustor illustrated in FIG. **2**B according to an embodiment of the present invention;

[0034] FIG. **5** is a sectional view of an alternate embodiment of the combustor illustrated in FIG. **1**B according to an embodiment of the present invention;

[0035] FIG. **6**A is a sectional view of an alternate embodiment of the combustor illustrated in FIG. **2**A an embodiment of the present invention;

[0036] FIG. **6**B is a sectional view of an alternate embodiment of the combustor illustrated in FIG. **2**A an embodiment of the present invention;

[0037] FIG. **7** is a schematic block diagram of a combustion management/fuel-gas supply system for providing flameless combustion according to an embodiment of the present invention;

[0038] FIG. **8** is a schematic block flow diagram illustrating a method of providing flameless combustion including steps for forming the combustor of FIG. **1**A according to an embodiment of the present invention;

[0039] FIG. **9** is a schematic block flow diagram illustrating a method of providing flameless combustion including steps for operating the combustor of FIG. **1**A according to an embodiment of the present invention;

[0040] FIG. **10** is a schematic block flow diagram illustrating substeps of the method shown in FIG. **9** according to an embodiment of the present invention; and

[0041] FIG. **11** is a schematic block flow diagram illustrating substeps of the method shown in FIG. **9** according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0042] The present invention will now be described more fully hereinafter with reference to the accompanying drawings, which illustrate embodiments of the invention. This invention may, however, be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

[0043] FIGS. **1A-11** illustrate a system **30** including combustor apparatus **31** and methods which improve upon the vortex combustion chamber and precombustion chamber of the Jirnov engine described in U.S. Pat. No. 5,839,270 by Jirnov et al., titled "Sliding-Blade Rotary Air-Heat Engine with Isothermal Compression of Air," to more efficiently accommodate use of more viscous fuels. According to various embodiments of the present invention, the combustor apparatus **31** can beneficially work under high pressure and high flow rate of air. The combustor apparatus **31** can be especially useful for burning waste fuel, such as Glycerol (Glycerin), and emulsified heavy oil (with water) fuels, along with a number of conventional liquid fuels, such as jet propellant (JP), Diesel, Kerosene, Gasoline, and any of the gaseous fuels, such as Hydrogen, CO and Carbohydrate, etc. Various embodiments of the combustor apparatus **31** provide substantially complete combustion with very low nitric oxide (NOx) and carbon monoxide (CO). Embodiments of the combustor apparatus **31** further provide no flame on the exit, making it an ideal apparatus for use in gas turbines and in heating systems.

[0044] More specifically, as perhaps best illustrated in FIGS. **1**A and **2**A, the apparatus **31** can include a vortex precombustion chamber **33** interfaced with a main vortex combustion chamber **35** as will be described in more detail, below. The precombustion chamber **33** is used for forming, a super-rich fuel and air mixture, ignition, partial combustion and pyrolysisation of heavy and low grade fuels. Note, FIGS. **3**B-**6**A illustrate various alternative embodiments of the apparatus **31**, particularly with respect to how the vortex precombustion chamber **33** is interfaced with the main vortex combustion chamber **35**. For simplicity, the same numbering will be maintained for like items across the various embodiments.

[0045] As shown in FIG. **2**A, according to an embodiment of the present invention, the precombustion chamber **33** has a hollow cylindrical housing **41** enclosing a cavity **42** at one end **43**, and can have one or more air inlets **45** extending through its sidewall (main body) **47**. A hollow cylindrical combustion stabilizer **49** is secured within the outer housing **41** and can have a large diameter side wall **51** spaced radially inward from the outer housing **41** to define an annulus **53** therebetween, and can have a reduced diameter neck portion **55** at one end. At least one, but preferably a plurality of air inlet ports **57** extend through the larger diameter sidewall **51** to provide combustion air communication with the air inlet **45** of the outer housing **41**. According to an embodiment of the precombustion chamber **33**, the air inlet ports **57** extend tangentially through the sidewall **51**.

[0046] According to an embodiment of the precombustion chamber **33**, a funnel-shaped flame tube **61** is secured to the open end of the outer housing **41** by a radial flange **63** and has a hollow cylindrical side wall portion **65** received within the open end of the outer housing **41**, a conical side wall portion **67**, and a reduced diameter neck portion **69** at one end. The radial flange **63** is secured between the open end of the outer housing **41** and a conical flanged fitting **71** on the outer housing of the vortex combustion chamber **35**. The conical side wall portion **67** of the flame tube **61** is received within the conical flanged fitting **71**, and the reduced diameter neck portion **69** is connected with a tubular channel **73** disposed tangential to the periphery of the main vortex combustion chamber **35**. The exterior of the cylindrical side wall portion **65** is spaced radially inward from the interior of the outer housing **41** and the conical side wall portion **67**; and the reduced neck portion **69** is spaced radially inward from the interior of the conical flanged fitting **71** to define an annulus **75** therebetween. Further, a plurality of passageways **77** extend through the radial flange **63** to allow communication through the annulus **75**.

[0047] According to an embodiment of the present invention, the combustion stabilizer **49** is provided with one or more primary fuel injectors/nozzles **81** for injecting a primary fuel, a secondary fuel injector(s)/nozzle(s) **83** for injecting a secondary or ignition fuel positioned to ignite the primary fuel, and a fuel igniter or spark plug **85**. The secondary fuel injector **83** can provide fuel, e.g., propane, etc., to pre-heat the primary fuel, particularly if a heavy or viscous primary fuel is used or if the ambient temperature is below that required. According to a preferred configuration, the nozzles **81**, **83**, and the igniter **85** are located in the top cover portion **87** of the precombustion chamber **33**. A portion of air from the general airflow drawn or injected through opening **45**, is further drawn or injected into the combustion stabilizer **49** through air inlets **57** to create an air-fuel mixture near the secondary fuel injector **83** and the spark plug **85**.

[0048] According to another embodiment of the present invention, as perhaps best illustrated in FIG. **4**, rather than utilize a secondary or ignition fuel, the combustion stabilizer **49** is instead provided with a fuel vaporizer **91** having terminals **93** extending from the precombustion chamber **33**, which are connected with a source of electrical current (not shown). A portion of air from the general airflow drawn or injected through opening **45** is further drawn into the combustion stabilizer **49** through air inlets **57** to create an air-fuel mixture near the spark plug **85**. Such fuel vaporizer **91** provides an alternative methodology of preheating the primary fuel in cold seasons and/or if a heavy or viscous fuel is used. That is, low-grade or waste fuels, when used, can be pre-heated/combustion to reduce the viscosity of the fuel and to provide for an acceptable level of atomization.

[0049] According to an embodiment of the present invention, in operation, fuel is delivered to the precombustion chamber **33** through single or multiple primary fuel injector (s)/nozzle(s) **81** via a fuel supply system **37**. When multiple nozzles **81** are utilized, the fuel supply system **37** can beneficially allow the apparatus **31** to oxidize different types of liquid or gaseous fuels emanating from independent sources, separately or simultaneously. The fuel nozzle or nozzles **81** can be interfaced with a compressed air/gas supply, either directly or indirectly via taps (not shown) in the fuel supply lines **39**, to help breakup the liquid fuel jet expelled from the fuel nozzle(s) **81** and provide a minimal size of fuel droplets, i.e., form an aerosol or colloid, or at least a suspension. The resulting minimal size droplets can have a reduced (short) time of vaporization, and thus, reduced combustion time. This can be especially beneficial when combustion for waste fuels, such as Glycerin, is desired.

[0050] As noted above, combustion airflow, for example, provided by a cooling air (gas/fluid) supply system **36**, is provided through the one or more air inlets **45** extending through sidewall **47**. The required airflow rate and/or oxygen content of the combustion air can be determined and set based on the ratios of momentum and mass for a given liquid fuel flow rate to provide maximum instability of the air-fuel flow and efficient precombustion. Particularly, the combined airflow rate of the air entering/exiting the inlet(s) **45** and mass flow of primary fuel entering the precombustion chamber **33** can have a ratio between 20:1 to 40:1, with a preferred ratio of approximately 30:1; and the combustion gas (e.g., air) to mass flow of fuel can have a ratio of preferably between 30:1 to 50:1, with a more preferred ratio of approximately 40:1. Such fuel injection configuration can provide for the shortest breakup length and breakup time inside of the precombustion chamber **33**. Further, the precombustion chamber **33** can have an axial length to sidewall/main body cross-sectional diameter ratio of preferably between 2:1 to 4:1, with a more preferred ratio of approximately 3:1 to ensure sufficient precombustion prior to entering the main vortex combustion chamber **35**. Consequently, according to embodiments of the apparatus **31**, the combustion process is complete and occurs downstream inside of the main chamber **35** without flame on the exit. The absence of a flame on exit can beneficially extend the use of apparatus **31**/vortex combustion chamber **35** for many applications known to those skilled in the art, including for turbines, engines, and heaters.

[0051] As perhaps best shown in FIG. **7**, process control of apparatus **31** can be provided by a combustion management/fuel-gas supply system **200** which can include a controller **201** positioned to sense various fuel system and combustion system parameters to control the combustion process. The controller **201** can include a processor/logic circuit **203** and memory **205** coupled to the processor **203** to store software and/or database records therein. The memory **205** can include volatile and nonvolatile memory known to those skilled in the art including, for example, RAM, ROM, and magnetic or optical disks, just to name a few.

[0052] The combustion management/fuel-gas supply system **200** can also include various sensors, known to those skilled in the art, including, for example, a mass flow/density/momentum meter or meters **211** interfaced with the fuel system **37** to monitor fuel characteristics of the primary fuel; a combustion air pressure sensor **213** positioned to monitor air pressure of the air entering air inlet or inlets **45**; a combustion air oxygen content sensor **215** positioned to monitor the oxygen content of the combustion air; and an exhaust gas temperature (EGT) probe **217** positioned to sense the temperature of the exhaust gases emanating from combustion exhaust tube or conduit **115** (see FIG. **1**A), described in more detail later.

[0053] The combustion management/fuel-gas supply system **200** can further include various control devices including, for example, a combustion air/gas pump, injector, or valve **221** for adjusting combustion air pressure; a primary fuel pump or valve **223** for managing fuel pressure of the primary fuel; a secondary fuel control pump or valve **225** for managing the amount of secondary fuel used to help pre-combust the primary fuel in the combustion stabilizer **49** of the precombustion chamber **33**; an ignition circuit **227** for igniting the secondary fuel; and an fuel-air pump **229** for aerating the primary fuel. Note, it should be understood by one skilled in the art that the above described control devices can further include internal controllers within each device.

[0054] The combustion management/fuel-gas supply system **200** can also include a user interface **207** as known to those skilled in the art, to provide a user access to manipulate or access software and database records, and combustion management program product **231** stored in memory **205** of the controller **201** to provide combustion management. The program product **231**, according to an embodiment of the combustion management/fuel-gas supply systems **200** includes instructions that when executed by the controller **201** cause the controller to perform various operations to include gathering or otherwise collecting real-time data from sensors **211**, **213**, **215**, and **217**, to perform real-time combustion management to include, for example: adjusting fuel pressure of the primary fuel responsive to output requirements of a supported system (e.g., turbine, engine, etc.); adjusting combustion air pressure/rate to maximize instability of the air-fuel flow and/or adjusting aeration of the fuel responsive to the density or mass flow of the primary fuel to enhance combustibility of the fuel; and applying or discontinuing application of the secondary fuel responsive to the exhaust gas temperature to help ensure substantially complete oxidation of the primary fuel prior to exit from the main combustion chamber exhaust conduit **115**, just to name a few.

[0055] Note, the combustion management program product **231** can be in the form of microcode, programs, routines, and symbolic languages that provide a specific set for sets of ordered operations that control the functioning of the hardware and direct its operation, as known and understood by those skilled in the art. Note also, the combustion management program product **231**, according to an embodiment of the present invention, need not reside in its entirety in volatile memory, but can be selectively loaded, as necessary, according to various methodologies as known and understood by those skilled in the art.

[0056] As shown in FIGS. **2**A-**2**B, for example, the main vortex combustion chamber **35** receives through a joint precombustion chamber exhaust outlet and main combustion chamber fuel-air inlet (or "exhaust-inlet") **95**, a super-rich mixture of fuel and air formed in the precombustion chamber **33** along with partially burned and pyrolyzed products for after-burning. As perhaps best shown in FIGS. **3**A-**3**B, according to an embodiment of the present invention, the main combustion chamber **35** has an outer housing formed by a main body **101**, **101'**, enclosed at the bottom end by outer bottom end wall **103**, and at the top end by an outer top wall **105** and a collector member **107** secured to the outer top wall **105**, to form a combustion chamber cavity **109** therein in which nameless combustion occurs. The collector member **107** has a top flange **111** and a central bore **113** which can be connected to or otherwise interfaced with the inlet port of a powered/heated device, e.g., gas turbine, engine, etc. (not shown).

[0057] According to various embodiments of the present invention, the main body **101** of the main combustion chamber **35** preferably has a cylindrical form (FIG. **3**A), an elliptical form (see, e.g., FIG. **3**B) or a funnel shaped form (not shown), although other forms/configurations are within the scope of the present invention. The main combustion chamber **35** also has an axial length preselected based on the type of fuel expected to be combusted. For example, for a heavily viscous fuel such as glycerol, the main combustion chamber cavity **109** can have an axial length to main body cross-sectional diameter ratio sufficient to provide uniform volume distributed combustion for the type of fuel used. In the exemplary configuration, the main combustion chamber cavity **109** can have an axial length of at least half the diameter of the main combustion chamber cavity **109**, and more preferably, an axial length equivalent to the value of at least one chamber cavity diameter, with the overall main combustion chamber cavity **109** preferably having at least an axial length of 1.5 or more chamber cavity diameters, and more preferably at least a length of two or more chamber cavity diameters. In a more preferred configuration, where glycerol is the fuel, the main body axial length to cross-sectional diameter ratio is preferably between 5:1 to 6:1, with a preferred ratio of approximately 5:1.

[0058] According to embodiments of the present invention, the main combustion chamber **35** further includes a combustion exhaust tube or conduit **115**, which serves as the outlet or exhaust pipe for the near-axis zone of the main vortex combustion chamber **35**. The exhaust conduit **115** can be configured either as a separate unit, or as a tubular extension of collector member **107**, which extends distally therefrom through a central opening **117** in the inner top wall **105**. The combustion exhaust conduit **115** and central opening **117** together form an annulus **119** therebetween. The combustion exhaust conduit **115** can have various shapes to include cylindrical (see, e.g., FIG. **3**A), venturi (see, e.g., FIG. **3**B) shown at **115'**, or others known to those skilled in the art.

[0059] According to an embodiment of the present invention, the combustion exhaust tube or conduit **115** is positioned and extends within the main combustion chamber cavity **109** to a location, for example, at least beyond the midpoint of the main body **101** of the combustion chamber **35**, but preferably adjacent the bottom end wall **103** spaced apart therefrom at an axial distance equivalent to at least the value of the inner diameter of a distal/inlet portion **11.6** of the combustion exhaust conduit **115**. When heavily viscous fuel such as glycerol is used, which requires additional time to oxidize, the combustion exhaust tube or conduit **115** can have a axial offset distance from the inner surface of the bottom end wall **103** to combustion exhaust tube cross-sectional inner diameter ratio of between 1:1 to 3:1, with a preferred ratio of approximately 2:1. As perhaps best shown in FIG. **3**A, according to a preferred embodiment of the present invention, the exhaust conduit **115** can extend axially approximately 75% of the main body **101** (e.g., cylindrical part) of the vortex combustion chamber **35**, making the axial offset distance approximately 25% of the axial length of the main body **101**.

[0060] Accordingly, for the main combustion chamber **35** configuration having a main combustion chamber cavity **109**, combustion exhaust conduit **115**, and precombustion chamber **33** positioned, for example, as shown in FIG. **1**B, the pyrolyzed gases entering the main combustion chamber cavity **109** from precombustion chamber **33** must travel at least twice the distance through the vortex combustion chamber **35** as that of the Jirnov vortex combustion chamber before it can initiate escape through the combustor exhaust conduit **115**. Further, any remaining fuel inside the combustor exhaust conduit **115** also must travel at least approximately twice the distance before exiting the combustor exhaust conduit **115** as that of the Jirnov vortex combustor to further allow any remaining fuel to oxidize before exit through the exhaust port **113**. As such, the pyrolyzed gases entering the main combustion chamber cavity **109** from precombustion chamber **33** must ultimately travel four or five times the total distance to exit through the exhaust orifice or port **113**. Even in an embodiment of the present invention such as, for example, that shown in FIG. **5** having the joint precombustion chamber exhaust outlet-main combustion chamber inlet **95** positioned, for example, at a midpoint or some other medial position, the ultimate travel distance is at least two or more times the total distance to exit through the exhaust orifice or port **113**.

[0061] According to an embodiment of the present invention, an inner bottom wall **121** and an inner top wall **123** are secured within the outer bottom wall **103** and outer top wall **105**, respectively, in a spaced apart relation to define a flow passageway **125** therebetween. One or more swirl nozzles **127** are connected to or otherwise interfaced with the passageway **125** between the outer bottom wall **103** and inner bottom wall **121**. A plurality of passageways **129** extend longitudinally through the side wall of the cylindrical main body **101** of the combustion chamber housing to allow communication with the flow passageways **131**. The passageways **125**, **129**, and **131**, form an isolated fuel-air recirculation channel which passes around the interior of the main combustion chamber **35**.

[0062] According to an embodiment of the present invention, a bypass conduit **133** connects the radial passageways **131** to a compressed airflow entering the recirculation system of combustion chamber **35** via an external supply conduit **135**. According to a preferred configuration, the recirculation system via bypass conduit **133** and external supply conduit **135** receives both cooling air and another cooling fluid (e.g., water) to enhance cooling the main combustion chamber **35**.

[0063] As perhaps best shown in FIGS. **2**A and **3**A, the main combustion chamber **35** can include a perforated liner **141** having openings **143**. The liner **141** can be secured to the interior surfaces of the main body (sidewall) **101**, inner bottom wall **121**, and inner top wall **123** of the combustion chamber **35**. The vertically opposed interior surfaces of the liner **141** and the inner top wall **123** and inner bottom wall **121** have opposite facing, outwardly concave, curved surfaces with the axial distance between the curved surfaces increasing inversely from their periphery with respect to the radial distance. According to an embodiment of the combustion chamber **35**, the vertically opposed interior surfaces of the liner **141** are curved or contoured according to the Navier-Stokes' equation with the constraint to provide substantially constant vortex radial velocity conditions to ensure minimal hydrodynamic losses.

[0064] The liner **141** includes a cylindrical side wall **145** joined tangentially to the tubular channel **73** (see, e.g., FIG. **2**A) and serves as a cylindrical heat tube between the precombustion chamber **33** and the main combustion chamber **35**. An annulus/gap **147** between the inner surface of the main body **101** of the combustion chamber **35** and cylindrical side wall **145** of the liner **141**, and between the inner surface of the inner bottom wall **121** and inner surface of the inner top wall **123** and the perforated liner **141**, serves as a cooling jacket. The annulus/gap **147** is in communication with the annulus **75** (see, e.g., FIG. **2**A). According to an embodiment of the main combustion chamber **35**, the juncture of the combustor exhaust conduit **115** and the top flange **111** is contoured and has an annular raised lip ring **151** which extends angularly upwardly therefrom for a distance into the passageway **125** between the inner top wall **123** and outer top wall of the main combustion chamber **35**.

[0065] The cool and moist air (identified above) can be directed through the bypass conduit **133** and the radial passageways **131**, and onto the annular raised lip ring **151**, which serves as a fuel-air ejector ring, and which causes a Ventura effect to return trapped fuel film through the recirculation channel **125**, **129**, **131** and swirl nozzle(s) **127** back into the chamber combustion zone. The swirl nozzle(s) **127** are configured to swirl the recirculated fuel-air-water mixture flowing through the recirculation channels **125**, **129**, **131**, as it enters the interior of the main combustion chamber **35**. Because the swirl nozzle or nozzles **127** are located in the near-axis zone of the vortex combustion chamber **35** where the lowest pressure tends to occur, the fuel-air ejector ring **151** is subjected to a substantial pressure drop and its operation is thus intensified.

[0066] To initiate combustion of a primary fuel (e.g., glycerin), in the embodiment shown in FIG. **2**A, secondary or ignition fuel (e.g., propane, etc.) is introduced next to secondary fuel nozzle **83**, and the igniter/sparkplug **93** is momentarily activated to ignite the ignition fuel. Combustion air/gas is drawn or pumped into the precombustion chamber **33** through air/gas inlet(s) **45**. The primary fuel is then introduced into the combustion stabilizer **49** through the primary fuel injector(s) **81**, along with a portion of the combustion air/gas from the general air/gas flow and into the combustion stabilizer **49** through air openings/inlets **57**, to create an air-fuel mixture near the secondary fuel nozzle **83**, for ignition.

[0067] Similarly, in the embodiment shown in FIG. **4**, the primary fuel is introduced into the combustion stabilizer **49** through the primary fuel injector(s) **81** and a portion of air from the general air flow is drawn into the stabilizer **49** through the openings/inlets **57** to create an air-fuel mixture near the spark plug **93**, and the plug is activated to ignite the mixture. In this configuration, a fuel vaporizer **91** may used to heat the fuel, particularly if a heavy fuel is used in cold weather that does not require ignition by a more readily combustible secondary fuel.

[0068] As perhaps best shown in FIG. **2**B, the ignited and partly pyrolyzed fuel-air mixture formed in the combustion stabilizer **49** then passes through the interior of the funnel-shaped flame tube **143**, where it begins to swirl due to the orientation of the general air/gas flow and/or orientation of the primary and/or secondary fuel nozzles (first stage vortex **161** formation). The ignited and partially pyrolyzed fuel then passes through the channel **73**, for example, tangentially through exhaust-inlet **95** and into the vortex combustion chamber **35** for after-burning (see FIGS. **1**B, **2**B and **4**). Note, in an alternate embodiment of the present invention, perhaps best shown in FIG. **6A-6B**, the precombustion chamber **33** can be instead interfaced with the combustion chamber **35** at exhaust-inlet **95'** in a more normal orientation. Other orientations, however, are also within the scope of the present invention.

[0069] The air received through air/gas inlet(s) **45** can also flow through the annulus **53**, **75**, and passageways **77** between the flame tube **61** and the housing **41** of the precombustion chamber **33** and conical flanged fitting **71** of the vortex combustion chamber **35** and the annulus **147** surrounding the perforated liner **141**, to thereby cool the flame tube **61**, perforated liner **141** and cylindrical side wall **145**. According to an embodiment of the present invention illustrated in FIGS. **1A-2B**, the combustion products of partially burned and pyrolyzed fuel from the precombustion chamber **33**, already in a swirling state, are caused to swirl (to form a second stage vortex **163**) as they enter the vortex combustion chamber cavity **109** through the tangential channel **73**, thereby forming a two-stage complex vortex pattern. Note, in an alternate embodiment of the present invention, perhaps best shown in FIG. **6A-6B**, whereby the precombustion chamber **33** is instead interfaced with the combustion chamber **35** in a more normal orientation, the combustion exhaust tube or conduit **115** can include a swirl enhancer **171**, e.g., spiral, grooves or protuberances oriented to induce the swirling state within the combustion chamber cavity **109**.

[0070] It is perhaps best shown in FIG. **3A**, the inwardly contoured walls **121**, **123**, and liner **141** of the main combustion chamber cavity **109**, and the equinoctial condition of the centrifugal and aerodynamic forces acting on the condensed particles in the vortex stream of air in the main combustion chamber cavity **109** allow unvaporized fuel droplets to be confined in equilibrium in the orbit of rotation for a sufficient length of time such that fuel droplet migration to a small radius will only occur when the droplet diameters become sufficiently small during the combustion process. This feature can enhance stabilizing combustion and providing a high degree of completeness of combustion.

[0071] In the combustion process, a portion of the fuel, not participating in mixing and combustion, moistens the inner walls of the liner **141** in the vortex combustion chamber **35**, and in the form of a migrating film of unmixed and uncombusted fuel, migrates to the lower portion of the chamber **35**, at least in part, due to gravity, and is captured at the inward side of the annular raised lip ejector ring **151**. A portion of the preferably cool and moist air is directed through the conduit **135**, the bypass conduit **133**, and the radial passageways **131**, onto the outward side of the annular raised lip ejector ring **151**, which causes a venturi effect, which further functions to return the trapped unmixed and uncombusted fuel as a fuel-air mixture through the recirculation channels **125**, **129**, and swirl nozzle **127** back into the chamber combustion zone. The swirl nozzle **127** swirls the recirculated fuel-air mixture flowing through the recirculation channels **125**, **129**, as it enters the cavity **109** of the vortex combustion chamber **35**.

[0072] Efficient and reliable cooling of the combustion chamber **35** can be provided by air flows through the annulus **75** and **147** and by the flowing of part of the cooling air (preferably with a certain amount of water) through recirculation channels **125**, **129**. As noted previously, because the swirl nozzle or nozzles **127** are located in the near-axis zone of the vortex combustion chamber where re-refraction occurs, in such configuration, the fuel-air ejector ring **151** is subjected to a substantial pressure drop, and its operation is intensified. The combined total amount of air arriving at the main vortex chamber combustion zone through air inlet ports **57**, tubular channel **73**, annulus **75**, and bypass conduit **133**, form a lean fuel-air mixture for after-burning.

[0073] Beneficially, the various combinations of the structural and operational features of embodiments of the main vortex combustion chamber **35** provide a small combustion chamber capable of burning a variety of fuels with high energy efficiency and low toxicity of the products, including low amounts of NOx. According to various embodiments of the present invention, the process of combustion, managed by controlling the supply of a super-rich air-fuel mixture in the precombustion chamber **31**, supply of a lean mixture in the vortex chamber cavity **109**, and the introduction of a certain amount of water into the combustion zone, can help ensure a sufficiently low temperature of combustion, which is typically the significant, if not dominant, factor in decreasing the NOx content in exhaust gases, but that is also sufficiently high enough to prevent escape of other unwanted or toxic exhaust gases.

[0074] Embodiments of the present invention also include methods for providing flameless combustion of a fuel, in general, and for a heavy viscous waste fuel, such as glycerol, in particular. According to an embodiment of the present invention, such a method can include forming a combustor apparatus **31** including a precombustion chamber **33** and a main combustion chamber **35** (see, e.g., FIG. **8**), and controlling combustion (oxidation) of the fuel to produce heat and/or to dispose of a waste fuel (see, e.g., FIG. **9**), which can include controlling aeration of the primary fuel, controlling the flow of the secondary fuel into the precombustion chamber **33** (see, e.g., FIG. **10**), and controlling primary combustion airflow and primary combustion fuel flow (see, e.g., FIG. **11**).

[0075] As perhaps best shown in FIG. **8**, the combustor apparatus **31** can be formed by performing the steps of providing a main vortex combustion chamber **35** having a main body **101** substantially enclosing a main combustion chamber cavity **109** (block **301**), and interfacing a precombustion chamber **33** adapted to heat and at least partially combust the primary fuel with the main combustion chamber (block **303**). The step of providing a main vortex combustion chamber **35** can include the substeps of: preselecting the value of an axial length of a main combustion chamber cavity (block **305**); preselecting the value of an axial separation between a primary fuel inlet **95** and the distal inner surface of the main combustion chamber cavity **109** (block **307**); preselecting the value of an axial separation between a primary fuel inlet and a combustion exhaust conduit inlet (block **309**); and preselecting the value of an axial separation between the inlet of a combustion exhaust conduit **115** and the distal inner surface of the main combustion chamber cavity **109** (block **311**), in response to or otherwise based upon an amount of time necessary to sufficiently combust the primary fuel, which is further based upon fuel characteristics including viscosity, mass flow, density, and in the end temperature of the primary fuel expected to be utilized (combusted) in the combustor apparatus **31**.

[0076] As perhaps best shown in FIG. **9**, the combustion/oxidation of the primary fuel can be controlled by inducing a first stage vortex **161** in a primary fuel-air mixture within the main body **47** of precombustion chamber **33** (block **321**); receiving the primary fuel having the first stage vortex induced state within the main body **101** of the main combustion chamber **35** (block **323**); inducing a second stage vortex **163** in the received primary fuel-air mixture to form a complex vortex pattern (block **325**) which can include expelling the partially combusted fuel in the primary fuel-air mixture into the main combustion chamber cavity **109** through a combination precombustion chamber exhaust outlet and main combustion chamber fuel-air inlet **95**, **95'** (block **327**); and combusting (oxidizing) the primary fuel to produce heat and/or to dispose of a "waste" primary fuel.

[0077] As perhaps best shown in FIG. **10**, the step of inducing a first stage vortex **161** can include the substeps of: aerating the primary fuel prior to entry into the precombustion chamber **33** to minimize a size of fuel droplets entering the precombustion chamber (block **331**); igniting a preferably gas-type secondary fuel within the precombustion chamber **33** adjacent a flowpath of the primary fuel to at least partially combust the primary fuel within the precombustion chamber **33** (block **333**); sensing a temperature of the exhaust gas exiting the combustion exhaust conduit of the main combustion chamber (block **335**); and controlling the flow of the secondary fuel into the precombustion chamber **33** responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit **115** (block **337**). Further, as perhaps best shown in FIG. **11**, the step of inducing the first stage vortex **161** can further include the substeps of sensing massflow, density, and/or momentum of the primary fuel (block **341**), and controlling the primary combustion fuel flow rate and/or pressure, and correspondingly, the combustion airflow rate and/or pressure (block **343**).

[0078] This patent application is related to U.S. Provisional Application No. 61/052,076 by Anatoli Borissov, filed May 9, 2008, titled "Apparatus And Methods For Providing Uniformly Volume Distributed Combustion of Fuel and U.S. Pat. No. 5,839,270 by Jirnov et al., titled "Sliding-Blade Rotary Air-Heat Engine with Isothermal Compression of Air," incorporated by reference in its entirety.

[0079] In the drawings and specification, there have been disclosed a typical preferred embodiment of the invention, and although specific terms are employed, the terms are used in a descriptive sense only and not for purposes of limitation. The invention has been described in considerable detail with specific reference to these illustrated embodiments. It will be apparent, however, that various modifications and changes can be made within the spirit and scope of the invention as described in the foregoing specification.

That claimed is:

1. An apparatus for providing flameless combustion of a viscous fuel, the apparatus comprising:

a precombustion chamber adapted to heat and at least partially combust a primary fuel, the precombustion chamber including:

an outer housing having an enclosed proximal end portion, an open distal end portion, and a substantially hollow main body portion extending therebetween and substantially enclosing a precombustion chamber cavity,

at least one air injection inlet port extending through the main body portion of the outer housing and positioned to inject combustion air into the precombustion chamber, the at least one air injection inlet port further positioned to induce a first stage vortex in the main body portion of the housing of the precombustion chamber,

at least one primary fuel nozzle positioned to inject the primary fuel into the precombustion chamber,

an igniter fuel nozzle positioned to inject ignition fuel into the precombustion chamber, and

a hollow cylindrical combustion stabilizer positioned within the precombustion chamber cavity to receive igniter fuel and primary fuel and to isolate the primary fuel from a portion of the combustion air when being heated with the igniter fuel, and having a proximal end portion, a distal end portion, and a main body portion extending between the proximal end portion and the distal end portion, the combustion stabilizer main body portion comprising a large diameter sidewall spaced radially inward from the precombustion chamber housing to define an annulus therebetween and having at least one air inlet aperture extending therethrough to receive a portion of the combustion air to thereby supply oxygen to the igniter fuel and to thereby initiate oxidation of the fuel within the combustion stabilizer, the distal end portion in fluid communication with the combustion stabilizer main body portion and having a small diameter sidewall having a diameter substantially smaller than the large diameter sidewall of the main body, the distal end portion of the combustion stabilizer further having an unobstructed distal end aperture for expelling heated primary fuel into the precombustion chamber cavity adjacent to the distal end portion of the precombustion chamber housing; and

a main combustion chamber adapted to combust the primary fuel, the main combustion chamber including:

a housing having an at least partially enclosed proximal end portion including an exhaust aperture, an enclosed distal end portion, and an elongate main body extending therebetween and substantially enclosing a main combustion chamber cavity, the main body having an inner main body diameter and having a main body axial length extending at least approximately twice the main body diameter, the main body axial length having a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance within the main combustion chamber based upon one or more fuel performance characteristics of the primary fuel to provide substantially complete pyrolization thereof,

an exhaust-inlet located adjacent the proximal end portion of the main combustion chamber housing and extending through the main body of the main combustion chamber housing, and positioned to receive the at least partially combusted primary fuel from the precombustion chamber and to induce a second stage vortex within the main body of the main combustion chamber housing, and

a combustion exhaust tube extending from and interfaced with the proximal end portion of the main combustion chamber housing and extending coaxially along a same longitudinal axis as the main combustion chamber housing, and having an open distal end portion and an elongate main body extending between the open distal end portion of the combustion exhaust tube and the proximal end portion of the main combustion chamber housing, the distal end portion of the combustion exhaust tube extending axially within the main combustion chamber cavity to a location between a position distally forward of an axial mid-point position of the elongate main body of the main combustion chamber housing and a position located axially a distance of at least one exhaust tube main body diameter from the distal end portion of the main combustion chamber housing.

2. An apparatus as defined in claim **1**, wherein the primary fuel is viscous at ambient supply temperature, the apparatus further comprising a primary fuel supply system to provide the primary viscous fuel for combustion, the primary fuel supply system including:

a compressed gas injector connected to a portion of the primary fuel supply system to form at least a suspension to thereby minimize a size of fuel droplets exiting the at least one primary fuel nozzle;

a temperature sensor positioned to detect an exhaust gas temperature of the exhaust gas exiting the combustion exhaust tube; and

a logic circuit positioned to control a flow of the igniter fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust tube.

3. An apparatus as defined in claim **1**, wherein a diameter of the second stage vortex is substantially larger than the diameter of the first stage vortex.

4. An apparatus as defined in claim **1**,

wherein the pre-combustion chamber housing has an axial length to main body cross-sectional diameter ratio of between 2.5:1 to 4:1; and

wherein the combustion air to mass flow of the primary fuel has a ratio of between 35:1 to 45:1.

5. An apparatus as defined in claim **1**, wherein the combined airflow rate of the combustion air entering the precombustion chamber is set based upon predetermined ratios of momentum and mass flow of primary fuel for a given fuel flow rate defining an air-fuel flow to thereby enhance instability of the air-fuel flow.

6. An apparatus as defined in claim **1**,

wherein the primary fuel is glycerin;

wherein the housing of the pre-combustion chamber is of a substantially cylindrical shape;

wherein the housing of the main combustion chamber is of a substantially cylindrical shape;

wherein the combustion exhaust tube has a configuration comprising one or more of the following: a cylindrical shape and a venturi shape; and

wherein the combined airflow rate of the air exiting the at least one air inlet port and mass flow of primary fuel entering the precombustion chamber has a ratio between 20:1 to 40:1 to thereby enhance instability of the air-fuel flow.

7. An apparatus as defined in claim **1**,

wherein the primary fuel is glycerin; and

wherein a shape of the main body of the main combustion chamber housing is configured to provide a uniform temperature and pressure distribution inside of the main combustion chamber cavity and to optimize a pressure drop adjacent the open distal end portion of the combustion exhaust tube.

8. An apparatus as defined in claim **1**,

wherein the primary fuel is glycerin;

wherein the main combustion chamber cavity has an axial length to main body cross-sectional diameter ratio of between 4:1 to 6:1; and

wherein the combustion exhaust tube has an axial offset distance from the distal end portion of the housing of the main combustion chamber-to-combustion exhaust tube cross-sectional diameter ratio of between approximately 1.5:1 to 2.5:1.

9. An apparatus as defined in claim **1**,

wherein the main combustion chamber housing further includes an annulus extending between the proximal end and distal end portions of the housing; and

wherein the distal end portion of the main combustion chamber housing includes a passageway extending from and in communication with the annulus and a plurality of swirl nozzles positioned to supply a cooling fluid to a portion of the cavity of the housing adjacent the distal end of the combustion exhaust tube, the cooling fluid including oxygen and trapped fuel film extracted from within the cavity adjacent the proximal end portion of the housing, the nozzles oriented to enhance instability of the fuel flow adjacent the distal end of the combustion exhaust tube.

10. An apparatus as defined in claim **1**,

wherein the main combustion chamber further comprises a perforated liner secured to interior surfaces of the outer housing, inner bottom wall and inner top wall, the portion of the liner adjacent the inner bottom wall and inner top wall having an arc configured to provide constant vortex radial velocity conditions to thereby provide minimal hydrodynamic losses and to thereby confine unvaporized fuel droplets in equilibrium in an orbit of rotation of the second stage vortex stream;

wherein the apparatus further comprises:

a cooling air supply system to provide a fluid to cool inner surfaces of the main combustion chamber housing and to provide the fluid to the plurality of swirl nozzles to thereby enhance instability of the fuel flow adjacent the distal end of the combustion exhaust tube, and

a recirculation passageway extending between the proximal end and distal end portions of the housing positioned to return trapped fuel film received from a portion of the cavity of the housing adjacent the proximal end of the combustion exhaust tube; and

wherein the at least partially enclosed proximal end portion of the main combustion chamber housing includes an annular raised lip ring extending into the recirculation passageway and configured to cause a venturi effect within the recirculation passageway.

11. An apparatus for providing flameless combustion of a fuel, the apparatus comprising a main combustion chamber adapted to combust a primary fuel, the main combustion chamber including:

a housing having a proximal end portion including an exhaust aperture, a distal end portion, and an elongate main body extending therebetween and substantially enclosing a main combustion chamber cavity, the main body having an inner main body diameter and having a main body axial length; and

an exhaust-inlet extending through the main body of the main combustion chamber housing at an inlet location, and positioned to receive at least partially combusted primary fuel from a precombustion chamber and to induce a vortex within the main body of the main combustion chamber housing, the main body axial length extending distally from the inlet location a distance approximately equal to or greater than a value of the inner main body diameter.

12. An apparatus as defined in claim **11**, wherein the main body axial length has a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance from the exhaust-inlet within the main combustion chamber cavity based upon one or more fuel performance characteristics of the primary fuel to provide substantially complete pyrolization thereof.

13. An apparatus as defined in claim **11**, wherein the main combustion chamber further comprises:

a combustion exhaust conduit extending from and interfaced with the proximal end portion of the main combustion chamber housing and extending coaxially along a same longitudinal axis as the main combustion chamber housing, and having an open distal end portion and an elongate main body extending between the open distal end portion of the combustion exhaust conduit and the proximal end portion of the main combustion chamber housing, the distal end portion of the combustion exhaust conduit extending within the main combustion chamber cavity to a location between a position distally forward of an axial midpoint position of the elongate main body of the main combustion chamber housing and a position axially adjacent to the distal end portion of the main combustion chamber housing, an axial spacing of the distal end portion of the combustion exhaust conduit from an inner surface of the distal end portion of the main combustion chamber housing having a value approximately equal to or greater than that of the inner diameter of the distal end portion of the exhaust conduit main body.

14. An apparatus as defined in claim **13**,

wherein the exhaust-inlet is positioned normal to an inner surface portion of the main body of the main combustion chamber housing adjacent thereto; and

wherein an outer surface of the combustion exhaust conduit includes a swirl enhancer comprising at least one of the following: a spiral recess extending along a substantial portion of the longitudinal length thereof, or a spiral protuberance extending along the substantial portion of the longitudinal length thereof, to thereby enhance the inducement of the vortex within the main body of the main combustion chamber housing.

15. An apparatus as defined in claim **13**,

wherein the main body of the main combustion chamber housing has an axial length to main body cross-sectional inner diameter ratio of between approximately 4:1 to 6:1; and

wherein the distal end portion of the combustion exhaust conduit has an axial offset distance from the distal end portion of the housing of the main combustion chamber to combustion exhaust conduit distal end portion cross-sectional diameter ratio of between approximately 5:1 to 2.5:1.

16. An apparatus as defined in claim **11**, wherein the vortex is a second stage vortex, the apparatus further comprising a precombustion chamber adapted to heat and at least partially combust the primary fuel, the precombustion chamber including:

a housing having a proximal end portion, an open distal end portion, and a substantially hollow main body portion extending therebetween and having a substantially cylindrical inner surface substantially enclosing a precombustion chamber cavity; and

at least one air injection inlet port extending through the main body portion of the precombustion chamber housing and positioned to inject combustion air into the precombustion chamber, the at least one air injection inlet port further positioned to induce a first stage vortex in the main body portion of the housing of the precombustion chamber.

17. An apparatus as defined in claim **11**, further comprising a precombustion chamber adapted to heat and at least partially combust the primary fuel, the precombustion chamber including:

a housing having a proximal end portion, an open distal end portion, and a substantially hollow main body portion extending therebetween and ,substantially enclosing a precombustion chamber cavity;

at least one primary fuel nozzle positioned to inject primary fuel into the precombustion chamber;

an igniter fuel nozzle positioned to inject ignition fuel into the precombustion chamber; and

a hollow combustion stabilizer positioned within the precombustion chamber cavity to receive the igniter fuel and the primary fuel and to isolate the primary fuel from a portion of the combustion air when being initially heated with the igniter fuel, and having a proximal end portion, a distal end portion, and a main body portion extending between the proximal end portion and the distal end portion, the combustion stabilizer main body portion comprising a large diameter sidewall spaced radially inward from the precombustion chamber housing to define an annulus therebetween and having at least one air inlet aperture extending therethrough to receive a portion of the combustion air to thereby supply oxygen to the igniter fuel and to thereby initiate oxidation of the fuel within the combustion stabilizer, the distal end portion of the combustion stabilizer in fluid communication with the combustion stabilizer main body and having a small diameter sidewall having a diameter substantially smaller than the large diameter sidewall of the main body, the distal end portion further having an unobstructed distal end aperture for expelling heated primary fuel into the precombustion chamber cavity adjacent to the distal end portion of the precombustion chamber housing.

18. An apparatus as defined in claim **17**, wherein a diameter of the second stage vortex is substantially larger than the diameter of the first stage vortex.

19. An apparatus as defined in claim **17**, wherein the primary fuel is viscous at ambient supply temperature, the apparatus further comprising a primary fuel supply system to provide the primary viscous fuel for combustion, the primary fuel supply system including:

a compressed gas injector connected to a portion of the primary fuel supply system to form at least a suspension to thereby minimize a size of fuel droplets exiting the at least one primary fuel nozzle;

a temperature sensor positioned to detect an exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit; and

a logic circuit configured to control a flow of the igniter fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit.

20. An apparatus as defined in claim 17,
wherein the pre-combustion chamber housing has an axial length to main body cross-sectional diameter ratio of between 2.5:1 to 4:1;
wherein the combustion air to mass flow of the primary fuel has a ratio of between 30:1 to 50:1; and
wherein the combined airflow rate of the combustion air entering the precombustion chamber is set based upon predetermined ratios of momentum and mass flow of primary fuel for a given fuel flow rate defining an air-fuel flow to thereby enhance instability of the air-fuel flow.

21. A method of providing flameless combustion of a viscous fuel, the method comprising the steps of:
inducing a first stage vortex in a primary fuel-air mixture within a main body portion of a precombustion chamber of a flameless combustor;
receiving the primary fuel-air mixture having the first stage vortex induced state within a main body of a main combustion chamber of the flameless combustor; and
inducing a second stage vortex in the received primary fuel-air mixture to form a complex vortex pattern to thereby enhance flameless oxidation of the primary fuel within the main body of the main combustion chamber, a diameter of the first stage vortex being substantially smaller than a diameter of the second stage vortex.

22. A method as defined in claim 21,
wherein the step of inducing a second stage vortex includes expelling the primary fuel-air mixture tangentially into the main combustion chamber cavity through a precombustion chamber exhaust outlet; and
wherein the precombustion chamber exhaust outlet is axially spaced apart from the combustion exhaust conduit inlet a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance from the precombustion chamber exhaust outlet within the main combustion chamber cavity based upon one or more fuel performance characteristics of the primary fuel to provide substantially complete pyrolization thereof.

23. A method as defined in claim 22, wherein the primary fuel is a glycerol fuel, the method further comprising the step of:
preselecting the value of the axial separation between the precombustion chamber exhaust outlet and the combustion exhaust conduit inlet to provide the sufficient pyrolyzed fuel travel distance from the exhaust-inlet port within the main combustion chamber cavity responsive to one or more fuel performance characteristics of the glycerol fuel.

24. A method as defined in claim 21, further comprising the steps of:
interfacing a precombustion chamber with the main combustion chamber, the precombustion chamber adapted to heat and at least partially combust the primary fuel;
igniting a secondary fuel within the precombustion chamber adjacent a flowpath of the primary fuel to at least partially combust the primary fuel within the precombustion chamber of the flameless combustor;
sensing a temperature of the exhaust gas exiting the combustion exhaust conduit of the main combustion chamber; and
controlling a flow of the secondary fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit.

25. A method as defined in claim 21, further comprising the steps of:
interfacing a precombustion chamber with the main combustion chamber, the precombustion chamber adapted to heat and at least partially combust the primary fuel; and
aerating the primary fuel prior to entry into the precombustion chamber to minimize a size of fuel droplets entering the precombustion chamber.

26. A method as defined in claim 21, further comprising the steps of:
providing a main vortex combustion chamber of a flameless combustor having a main body substantially enclosing a main combustion chamber cavity, the main combustion chamber cavity having an axial length approximately equal to or greater than an inner diameter of the main combustion chamber cavity; and
providing a combustion exhaust conduit within and axially coincident with the main combustion chamber cavity, the combustion exhaust conduit having an inlet positioned at a location between an axial position distally forward of an axial midpoint position of the elongate main body of the main combustion chamber housing and an axial position within the main combustion chamber cavity adjacent the distal end portion of the main combustion chamber housing, an axial spacing of the distal end portion of the combustion exhaust conduit from an inner surface of the distal end portion of the main combustion chamber housing having a value approximately equal to or greater than that of the inner diameter of the distal end portion of the exhaust conduit.

27. A method of providing flameless combustion of a viscous fuel, the method comprising the steps of:
providing a main vortex combustion chamber of a flameless combustor having a main body substantially enclosing a main combustion chamber cavity, the main combustion chamber cavity having an axial length approximately equal to or greater than an inner diameter of the main combustion chamber cavity; and
inducing flameless oxidation of a primary fuel within the main combustion chamber cavity, the step of inducing flameless oxidation comprising the step of inducing a vortex within the main combustion chamber cavity to enhance formation of a fuel air mixture.

28. A method as defined in claim 27, wherein the main body (101) is an elongate main body (101), the method further comprising the step of providing a combustion exhaust conduit within and axially coincident with the main combustion chamber cavity, the combustion exhaust conduit having an inlet positioned at a location between an axial position distally forward of an axial midpoint position of the main body of the main combustion chamber housing and an axial position within the main combustion chamber cavity adjacent the distal end portion of the main combustion chamber housing, an axial spacing of the distal end portion of the combustion exhaust conduit from an inner surface of the distal end portion of the main combustion chamber housing having a value approximately equal to or greater than that of the inner diameter of distal end portion of the exhaust conduit.

29. A method as defined in claim 27, further comprising the step of:
injecting the primary fuel into the main combustion chamber cavity through a precombustion chamber exhaust outlet, the precombustion chamber exhaust outlet axially spaced apart from the combustion exhaust conduit

inlet a preselected value preselected to provide a sufficient pyrolyzed fuel travel distance from the precombustion chamber exhaust outlet within the main combustion chamber cavity based upon one or more fuel performance characteristics of the primary fuel to provide substantially complete pyrolization thereof.

30. A method as defined in claim **29**, wherein the primary fuel is a glycerol fuel, the method further comprising the step of:

preselecting the value of the axial separation between the precombustion chamber exhaust outlet and the combustion exhaust conduit inlet to provide the sufficient pyrolyzed fuel travel distance from the precombustion chamber exhaust outlet within the main combustion chamber cavity responsive to one or more fuel performance characteristics of the glycerol fuel.

31. A method as defined in claim **27**, further comprising the steps of:

interfacing a precombustion chamber with the main combustion chamber, the precombustion chamber adapted to heat and at least partially combust the primary fuel;

igniting a secondary fuel within the precombustion chamber adjacent a flowpath of the primary fuel to at least partially combust the primary fuel within the precombustion chamber of the flameless combustor;

sensing a temperature of the exhaust gas exiting the combustion exhaust conduit of the main combustion chamber; and

controlling a flow of the igniter fuel into the precombustion chamber responsive to the exhaust gas temperature of the exhaust gas exiting the combustion exhaust conduit.

32. A method as defined in claim **31**, wherein the induced vortex in the main combustion chamber is the second stage vortex, the method further comprising the step of:

inducing a first stage vortex in a precombustion chamber of a flameless combustor to form a complex vortex pattern, a diameter of the first stage vortex being substantially smaller than a diameter of the second stage vortex.

33. A method as defined in claim **27**, further comprising the steps of:

interfacing a precombustion chamber with the main combustion chamber, the precombustion chamber adapted to heat and at least partially combust the primary fuel; and

aerating the primary fuel prior to entry into the precombustion chamber to minimize a size of fuel droplets entering the precombustion chamber.

34. A method as defined in claim **28**, further comprising the step of:

selecting a shape of the main body of the main combustion chamber that provides a substantially uniform temperature and pressure distribution inside at least a substantial portion of the main chamber and that substantially optimizes a pressure drop adjacent the inlet of the combustion exhaust conduit.

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