

BURNER, METHOD OF OPERATION AND COMBUSTION APPARATUS**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims priority to U.S. Provisional Application 63/568,072 filed March 21, 2024, U.S. Non-Provisional Application 18/233,455 filed August 14, 2023, and U.S. Provisional Application 63/532,498 filed August 14, 2023.

FIELD OF THE INVENTION

[0002] The present invention relates to burners and particularly to industrial burners for gaseous fuels, and especially to the field of multi-fuel (e.g., two-fuel) burners.

BACKGROUND OF THE INVENTION

[0003] Burners can be designed utilized to use a fuel and an oxidant to generate a flame for combustion of a fuel. Examples of different types of burners can be appreciated from U.S. Patent Nos. 6,019,595, 6,835,360, 10,393,373, 10,584,051, 11,592,178, and 11,808,457, U.S. Patent Application Publication Nos. 2024/0019123, 2024/0019118, 2014/0069079, and Chinese Patent Publication No. CN 111336515.

SUMMARY OF THE INVENTION

[0004] We have determined that there is a need of a burner that can be operated across a wide range of turndown, equivalence ratio, and/or flexibility to choose a fraction of heat supplied to the process from the different fuel options. Furthermore, with increased focus on alternative fuels and availability of diverse gaseous fuels across geographical locations, we determined that there is a need for a burner that can operate for a wide range of fuels for various different applications. This can be particularly challenging to facilitate reliably starting or igniting a burner at a low equivalence ratio (fuel lean start-ups), in particular in situations where one is unable to drop the air flow rate below a particular set point and one needs to flow fuel at a minimum fuel flow rate.

[0005] For example, fuel-flexible burners that can operate using a gaseous fuel such as natural gas ("NG"), liquefied petroleum gas ("LPG"), biogas, synthesis gas, hydrogen, ammonia or other gases, and meet the emissions and thermal performance criteria of the heating application of a furnace or a melting furnace can have various design challenges depending on the burner type and design. For example, the wide variation in the combustion behavior of these fuels (e.g., the differences in heating value, reaction rates and flammability limits of the gaseous fuels) can create a significant challenge

when designing a burner. This can be particularly difficult when design criteria for a burner involves keeping nitrous oxide (NO_x) emissions low and there is a desire to have a reduced flame length to provide a shorter flame that can be positioned within a compact combustion chamber (e.g. a combustion chamber of a smaller reformer, a smaller combustion chamber of furnace, a smaller combustion chamber of a boiler or furnace, etc.).

[0006] We have also determined that improved burner designs that can facilitate use of multiple types of fuel that can be utilized in a range of splits for use of such fuels (e.g. variation in how much of a combusted fuel is from a primary fuel source as compared to a secondary fuel source, or variation in how much of a combusted fuel is from a first fuel source as compared to a second fuel source, etc.) can provide improved operational flexibility, while also accounting for the different combustion characteristics that may result from the different fuel composition splits that may be used. Such embodiments that can also provide shorter flame lengths and low NO_x emissions can help facilitate improved operational performance and flexibility while also reducing the environmental impact associated with the operation of one or more such burners in an industrial environment.

[0007] Embodiments of our burner, combustion devices that can utilize one or more such burners, and processes for combustion of fuels that can utilize one or more such burners can be provided to facilitate improved operational flexibility that can also provide improved operational efficiency and reduced environmental impacts. We have also found that embodiments can be configured for use in smaller sized combustion devices that can provide improved combustion device design flexibility as well.

[0008] In a first aspect, a burner can include a first fuel conduit positioned to pass a first fuel flow to an ignition chamber positioned in a downstream portion of the burner and an oxidant conduit positioned to pass an oxidant flow to a combustion chamber of a combustion device. The oxidant conduit can have a first oxidant conduit segment and a second oxidant conduit segment that is separated from the first oxidant conduit segment via a first partition wall such that the oxidant flow passable through the oxidant conduit is splittable into a first oxidant flow that is passed through the first oxidant conduit segment and a second oxidant flow that is passable through the second oxidant conduit segment. The first oxidant conduit segment can be configured so that a first portion of the first oxidant flow is passable to the ignition chamber for mixing with fuel therein via holes of the ignition chamber that are in fluid communication with the first oxidant conduit segment and a second portion of the first oxidant flow is outputable from the oxidant conduit via at least one oxidant exit hole in fluid communication with the first oxidant

conduit segment. The burner can also include a second fuel conduit positioned to pass a second fuel flow to a combustion chamber of a combustion device.

[0009] In some embodiments, the first fuel can be or include natural gas and the second fuel can include hydrogen, a mixture of hydrogen and nitrogen, or a mixture of nitrogen, hydrogen, and ammonia. In yet other embodiments, the first fuel can be a first type of fuel and the second fuel can be a second type of fuel that differs from the first type of fuel.

[0010] The oxidant can be an oxygen containing gas. In some embodiments, the oxidant can be air or oxygen enriched air, for example.

[0011] The burner can be configured for utilization in a combustion chamber of a combustion device. In some embodiments, the burner can be configured to generate a flame for use in a combustion chamber of a reformer or an ammonia cracking furnace, for example. Other embodiments can be configured for uses in other types of combustion devices as well.

[0012] In some embodiments, the burner can be configured to operate in multiple different modes of operation. For example, the burner can be configured to operate in a multiple fuel mode of operation in which both a first fuel and a second fuel are passed to the burner for passing through the first fuel conduit and the second fuel conduit. The burner can also be configured to operate in a first fuel only mode of operation in which only the first fuel is passed through the first fuel conduit and the second fuel is not passed through the second fuel conduit and is not utilized. The burner can also be configured to operate in a second fuel only mode of operation in which only the second fuel is passed through the second fuel conduit and the first fuel is not passed through the first fuel conduit and is not utilized. The burner can be configured to be adjustable between use in any of these modes of operation (e.g. via passing of both the first fuel and second fuel to the burner and/or cessation of feeding the first fuel or second fuel to the burner).

[0013] In a second aspect, the oxidant conduit can be positioned between the first fuel conduit and the second fuel conduit and there can be a fuel distribution plate having a plurality of second fuel exit holes in fluid communication with an outlet end of the second fuel conduit. In some embodiments, an inner series of the second fuel exit holes can be angled via an angle ω to direct streams of the second fuel output via the fuel distribution plate toward a central axis of the burner into the combustion chamber.

[0014] In a third aspect, the oxidant conduit can be positioned between the first fuel conduit and the second fuel conduit and there can also be an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall.

The second fuel conduit can have at least one internal second fuel injection hole in fluid communication with the inner second fuel conduit to divert a portion of second fuel passing through the second fuel conduit into the inner second fuel conduit for being output from the burner via an outlet of the inner second fuel conduit.

[0015] In some embodiments, the inner second fuel conduit can be in fluid communication with the second oxidant conduit segment such that the second oxidant flow is splittable to form a third oxidant flow that is passable through the inner second fuel conduit to mix with the portion of second fuel diverted into the second inner second fuel conduit via the at least one internal second fuel injection hole while a portion of the second oxidant flow is passed through the second oxidant conduit segment for being output from at least one oxidant exit hole in fluid communication with the second oxidant conduit segment. In other embodiments, the inner second fuel conduit can be structured to prevent any formation of such a third oxidant flow is not formed and does not pass into the inner second fuel conduit.

[0016] In some embodiments, the second fuel conduit can also be in fluid communication with an inner row of spaced apart holes that each extend to an outlet of the burner inwardly towards a central axis of the burner at a pre-selected angle ω . the pre-selected angle ω can be at between 2° and 80° in some embodiments.

[0017] In a fourth aspect, the ignition chamber can include an ignition cup that is upstream of a bleed cup and a mixer plate that is positioned between the ignition cup and the bleed cup. The mixer plate can have holes positioned so that jets of fuel output from the first fuel conduit are broken up and partially premix with oxidant feedable into the ignition cup via holes of the ignition cup that are in fluid communication with the first oxidant conduit segment so that the partially premixed fuel and oxidant are passable through the holes of the mixer plate into the bleed cup. Some embodiments can also include a first oxidant distribution plate and/or a second oxidant distribution plate that can be positioned so that oxidant passing through the first oxidant conduit segment are outputtable via the oxidant exit holes in different upstream and downstream locations and/or in different inner and outer positions relative to a central axis of the burner.

[0018] For example, in a fifth aspect, the burner can include a first oxidant distribution plate that can be positioned between the ignition cup and the bleed cup. The first oxidant distribution plate can have oxidant exit holes through which oxidant from the first oxidant conduit segment is outputtable. Alternatively (or also), the burner can include a second oxidant distribution plate positioned adjacent an outlet of the bleed cup between the bleed cup and the first partition wall. The second oxidant distribution plate

can have oxidant exit holes through which oxidant from the first oxidant conduit segment is outputable as well. The oxidant exit holes of the second oxidant distribution plate can be positioned so that the oxidant exit holes of the first oxidant distribution plate are between the oxidant exit holes of the second oxidant distribution plate and the central axis of the burner.

[0019] In a sixth aspect, the burner can be configured so that the first fuel conduit has an inner diameter or width D3, the oxidant conduit has an inner diameter or width D4, the second fuel conduit has an inner diameter or width D5, a downstream portion of the ignition chamber has a diameter or width D6, and second fuel exit holes through which the second fuel flow passed through the second fuel conduit are outputable have a diameter or width D7.

[0020] In a seventh aspect, the second fuel exit holes can include an inner row of spaced apart holes arranged in a ring pattern and an outer row of spaced apart holes arranged in a ring pattern that are in fluid communication with the second fuel conduit. A distance between the second fuel exit holes on opposite sides of the inner row of spaced apart holes can be a distance D8 and a distance between the second fuel exit holes on opposite sides of the outer row of spaced apart holes can be a distance D9 that is greater than distance D8. The burner can be configured so that the burner includes one or more of the following design parameters:

D7 is between 0.12 cm and 0.762 cm;

a ratio of D8/D4 is between 1.1 and 1.3; and

a ratio of D9/D4 is between 1.6 and 2.2.

[0021] For example, two or more of the above parameters or all three of the above parameters may be utilized in embodiments of the burner. As another example, only one of the above parameters may be utilized in the burner.

[0022] In an eighth aspect, a diameter of the holes in a downstream portion of the ignition chamber can have a pre-selected diameter P1 and a space between spaced apart rows of the holes of the ignition chamber can be a distance H and wherein H/P1 is between 1.25 and 2.5.

[0023] In a ninth aspect, the first fuel conduit can be positioned around a receptacle having a diameter or width D2 and the first fuel conduit can have an outlet in fluid communication with first fuel exit holes having a diameter D0. The oxidant conduit can be in fluid communication with oxidant exit holes having a diameter D1. The first partition wall can be positioned and configured so that the first oxidant conduit segment is defined

to have a pre-selected diameter or width L4 and extends along a first portion L02 of an overall length L0 of the ignition chamber that extends from an upstream end of the ignition chamber to a downstream end of the ignition chamber and also has a pre-selected diameter or width L5 that extends along a second portion L01 of the overall length L0 of the ignition chamber such that mixing of oxidant within a downstream portion the ignition chamber occurs about a length L01 of the overall length L0 of the ignition chamber wherein L01 is less than L0. The pre-selected with or diameter L5 can be less than the pre-selected width or diameter L4 in some embodiments.

[0024] A diameter of the holes of the ignition chamber in the downstream portion of ignition chamber can have a pre-selected diameter P1 and a space between spaced apart rows of the holes of the downstream portion of the ignition chamber is distance H. Embodiments of the burner can be configured to also include at least one of the following parameters as well:

- i. a value of P1 is between 0.12 cm and 0.51 cm;
- ii. a ratio of P1/D2 is between 0.06 and 0.6;
- iii. a value of D7 is between 0.12 cm and 0.762 cm;
- iv. a ratio of D7/D2 is between 0.05 and 0.6;
- v. a value of D0 is between 0.12 cm and 0.64 cm;
- vi. a ratio of D0/D2 is between 0.05 and 0.6;
- vi.. a value of D1 is between 0.12 cm and 0.381 cm;
- vii. a ratio of D1/D2 is between 0.06 and 0.15;
- viii. a ratio of D3/D2 is between 1.5 and 5;
- ix. a ratio of D4/D2 is between 2 and 12;
- x. a ratio of D5/D2 is between 5 and 25;
- xi. a ratio of D6/D2 is between 1.5 and 6;
- xii. a ratio of D8/D4 is between 1.1 and 1.3;
- xiii. a ratio of D9/D4 is between 1.6 and 2.2;
- xiv. a ratio of L0/D3 is between 0.2 and 2;
- xvi. a ratio of L01/D3 is between 0.1 and 1;
- xvii. a ratio of L4/D3 is between 0.05 and 1; and
- xviii. a ratio of L5/L01 is between 0.2 and 1.

[0025] For example, two or more of the above parameters i. through xviii or all of the above parameters i through xviii may be utilized in embodiments of the burner. As another example, only one of the above parameters may be utilized in the burner.

[0026] In a tenth aspect, the burner can include an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall such that the inner second fuel conduit is between the second oxidant conduit segment and the second fuel conduit wherein the second fuel conduit has at least one internal second fuel injection hole in fluid communication with the inner second fuel conduit to divert a portion of second fuel passing through the second fuel conduit into the inner second fuel conduit for being output from the burner via an outlet of the inner second fuel conduit. A flame stabilization plate (FSP) can be positioned adjacent to an outlet of the inner second fuel conduit.

[0027] In some embodiments, the FSP can also be positioned adjacent to an outlet of the inner second fuel conduit to provide a flame stability surface.

[0028] In some embodiments, the burner can be configured so that the oxidant conduit has an inner diameter or width D_4 and the oxidant conduit is positioned between the first fuel conduit and the second fuel conduit. The second partition wall can have a length L_7 ; the at least one second fuel injection hole can be located upstream of an outlet of the burner by a distance L_8 that is less than L_7 ; and the FSP can be annular shaped and have an inner diameter D_{10} and an outer diameter D_{11} and the inner second fuel conduit can have an inner width or diameter D_{12} . The FSP can be positioned so that the FSP is recessed relative to an output plane of the burner a recessed distance L_6 wherein L_6 is a distance axially inward from the output plane that is adjacent the combustion chamber to the FSP. L_6 can also be less than L_8 and L_6 can also be less than L_7 . Embodiments of the burner can also be configured to include one or more of the following features:

- a. a ratio of D_{12}/D_4 is between 0.75 and 0.95
- b. a ratio of L_6/D_4 is between 0.04 and 0.5;
- c. a ratio of D_{10}/D_4 is between 0.70 and 0.85;
- d. a ratio of D_{11}/D_4 is between 0.90 and 0.99; and
- e. a ratio of L_7/D_4 is between 0.25 and 2.0.

[0029] For example, two or more of the above parameters a-e or all five of the above parameters a-e may be utilized in embodiments of the burner. As another example, only one of the above parameters may be utilized in the burner.

[0030] In an eleventh aspect, the burner of the first aspect can be configured to include one or more features of the second aspect, third aspect, fourth aspect, fifth aspect, sixth aspect, seventh aspect, eighth aspect, ninth aspect and/or tenth aspect. Additional features can also be included in such a burner. For instance, examples of additional features that may be included can be appreciated from the exemplary embodiments of the burner discussed herein.

[0031] In a twelfth aspect, a process of combusting at least one fuel in a combustion chamber of a combustion device is provided. Embodiments of the process can include passing a first fuel flow through a first fuel conduit of a burner positioned to generate a flame in the combustion chamber, passing an oxidant flow through an oxidant conduit of the burner such that the oxidant flow is split into a first oxidant flow that passes through a first oxidant conduit segment of the oxidant conduit that is separated from a second oxidant conduit segment via a first partition wall and a second oxidant flow that passes through the second oxidant conduit segment. The process can also include passing a first portion of the first oxidant flow to an ignition chamber of the burner for mixing with fuel therein via holes of the ignition chamber that are in fluid communication with the first oxidant conduit segment and passing a second portion of the first oxidant flow through the first oxidant conduit segment for being output out of the oxidant conduit via at least one oxidant exit hole in fluid communication with the first oxidant conduit segment.

[0032] Embodiments of the burner can be utilized in the process. Also, the process can utilize other steps (e.g. use of a second fuel in combination with the first fuel or instead of use of the first fuel, etc.). For instance, (and as also noted above), in some embodiments, the first fuel can be or include natural gas and the second fuel can include hydrogen, a mixture of hydrogen and nitrogen, or a mixture of nitrogen, hydrogen, and ammonia. In yet other embodiments, the first fuel can be a first type of fuel and the second fuel can be a second type of fuel that differs from the first type of fuel.

[0033] The oxidant can be an oxygen containing gas. In some embodiments, the oxidant can be air or oxygen enriched air, for example.

[0034] The process can be utilized for generation of a flame in a combustion chamber of a combustion device. In some embodiments, the flame can be formed in a combustion chamber of a reformer or an ammonia cracking furnace, for example. Other embodiments of the process can be adapted for use in other types of combustion devices as well.

[0035] In a thirteen aspect, the process can include passing a second fuel flow through a second fuel conduit of the burner. In some embodiments, the oxidant conduit can be positioned to be between the first fuel conduit and the second fuel conduit.

[0036] In a fourteenth aspect, the process can also include diverting of a portion of the second fuel flow being passed through the second fuel conduit so that the diverted portion of the second fuel flow passes through at least one internal second fuel injection hole of the second fuel conduit that is in fluid communication with an inner second fuel conduit, the inner second fuel conduit being positioned between the second fuel conduit and the second oxidant conduit segment.

[0037] In a fifteenth aspect, the process can be implemented such that the passing of the oxidant flow through the oxidant conduit of the burner includes passing the second oxidant flow through the second oxidant conduit segment such that a portion of the oxidant is split from the second oxidant flow to form a third oxidant flow that passes through an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall. The second oxidant conduit segment can be between the first oxidant conduit segment and the inner second fuel conduit and the inner second fuel conduit can be between the second fuel conduit and the second oxidant conduit segment. The passing of the second fuel flow through the second fuel conduit can include passing a portion of the second fuel flow through at least one internal second fuel injection hole of the second fuel conduit that is in fluid communication with the inner second fuel conduit to mix with the third oxidant flow passing through the third oxidant conduit segment in such embodiments.

[0038] In a sixteenth aspect, the process can include outputting a portion of the second fuel flow via second fuel exit holes in fluid communication with the second fuel conduit. The second fuel exit holes can include an inner row of spaced apart angled holes that each extend to an outlet of the burner inwardly towards a central axis of the burner at a pre-selected angle ω , which can be at an angle of between 2° and 80° in some embodiments. There may also be other outer rows of spaced apart second fuel exit holes that are farther from the burner's central axis as compared to this inner row.

[0039] In a seventeenth aspect, the process can also include ceasing of the passing of the first fuel flow through the first fuel conduit of the burner so that only the second fuel is passed through the burner to provide the flame within the combustion chamber. In some embodiments, this process step can be performed in conjunction with a burner

having a flame stabilization plate (FSP) (e.g. an embodiment of an FSP as discussed herein, etc.).

[0040] In an eighteenth aspect, the process can also include feeding the first fuel through the first fuel conduit of the burner after the ceasing of the passing of the first fuel flow through the first fuel conduit for a pre-selected time period so that the first fuel and the second fuel are combusted to form the flame in the combustion chamber.

[0041] In a nineteenth aspect, the process can also include ceasing of the passing of the second fuel flow through the second fuel conduit of the burner so that only the first fuel is passed through the burner to provide the flame within the combustion chamber. The process can also include feeding the second fuel through the second fuel conduit of the burner after the ceasing of the passing of the second fuel flow through the second fuel conduit for a pre-selected time period so that the first fuel and the second fuel are combusted to form the flame in the combustion chamber.

[0042] In a twentieth aspect, the process of the twelfth aspect can include one or more features of the thirteenth aspect, fourteenth aspect, fifteenth aspect, sixteenth aspect, seventeenth aspect, eighteenth aspect, and/or nineteenth aspect. Embodiments of the process can also utilize an exemplary embodiment of the burner and/or other features. For instance, examples of additional features that may be included in an embodiment of the process can be appreciated from the exemplary embodiments of the process discussed herein.

[0043] Embodiments of a combustion device are also provided. Embodiments of the combustion device can include an embodiment of the burner. Embodiments can also utilize a source of oxidant, a source of a first fuel, and a source of a second fuel that can be in fluid communication with the burner.

[0044] Embodiments of the burner, combustion device, and process can be configured to utilize a distributed control system (DCS) and/or an automated process control system that can involve use of controllers, valves, sensors, detectors, and other process control elements. At least one operator workstation can be utilized in conjunction with such a system to help monitor and/or control operations as well.

[0045] Other details, objects, and advantages of burners, combustion devices, processes for combusting multiple fuels, and methods of making and using the same will become apparent as the following description of certain exemplary embodiments thereof proceeds.

BRIEF DESCRIPTION OF THE DRAWINGS

[0046] Exemplary embodiments of burners, combustion devices, plants utilizing one or more burners in at least one combustion device (e.g., furnace, combustor, etc.), processes of combusting multiple fuels, and methods of making and using the same are shown in the drawings included herewith. It should be understood that like reference characters used in the drawings may identify like components.

[0047] Figure 1 is a schematic diagram of a first exemplary embodiment of a combustion device 3 having at least one burner 5 that can generate a flame 7 within a combustion chamber CC of the combustion device 3.

[0048] Figure 2 is a schematic diagram of a first exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0049] Figure 3 is a front view of a face 5F of the downstream portion 5dp of an exemplary embodiment of the burner 5 that can be positioned in or adjacent a wall of the combustion chamber CC for emitting a flame 7 therein.

[0050] Figure 4 is a schematic cross-sectional view of the downstream portion 5dp of the first exemplary embodiment of the burner 5.

[0051] Figure 5 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0052] Figure 6 is a schematic cross-sectional view similar to that of Figure 4 of the downstream portion 5dp of the first exemplary embodiment of the burner 5.

[0053] Figure 7 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 similar to Figure 5.

[0054] Figure 8 is a schematic cross-sectional view similar to that of Figure 4 of the downstream portion 5dp of a second exemplary embodiment of the burner 5.

[0055] Figure 9 is a schematic cross-sectional view similar to that of Figures 4, 6, and 8 of the downstream portion 5dp of a third exemplary embodiment of the burner 5.

[0056] Figure 10 is a schematic cross-sectional view similar to that of Figure 6 illustrating the downstream portion 5dp of the first exemplary embodiment of the burner 5.

[0057] Figure 11 is a series of schematic cross-sectional views of the downstream portion 5dp of the first exemplary embodiment of the burner 5 that help illustrate example fuel and oxidant mixing that can be provided via the burner 5.

[0058] Figure 12 is an enlarged schematic cross-sectional view of the downstream portion 5dp of the first exemplary embodiment of the burner 5.

[0059] Figure 13 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 similar to Figure 5.

[0060] Figure 14 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0061] Figure 15 is a schematic cross-sectional view illustrating the downstream portion 5dp of a fourth exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figure 14 can be used in conjunction with this embodiment.

[0062] Figure 16 is a schematic cross-sectional view illustrating the downstream portion 5dp of a fifth exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figure 14 can be used in conjunction with this embodiment.

[0063] Figure 17 is a schematic cross-sectional view illustrating the downstream portion 5dp of a sixth exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figure 18 can be used in conjunction with this embodiment.

[0064] Figure 18 is a front view of a face 5F of a downstream portion 5dp of the sixth exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0065] Figure 19 is a schematic cross-sectional view illustrating the downstream portion 5dp of the seventh exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figure 20 can be used in conjunction with this embodiment.

[0066] Figure 20 is a front view of a face 5F of a downstream portion 5dp of the seventh exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0067] Figure 21 is a schematic cross-sectional view illustrating the downstream portion 5dp of an eighth exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figure 22 can be used in conjunction with this embodiment.

[0068] Figure 22 is a front view of a face 5F of a downstream portion 5dp of the eighth exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0069] Figure 23 is a graph illustrating a plot of the flux of thermal energy in relation to normalized nitrous oxide (NO_x) emissions relating to a first example of conducted testing discussed herein.

[0070] Figure 24 is a schematic cross-sectional view similar to that of Figures 4 and 6 of the downstream portion 5dp of the first exemplary embodiment of the burner 5.

[0071] Figure 25 is a schematic cross-sectional view similar to that of Figures 4, 6, and 24 of the downstream portion 5dp of the first exemplary embodiment of the burner 5 illustrating an exemplary initial flame development that can be provided in a first operational mode that can be a multi-fuel operational mode (e.g. use of first and second fuels).

[0072] Figure 26 is a schematic cross-sectional view similar to that of Figures 4, 6, 24, and 25 of the downstream portion 5dp of the first exemplary embodiment of the burner 5 illustrating an exemplary initial flame development that can be provided in a second operational mode that can be a first fuel operational mode in which there is a low firing rate and/or low equivalence ratio of first fuel. In the first fuel operational mode only the first fuel may be fed to the burner 5 to form a flame.

[0073] Figure 27 is a schematic cross-sectional view illustrating the downstream portion 5dp of a ninth exemplary embodiment of a burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3. The front face 5F illustrated in Figures 28, 32 and 34-35 can be used in conjunction with this embodiment.

[0074] Figure 28 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 that can be utilized in the first exemplary embodiment of the combustion device 3.

[0075] Figure 29 is a schematic cross-sectional view similar to that of Figure 27 of the downstream portion 5dp of a tenth exemplary embodiment of the burner 5.

[0076] Figure 30 is a schematic cross-sectional view similar to that of Figures 27 and 29 of the downstream portion 5dp of an eleventh exemplary embodiment of the burner 5.

[0077] Figure 31 is a schematic cross-sectional view similar to that of Figure 27 of the downstream portion 5dp of the ninth exemplary embodiment of the burner 5.

[0078] Figure 32 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 similar to that of Figure 28.

[0079] Figure 33 is a schematic cross-sectional view similar to that of Figures 27 and 31 of the downstream portion 5dp of the ninth exemplary embodiment of the burner 5.

[0080] Figure 34 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 similar to that of Figures 28 and 32.

[0081] Figure 35 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5 similar to that of Figures 28 and 32-33.

[0082] Figure 36 is a front view of a face 5F of a downstream portion 5dp of an exemplary embodiment of the burner 5.

[0083] Figure 37 is a schematic cross-sectional view similar to that of Figures 27, 31 and 33 of the downstream portion 5dp of the ninth exemplary embodiment of the burner 5.

[0084] Figure 38 is a graph illustrating a plot of the flux of thermal energy in relation to normalized nitrous oxide (NO_x) emissions relating to a second example of conducted testing discussed herein.

[0085] Figure 39 is a schematic cross-sectional view similar to that of Figures 27, 31, 33 and 37 of the downstream portion 5dp of the ninth exemplary embodiment of the burner 5 illustrating an exemplary initial flame development that can be provided in a first operational mode that can be a high firing rate operational mode that can utilize both first and second fuel flows 1F and 2F.

[0086] Figure 40 is a schematic cross-sectional view similar to that of Figures 27, 31, 33, 37 and 39 of the downstream portion 5dp of the ninth exemplary embodiment of the burner 5 illustrating an exemplary initial flame development that can be provided in a second operational mode that can be a low firing rate operational mode that utilizes only a second fuel flow 2F for operation.

[0087] Figure 41 is a perspective cross-sectional view of the downstream portion 5dp of the eighth exemplary embodiment of the burner 5.

[0088] Figure 42 is a series of schematic diagrams of a twelfth exemplary embodiment of a burner 5 that can be used in the first exemplary embodiment of the combustion device 3. The diagrams include a perspective side view of the burner 5, an

enlarged cross sectional view of the downstream portion 5dp of the burner 5, as well as a front face view of the burner 5.

[0089] Figure 43 is a schematic cross-sectional view of the downstream portion 5dp of a thirteenth exemplary embodiment of the burner 5.

DETAILED DESCRIPTION OF THE INVENTION

[0090] A combustion apparatus 1 can include a combustion device 3. The combustion device 3 can include a vessel having a combustion chamber CC. At least one burner 5 can be positioned on, in, or adjacent a wall (e.g. sidewall, floor, ceiling, etc.) of the combustion device 3 that at least partially defines the combustion chamber CC so that the burner can combust at least one fuel and emit a flame 7 into the combustion chamber CC. The burner 5 can be configured to control the flame 7 that is generated so that the flame 7 can have a pre-selected size or profile within the combustion chamber CC and can be formed to be a stable flame therein during combustion operations.

[0091] The combustion apparatus 1 can be configured as an ammonia cracker furnace, a reformer, a steam methane reformer, a melt furnace, a remelt furnace, or another type of combustion apparatus 1. In some embodiments, the combustion device 3 can include one or more tubes 2 that pass through a radiant section of the combustion device 3 for heating a fluid therein. For example, ammonia can be passed through one or more tubes for cracking of the ammonia to facilitate formation of hydrogen. As another example, methane or other type of feed can be passed through the one or more tubes 2 for being reformed into hydrogen. In some embodiments, catalytic material can be included in the one or more tube 2. In other embodiments, the combustion device 3 can be configured as a furnace. The combustion device 3 can combust at least one fuel to generate combustion products. The combustion products can be emitted as a flue gas FG. The flue gas can be output from the combustion chamber CC for being fed to one or more other elements of a plant (e.g., heat exchangers, carbon dioxide capture systems, particulate filtration devices, etc.) and/or be emitted to atmosphere.

[0092] The burner 5 can be configured to operate to form the flame 7 via combustion of a single fuel or a combination of fuels. For example, a flow of a first fuel 1F can be fed to the burner along with at least one flow of an oxidant OX for combustion of the fuel to form the flame 7. In some embodiments, the burner 5 can be configured to receive the oxidant flow OX as well as the first fuel flow 1F and/or the second fuel flow 2F so that the burner 5 can combust only the first fuel of the first fuel flow 1F, only the second fuel of the second fuel flow 2F, or a combination of the first and second fuels via combusting

the first fuel flow 1F and second fuel flow 2F via an ignition mechanism 5i and the oxidant of the oxidant flow OX. The oxidant can be provided via air, can be an oxygen enriched air, or can be another source of gas that includes a sufficient concentration of oxygen for combustion of the fuel(s) to form the flame 7.

[0093] The fuel fed to the burner 5 can be stored in fuel storage vessels. There can be a control manifold that is positioned between the storage vessels and the burner 5 to facilitate the flow of the first and second fuels to the burner in some embodiments.

[0094] The oxidant OX can be fed to the burner 5 via an oxidant feed conduit arrangement. This can include a compressor, blower, fan, and/or other oxidant flow driving mechanism that can be positioned to facilitate the passing of a sufficient amount of the oxidant to the burner 5 to facilitate combustion of the fuel(s) fed to the burner 5.

[0095] Some embodiments of the burner 5 can be configured to enable rapid and thorough mixing of a portion of the oxidant-fuel mixture. This can be enabled, for example, via oxidant entrainment in the fuel jet through an ignition chamber 25 having an ignition cup 70 that can be configured to allow for reducing peak temperatures relative to common characteristics of non-premixed burners. The lower peak temperatures can help to reduce thermal NO_x formation as compared to conventional air-fuel non-premixed combustion. Some embodiments can also utilize a bleed cup 80 downstream of the ignition cup 70 to help enable partial pre-mixing of fuel and oxidant in the ignition chamber 25 that can assist in reducing the peak temperature.

[0096] The burner 5 may be operated in a cold combustion device (e.g. a furnace operating a temperature that is below the autoignition temperature of a fuel, a furnace at a temperature that is less than 205°C, etc.) without the need of oxygen assistance or a continuous ignition source. Embodiments of the burner 5 can be configured to be stably operated in a fuel lean, low flame temperature mode, for example. For instance, the burner 5 can be configured to produce a stable flame (without any lift-off) over a very broad 30:1 turndown range, even with an equivalence ratio as low as 0.25. Such functionality can help enable pre-heating of a combustion device (e.g. a furnace) at a controlled rate to allow the process to initiate and come to a steady-state condition within a pre-selected time-frame that can be defined or selected based on a pre-selected set of process criteria.

[0097] Embodiments of the burner 5 can be configured to start/ignite the burner at low equivalence ratio (fuel lean start-ups), in particular in situations where it is not possible to reduce the oxidant flow rate below a particular set point while start-up fuel flow is simultaneously minimized for safety reasons. The equivalence ratio can be defined as

the ratio of the actual fuel/oxidant molar ratio to the stoichiometric fuel/oxidant molar ratio.

[0098] The burner 5 can be configured to facilitate operating the combustion device 3 over a wide range of the ratio of a first fuel to a second fuel total heating value (i.e. firing rate ratio). For instance, in some situations, the first fuel can be a primary fuel and the second fuel can be a secondary fuel and the ratio of the primary fuel to the secondary fuel total heating value can vary widely for operations utilizing embodiment of the burner. As another example, the first fuel can be natural gas or methane and the second fuel can be a fuel that includes hydrogen and/or ammonia. For example, in an ammonia cracker combustion device configuration, the second fuel can be off gas from a pressure swing adsorption (PSA) system that includes hydrogen, nitrogen, and ammonia therein. In such a configuration, the source of the second fuel can be the PSA system that can be fluidly connected to the burner 5 to feed the second fuel to the burner 5 and the burner can be configured to utilize such a flow of second fuel over a wide range of the ratio of the first fuel to the second fuel total heating value.

[0099] Embodiments of the burner 5 can allow operation flexibility to which fuel can be used for process heating as well. Embodiments of the burner can be configured to produce a stable flame for one fuel operation (e.g. formation of a flame using only the first fuel or only the second fuel, etc.) and multiple fuel operation (e.g. formation of the flame by use of both the first fuel and the second fuel). The burner 5 can be configured so it can be adjustable in operation to use only the first fuel, only the second fuel, or both the first and second fuel for formation of the flame depending on different operational conditions or a pre-defined process control scheme.

[0100] Embodiments of the burner 5 can also be configured so that the oxidizer back pressure may be such that it is not required to have any external secondary compression device for the oxidant streams. Such a configuration can help reduce the capital costs, operating costs and any maintenance involved with burner operations for such embodiments.

[0101] As may best be appreciated from Figures 2 and 42, the burner 5 can be configured to have a central axis. An ignition mechanism 5i can be positioned to extend along its length so a downstream end of the ignition mechanism 5i is positioned in an ignition chamber 25 of the burner. For example, the ignition mechanism can include a spark igniter, a pilot burner, a heating rod, or other type of ignition mechanism. In some embodiments, the ignition mechanism 5i can extend along its length along the central

axis of the burner 5 to have this positioning. In other embodiments, the ignition mechanism can be positioned so its igniting end is positioned in the ignition chamber.

[0102] The burner can also include a plurality of conduits arranged concentrically about its central axis. For instance, the burner can have a first fuel inlet 5ff that is in fluid communication with a first fuel conduit 20 that can be inwardly positioned to be adjacent to the central axis of the burner. An oxidant inlet 5ox of the burner can be positioned in fluid communication with an oxidant conduit 30 that can be positioned around the first fuel conduit 20 such that the first fuel conduit 20 is between the oxidant conduit 30 and the central axis of the burner.

[0103] In some configurations, the burner 5 can also include a second fuel inlet 5sf that is in fluid communication with a second fuel conduit 40. The second fuel conduit 40 can be positioned around the oxidant conduit 30 so that the oxidant conduit 30 is between the first fuel conduit 20 and the second fuel conduit 40. In some configurations, the second fuel conduit 40 can be an outermost conduit of the burner 5.

[0104] The burner 5 can be positionable in a wall or adjacent a wall of the combustion device 3 (e.g. a wall that helps define a combustion chamber CC, etc.). A wall of the combustion device can include a sidewall, a floor, or a ceiling of a combustion device that helps define the combustion chamber CC, for example, and the burner 5 can be positioned in such a wall or adjacent such a wall. In some embodiments, there can be multiple burners for a combustion chamber CC and one or more burners 5 can be positioned in a sidewall while one or more other burners are positionable in a ceiling and/or one or more other burners can be positioned in a floor.

[0105] The burner 5 can have a downstream portion 5dp that is adjacent and/or at the combustion chamber CC. The downstream portion 5dp of the burner 5 can also have a front face 5F that can face into the combustion chamber CC when the burner 5 is installed in the combustion device 3 so that the flame 7 can be formed out of the burner 5 into the combustion chamber CC and/or the flame can be formed in the combustion chamber CC via one or more openings of the front face 5F of the burner 5.

[0106] The downstream portion 5dp of the burner 5 can have different configurations to help facilitate the partial pre-mixing of oxidant with fuel as well as the output of oxidant and fuel to facilitate stable flame generation within the combustion chamber CC. Different configurations can be appreciated from Figures 3-22, 24-37, and 39-43, for example.

[0107] The downstream portion 5pd of the burner 5 can include an ignition end of the ignition mechanism 5i positioned in alignment with a central axis of the burner 5. The

burner can be structured to have an exit plane 5plane that is a plane at which the burner 5 outputs fuel, oxidant and/or a flame 7. The burner plane 5plane can extend in a direction that is perpendicular to the central axis of the burner 5. The central axis of the burner can extend along a length of the burner 5 in some embodiments and help define a center region of the burner 5.

[0108] The first fuel conduit 20 can extend along a length of the burner in a position that is coincident with the central axis and be defined to provide a conduit for a first fuel flow 1F to be passed therethrough toward an ignition chamber 25. An outer wall 20w of a first pipe ("pipe 1") in which the ignition mechanism 5i can be positioned can define an inner side of the first fuel conduit 20. This first pipe can be a receptacle 10 that can retain the ignition mechanism 5i and can be positioned to extend along a central axis of the burner 5 in some embodiments.

[0109] The oxidant conduit 30 can be positioned at an external side of the first fuel conduit 20. An outer wall 30w of a second pipe ("pipe 2") positioned around the first pipe can define an inner side of the oxidant conduit and can also define an outer side of the first fuel conduit 20. An outer wall 40w of a third pipe ("pipe 3") can define an outer side of the oxidant conduit 30 and an inner side of a second fuel conduit 40. A burner external sidewall 5ew can be defined by a fourth pipe ("pipe 4") positioned around the third pipe to define an outer side of the second fuel conduit 40.

[0110] One or more of the conduits can also include a swirler section 33 positioned therein. A swirler section 33 can include one or more swirlers or swirl inducing bodies positioned in the conduit to help facilitate swirling of the flow of fluid passed along the conduit via contact with the one or more swirler bodies. For example, a swirler section 33 can be positioned in a portion of the oxidant conduit and/or a portion of the second fuel conduit 40.

[0111] For example, the oxidant conduit 30 can include a first partition wall 37 having a length LW that is positioned therein at a downstream portion of the oxidant conduit 30 to split the flow of oxidant OX into multiple flows of oxidant. The multiple flows of oxidant can include a first oxidant flow OX1 and a second oxidant flow OX2, for example. In some embodiments, the first partition wall 37 can be short pipe or conduit segment positioned to extend from adjacent the downstream output end of the burner 5 to a position within the burner that extends a pre-selected first partition wall distance inward past the inner end of the ignition chamber 25. The first partition wall 37 can be positioned so that the oxidant flow OX passing through the oxidant conduit 30 is split into a first oxidant flow OX1 and second oxidant flow OX2.

[0112] The first oxidant flow OX1 can be formed for being further split so a portion of this flow is passed through holes 25h in the ignition chamber 25 of the burner 5 for partial pre-mixing with the fuel of the first fuel flow 1F to facilitate combustion of the fuel via the ignition end of the ignition mechanism 5i positioned in the ignition chamber 25 of the burner.

[0113] A first portion of the first oxidant flow OX1 can be passed into the ignition chamber 25 via holes 25h of the combustion chamber that are in fluid communication with the oxidant conduit 30 via oxidant conduit passageways OXC that are in fluid communication with the oxidant conduit 30 and the combustion chamber holes 25h so that the oxidant can be passed from the first oxidant conduit segment 30a and/or oxidant conduit 30 into the ignition chamber 25 via the holes 25h. A second portion of the first oxidant flow OX1 can be passed out of an inner opening of a first oxidant conduit segment 30a of the oxidant conduit 30 at an outlet end of the first oxidant conduit segment 30a, which can be at least partially defined by the first partition wall 37 and a first oxidant distribution plate 73 having oxidant exit holes 32. In some embodiments, the second portion of first oxidant flow OX1 can be passed out of one or more oxidant distribution plates 73 located in the downstream section of the first oxidant segment 30a via a second oxidant distribution plate 73 that can be positioned downstream of the first oxidant distribution plate 73.

[0114] The second oxidant flow OX2 can be passed through a second oxidant conduit segment 30b of the oxidant conduit 30. The first partition wall 37 can be positioned to define an outer wall of the first oxidant conduit segment 30a and an inner wall of the second oxidant conduit segment 30b so that these oxidant conduit segments of the oxidant conduit 30 are defined in a downstream portion of the oxidant conduit 30. The first oxidant conduit segment 30a can be an inner oxidant conduit segment of the oxidant conduit and the second oxidant conduit segment 30b can be an outer oxidant conduit segment of the oxidant conduit 30 in some embodiments.

[0115] In other embodiments, the second oxidant conduit segment 30b can be an intermediate oxidant conduit segment of the oxidant conduit 30 and there can be a third oxidant conduit segment that can be positioned such that the second oxidant conduit segment 30b is between the first and third oxidant conduit segments. In such embodiment, this third oxidant conduit segment can be an inner second fuel conduit 30c that is positioned to receive a portion of the oxidant passed through the oxidant conduit 30 for pre-mixing with a portion of the second fuel passed through this inner second fuel conduit 30c.

[0116] In embodiments where the inner second fuel conduit 30c is configured to prevent mixing with oxidant, this inner second fuel conduit 30c may not be considered an oxidant conduit segment of the oxidant conduit 30. Instead, the inner second fuel conduit 30c can be considered a separate conduit positioned between the second fuel conduit 40 and the second oxidant conduit segment 30b.

[0117] The oxidant conduit 30 may have more than two or three oxidant conduit segments defined in its downstream portion in some embodiments. For instance, in yet other contemplated embodiments, the oxidant conduit can be further segmented to also include a fourth oxidant conduit segment (not shown) in its downstream portion.

[0118] The oxidant conduit 30 can have at least one swirler body therein to have a swirler section 33. A swirler section 33 having one or more swirler bodies can be positioned in each of these oxidant conduit segments or in one or more of these segments (e.g., only in the second oxidant conduit segment 30b or inner second fuel conduit 30c, in a combination of two or more of these conduit segments, etc.) in some embodiments.

[0119] The strength of the swirl imparted to the fluid via a swirler body of the swirler section 33 included in the oxidant conduit or conduit segment can be quantified by the swirl number, which can be defined as the ratio of the axial flux of the angular momentum $G\phi$ to the product of the axial thrust Gx and the exit radius R of an exit hole or burner output plane 5plane. When the swirl number, which equals $G\phi / GxR$, is less than 0.6, the fluid can be considered to be in the weak swirl regime, and when the swirl number is greater than 0.6 the fluid can be considered to be in the strong swirl regime. The swirl number for swirler section(s) 33 can be in the range of 0.1 to 1.5 in some embodiments. This swirl number or strength can be produced by using an axial swirler, radial swirler, and/or tangential swirler.

[0120] The ignition chamber 25 can be positioned in the downstream portion 5dp of the burner adjacent its exit plane 5plane, which can also be considered its output plane. The ignition chamber 25 can be positioned so that there is a gap between the output plane 5plane and the downstream end 26 of the ignition chamber 25. The downstream end 26 can be an output end having an ignition chamber output plane 24 through which the igniting fuel and oxidant are output from the ignition chamber 25 for formation of the flame 7. The ignition chamber 25 can also have an inlet plane CP at which it can receive fuel from the first fuel conduit 20 or at which the first fuel flow 1F can be passed into the ignition chamber 25 via the ignition chamber's upstream end.

[0121] The ignition chamber 25 can also have an upstream end opposite its downstream end 26. The upstream end can be in fluid communication with the first fuel conduit 20 to receive the first fuel flow 1F from the first fuel conduit 20. The first oxidant conduit segment 30a can be in fluid communication with the upstream end and/or an intermediate portion of the ignition chamber 25 for feeding some of the first oxidant flow OX1 into the ignition chamber for partial pre-mixing with the first fuel output from the first fuel conduit within the ignition chamber 25 via the holes 25h of the ignition chamber 25.

[0122] The ignition chamber 25 and the first fuel conduit 20 can be structured such that the output end of the first fuel conduit includes multiple feed passageways 50a and 50b for feeding the first fuel flow 1F into the ignition chamber 25 at different locations about the central axis of the burner 5. This can help facilitate at least partial pre-mixing of the fuel and oxidant in the ignition chamber 25 of the burner, for example.

[0123] For instance, there can be one or more inner passageways 50a for injecting one or more inner jets of fuel into the ignition chamber 25 of the burner 5. There can also be one or more outer passageways 50b for injecting one or more outer jets of fuel into the ignition chamber 25. The one or more outer passageways 50b can be further from the central axis than the one or more inner passageways 50a so that the one or more outer jets of fuel can be further from the central axis of the burner than the inner jets. Also, the one or more outer passageways 50b can extend further downstream into a more downstream portion of the ignition chamber 25 than the inner passageways 50a so that the jets of fuel are emitted into the ignition chamber at different upstream and downstream locations within the ignition chamber 25 of the burner 5.

[0124] For instance, in some configurations the ignition chamber 25 can include an ignition cup 70 that can be a portion of the ignition chamber that is upstream of a bleed cup 80 of the ignition chamber. The ignition cup 70 can have an inlet plate (Plane IC) that is at its upstream end through which it can receive fuel from the first fuel conduit 20. The ignition cup can have holes 70h defined therein for receiving some of the first oxidant flow OX1 for at least partial pre-mixing with fuel output from the inner passageway(s) 50a. The bleed cup 80 can be downstream of the ignition cup 70 and have an inlet plate (Plane BC) through which it can receive fuel and oxidant that have been output from the ignition cup for further mixing with additional oxidant via holes 80h as well as receiving other fuel for mixing with other oxidant. In some embodiments, the bleed cup 80 can have holes 80h defined therein for receiving some of the first oxidant flow OX1 for at least partial pre-mixing with fuel output from the outer passageway(s) 50b as well as the fuel and oxidant passed into the bleed cup via the ignition cup 70.

[0125] In some embodiments, the ignition chamber 25 of the burner can also have one or more mixer plates 74 positioned between the bleed cup 80 and the ignition cup 70 to contact with the fuel and oxidant therein to facilitate mixing of the oxidant with the fuel. One or more mixer plates 74 can also (or alternatively) be positioned in the bleed cup 80 and/or the ignition cup 70 to facilitate mixing of fuel and oxidant.

[0126] In some embodiments, each mixer plate 74 can be mechanical mixer plate that can have a disk type structure that is positioned and configured to break the fuel jet flow that is to be output from the inner feed passageways 50a that can feed fuel from the first fuel conduit 10 into the ignition cup 70 of the combustion chamber 25. For example, a first mechanical mixer plate 74 can have a disk type structure that can have holes 74h that are positioned and oriented out of alignment with the inner feed passageways 50a and/or outer feed passageways 50b so fuel output from those passageways into the ignition cup 70 collide with the mixer plate 74 and are directed back to the chamber of the ignition cup 70 to mix with oxidant fed therein via ignition cup holes 70h for being output out of the ignition cup 70 and into the bleed cup 80 via the holes 74h and the center hole of the mixer plate 74. The at least partially mixed oxidant/fuel jets outputable from the holes 74h of the mixer plate 74 can be passed into the bleed cup 80 downstream of the ignition cup 70. Oxidant passed into the bleed cup via bleed cup holes 80h can further mix with the fuel/oxidant mixture therein before the fuel and oxidant mixture is passed into the combustion chamber CC.

[0127] In some embodiments, a second mixer plate 74 can be positioned downstream of the first mixer plate 74 that adjacent the bleed cup 80. The second mixer plate 74 can also have a disk type structure with holes 74h that are positioned to facilitate breaking up of the fuel flow coming out of a series of outer feed passageways 50b farther away from inner a. The mixer plates 74 can be positioned and configured to break the fuel jets and help with rapid mixing of fuel and oxidant inside the ignition chamber 25 (e.g. being positionable within the ignition cup, bleed cup, and/or being positioned between the bleed cup 80 and the ignition cup 70, etc.). The mixer plate(s) 74 can be configured to have porosity to allow fuel and/or oxidant to flow through the mixer plate 74, which can help cool the mixer plate and help keep the mixer plate at or below a pre-selected temperature.

[0128] The burner 5 can be configured so that the second fuel conduit 40, oxidant conduit 30, and first fuel conduit 20 have different output ends to define different exit planes so that flows of fuel, oxidant, and a mixture of fuel and oxidant can be output from the burner at different downstream and upstream positions for being emitted into the combustion chamber CC of the combustion device 3. The output of oxidant flows can

also be staggered between more upstream and downstream output planes as well via the different oxidant conduit segments of the oxidant conduit 30. We have found that this type of staggered output of oxidant can facilitate stable flame formation within the combustion chamber CC of the combustion device 3.

[0129] For instance, the ignition chamber 25 of the burner 5 can have its output end 26 positioned so that there is a first distance L1 between the output end 26 of the ignition chamber 25 and the output end of the second oxidant conduit segment 30b. The output end of the second oxidant conduit segment 30b can be positioned so it is a second distance L2 upstream of the output plane 5plane of the burner 5.

[0130] The first partition wall 37 can be positioned so that the first oxidant conduit segment 30a is defined to have a pre-selected diameter or width L4 and extends along an upstream portion L02 of the length L0 of the ignition chamber 25 that extends from the ignition chamber's upstream end (e.g. upstream end of the ignition cup 70) to its downstream end (e.g. downstream end of the bleed cup). The length L0 can be pre-selected to provide a desired amount of pre-mixing of a portion of the first oxidant flow OX1 passed through the first oxidant conduit segment 30a that is mixed with the first fuel flow 1F via the ignition chamber's holes 25h. A conduit wall of the first oxidant conduit segment 30a can have one or more oxidant feed holes 34 in fluid communication with the first oxidant conduit segment 30a and the ignition cup 70 and/or bleed cup 80 of the ignition chamber 25 to facilitate the feeding of oxidant into the ignition cup and/or bleed cup 80 for at least partially mixing with the first fuel fed therein via the first fuel conduit 10.

[0131] The first partition wall 37 and the bleed cup 80 can be structured and arranged so that the first oxidant conduit segment 30a narrows in width at a location that is downstream of the upstream end of the first oxidant conduit segment or the upstream end of the ignition chamber 25. For example, a second portion L01 of the length L0 of the ignition chamber can be sized via sizing of the bleed cup 80 or other ignition chamber component so that the downstream portion of the first oxidant conduit segment 30a has a pre-selected diameter or width L5 that extends along a second portion L01 of the length of the ignition chamber 25. The second portion L01 of the length L0 of the ignition chamber 25 can be the length of the bleed cup 80 in some embodiments and the first portion L02 of the length of the ignition chamber 25 can be the length of the ignition cup 70 in some embodiments. The width or diameter L5 of the downstream portion of the first oxidant conduit segment 30a that extends along the second portion L01 of the length L0 of the ignition chamber 25 can be narrower than the width or diameter L4 of the

upstream portion of the first oxidant conduit segment 30a that extends along the first portion L02 of the length L0 of the ignition chamber 25.

[0132] As noted above, this pre-mixing can occur so that an upstream portion of mixing occurs in the upstream end of the ignition chamber 25 and that a second downstream portion of the ignition chamber 25 has additional pre-mixing of oxidant and fuel therein. For example, the length L0 of the ignition chamber 25 of the burner 5 can be segmented via the ignition chamber's structure so that the downstream portion of pre-mixing occurs about a length L01 of the overall length L0 of the ignition chamber. The distance of the length L01 can be less than the overall length L0. A remainder of the length of L0 can be the upstream portion L02 of the length L0 about which the upstream portion of mixing with oxidant can occur. The upstream portion distance L02 of the overall length L0 of the ignition chamber can be less than, greater than, or equal to the distance L01 of the upstream portion.

[0133] The different elements of the downstream portion 5pd of the burner can have other pre-selected dimensions to help facilitate a desired level of pre-mixing of fuel and oxidant as well as flow of fuel and oxidant to facilitate flame formation and flame stability.

[0134] For example, the first fuel conduit 20 can have a diameter or width D3 and can be annular in shape so that the inner first pipe having a diameter or width D2 is inside a central hole of the first fuel conduit 20. The diameter or width D3 can be an inner diameter of the first fuel conduit 20. The overall functional width of the first fuel conduit 20 through which the first fuel flow 1F passes can be a difference between the diameter or width D3 of the first fuel conduit and the diameter or width D2 of the first pipe (e.g. D3-D2), which can be a receptacle 10 for an ignition mechanism 5i in some embodiments.

[0135] The oxidant conduit 30 can have a diameter or width D4 and can be annular in shape so that a central inner region is not part of the conduit through which the oxidant OX passes (e.g. is a space in which the first fuel conduit 20 is positioned). The overall functional width of the oxidant conduit 30 through which the oxidant flow OX passes can be a difference between the diameter or width D4 of the oxidant conduit and the diameter or width D3 of the first fuel conduit 20 (e.g. D4-D3).

[0136] The oxidant conduit 30 can also have an output plane 30plane through which oxidant is output from the oxidant conduit 30 via oxidant conduit segments (e.g. second oxidant conduit segment 30b and/or third oxidant conduit segment (when the inner second fuel conduit 30c is utilized for pre-mixing with a portion of oxidant)). The outlet of the inner first oxidant conduit segment 30a can be more upstream than this oxidant

output plane 30plane to facilitate further mixing with the fuel and oxidant mixture that can be output from the ignition chamber 25 of the burner 5.

[0137] The second fuel conduit 40 can have a diameter or width D5 and can be annular in shape so that a central inner region is not part of the conduit through which the oxidant OX passes (e.g. is a space in which the oxidant conduit 30 is positioned). The overall functional width of the second fuel conduit 40 through which the second fuel flow 2F passes can be a difference between the diameter or width D5 of the second fuel conduit 40 and the diameter or width D4 of the oxidant conduit 30 (e.g. D5-D4).

[0138] The outer diameter or width D2 of the ignition mechanism receptacle 10 can be smaller than an inner diameter D3 of the first fuel conduit 20. The diameter or width D4 of the oxidant conduit 30 can be an inner diameter of the oxidant conduit and the diameter or width D5 of the second fuel conduit 40 can also be an inner diameter of the second fuel conduit 40.

[0139] The ignition chamber 25 of the burner 5 can also have a width or diameter. For example, a downstream portion of the ignition chamber 25 can have a diameter or width D6. The diameter or width of an upstream portion of the ignition chamber 25 can have a diameter or width that is less than or equal to the inner diameter or width D3 of the first fuel conduit 20. For example, the ignition cup 70 of the ignition chamber can have a diameter or width that is less than or equal to the inner diameter or width D3 of the first fuel conduit 20 and the bleed cup 80 portion of the ignition chamber 25 can have a diameter or width D6.

[0140] The second fuel conduit 40 can have one or more holes 40o at its outlet end adjacent (or at) the output plane 5plane of the burner. The holes 40o can be aligned with holes 45h defined in one or more second fuel distribution plates 45 that can be positioned in alignment with an outlet of the second fuel conduit 40. The holes 45h of the one or more second fuel distribution plates 45 can include an outer ring of holes 45h and an inner ring of holes 45h that are a row of spaced apart holes arranged in a ring that are inward relative to a row of outer holes that are spaced apart from each other in a ring orientation such that the outer holes are more outward from the central axis than the inner holes 45h. The distance between inner holes 45h of the second fuel conduit that are on opposite sides of other is a distance D8 and the distance between outer holes 45h of the outer ring of holes is a distance D9. Distance D8 can be measured from an inner most edges of the opposite inner ring holes as shown in Figure 7 for example and distance D9 can be measured from the outer edges of the opposite outer ring holes 45h

as shown in Figure 7, for example. These holes 45h can have a second fuel hole diameter or width D7.

[0141] We have found that the distance D8 can be pre-selected to facilitate flame stability over a wide range of fuel compositions (e.g., a wide range of hydrogen concentrations within the second fuel of the second fuel flow 2F). The pre-selection of a pre-determined distance D8 can help provide flexibility to supply total thermal input from the burner 5 divided in different ratios between the first and second fuels used in the first fuel conduit 20 and second fuel conduit 40.

[0142] We have also found that the pre-selection of the distance D9 can be utilized for the second fuel exit holes 45h for an outermost ring of such holes to facilitate lower NO_x emissions. We have found that if the distance D9 is too large, it can increase the size of the burner 5 and lead to incomplete fuel combustion in a cold furnace or other type of cold combustion device 3 (e.g. where conditions in the combustion chamber CC are below the autoignition temperature of the fuel(s)).

[0143] The second fuel exit holes 45h can be located on several different rows that define spaced apart rings of holes 45h around the central axis of the burner 5 helps to provide distributed combustion in the combustion chamber CC, which can help lower the NO_x emissions from fuels that have tendency to form higher NO_x (e.g. hydrogen and/or ammonia).

[0144] The fuel output from the first fuel conduit 20 can be output via first fuel exit holes 23 that can have a diameter D0. These holes 23 can be circular in shape or can have any other shape such as stars, triangles, double-stars, rectangles, etc. These first fuel exit holes 23 can be in fluid communication with inner and/or outer passageways 50a and 50b, for example for receipt of the fuel mixed with oxidant from the ignition chamber 25 for outputting the mixed fuel and oxidant via these first fuel exit holes 23. The first fuel exit holes 23 can include an outer ring of holes 23B and an inner ring of holes 23A that are a row of spaced apart holes arranged in a ring that are inward relative to a row of outer holes 23 that are spaced apart from each other in a ring orientation such that the outer holes 23 are more outward from the central axis than the inner holes 23. The inner holes 23A can be in fluid communication with the inner passageways 50a and be aligned with the outlets of these passageways and the outer holes 23B can be aligned with the outer passageways 50b and in fluid communication with the outlets of the outer passageways 50b in some embodiments.

[0145] The first fuel exit holes 23 can be defined in one or more first fuel distribution plates, which can each be an annular shaped plate having first fuel exit holes 23. For

example, a first fuel distribution plate 72 can be positioned to align with the inner passageways 50a and the jets of fuel from pathways 50a are at least partially premixed with oxidant that are passed through the ignition cup 70 of the ignition chamber 25 so that the inner exit holes 23A of that plate are generally aligned with the inner passageways 50a for providing inner flows of fuel at least partially premixed with oxidant. The first fuel distribution plate 72 can be positioned at an upstream end of the ignition cup 70 of the ignition chamber 25 in some embodiments.

[0146] A second first fuel distribution plate 72 or an outer portion of the first fuel distribution plate 72 can be positioned to align the first fuel exit holes 23 of that plate with the outer passageways 50b. The flow of first fuel can be output from the outer holes 23B defined in that second first fuel distribution plate 72 such that the first fuel in these flows can be mixed at least partially with oxidant to be output from the ignition chamber 25 (e.g. bleed cup 80). In some embodiments, the second first fuel distribution plate 72 can be positioned downstream of the first first fuel distribution plate 72 adjacent the outlet of the bleed cup 80, for example. Each fuel distribution plate 72 can be positioned so that the fuel and/or oxidant mixed with the first fuel (or just oxidant if oxidant is passed through the burner without the first fuel) can be passed out into the combustion chamber CC of a combustion device 3.

[0147] As noted above, there can be rows of spaced apart first fuel exit holes 23 that can be defined via one or more first fuel distribution plates 72 so that there can be an inner ring of spaced apart first fuel exit holes 23 that is closest to the central axis of the burner 5 and an outer ring of spaced apart first fuel exit holes 23 that is farthest from the central axis of the burner 5. In some embodiments, there can also be at least one intermediate row of spaced apart first fuel exit holes 23 in an intermediate ring that is positioned between the innermost ring and outermost ring in some embodiments.

[0148] For example, each first fuel distribution plate 72 can define a respective inner or outer ring of first fuel exit holes in some embodiments. In other embodiments, a single annular plate can be used or can be utilized to define holes for inner and outer rings of first fuel exist holes (e.g., so at least two such rows are defined in a single first fuel distribution plate 72). In some embodiments, a first fuel distribution plate 72 can have a porosity (defined by the total open area on the plate that allows the fuel to flow divided by cross-section area of the plate) in the range of 4% to 25% or other suitable range.

[0149] The oxidant conduit 30 can output oxidant of the first and second oxidant flows OX 1 and OX2 (and/or third oxidant flow OX3 when present) via oxidant exit holes 32 that are in fluid communication with the oxidant conduit 30 and aligned with the outlet

30bo of the second oxidant conduit segment. The oxidant exit holes 32 can have a diameter D1 in some embodiments.

[0150] The oxidant exit holes 32 can be arranged in concentric ring-like patterns or ring patterns. The oxidant exit holes 32 can be defined in one or more oxidant distribution plates 73 positioned over the outlet of the oxidant conduit 30 or positioned over the different first and second oxidant conduit segments 30a and 30b of the oxidant conduit 30. For example, an inner ring of oxidant exit holes 32 can be in fluid communication with the first oxidant conduit segment 30a for outputting a portion of oxidant of the first oxidant flow OX1 output from the first oxidant conduit segment 30a. The outer ring of oxidant exit holes 32 can also be in fluid communication with the first oxidant conduit segment 30a for outputting jets of a portion of oxidant output from the first oxidant conduit segment 30a. The outer ring of oxidant exit holes 32 can be arranged to be further from the central axis of the burner than the inner ring of oxidant exit holes 32. In some embodiments, the inner ring of oxidant exit holes 32 can be defined in a first annular oxidant distribution plate 73 positioned in alignment with the first oxidant conduit segment 30a and the second set of oxidant holes of the outer ring of oxidant exit holes can be defined in a second annular oxidant distribution plate 73 that is also positioned in alignment with the first oxidant conduit segment 30a and is more outwardly positioned relative to the burner center axis as compared to the first annular oxidant distribution plate 73. In other embodiments, a single annular oxidant distribution plate 73 can define the outer ring and inner ring of oxidant exit holes 32.

[0151] In some embodiments (e.g. the embodiment shown in Figure 41), the second first fuel distribution 72 can be integral with the second annular oxidant distribution plate 73. Such a configuration is indicated via broken line in Figure 41, for example. The second first fuel distribution plate 72 can be positioned more inward relative to the second annular oxidant distribution plate 73 in such an embodiment. The second annular oxidant distribution plate can be positioned adjacent the outlet of the bleed cup 80 and be positioned between the bleed cup 80 and an outer outlet of the first oxidant conduit segment 30a. The second first fuel annular conduit 72 can be positioned adjacent the outlet of the bleed cup 80.

[0152] In some embodiments, the oxidant distribution plate(s) 73 can have a porosity (defined by the total open area on the plate that allows the air to flow divided by cross-section area of the plate) in the range of 1% to 8% or other suitable range.

[0153] In some embodiments, the oxidant exit holes 32 can be arranged in a circular way on different concentric diameters as 1-7 series of spaced apart rings or circles of

oxidant exit holes 32. In some embodiments, there can be 1-3 concentric diameters of oxidant exit holes 32 in separate rows or rings of spaced apart oxidant exit holes 32, for example. Each ring can be spaced apart so there is an innermost ring and an outermost ring of oxidant exit holes as well as one or more other intermediate rings of oxidant exit holes 32 positioned between the innermost ring and outermost ring of such oxidant exit holes 32. The innermost ring of spaced apart oxidant exit holes 32 can be closest to the central axis of the burner 5 and the outermost ring of spaced apart oxidant exit holes 32 can be farthest from the central axis of the burner 5. The oxidant exit holes 32 can be of circular shape or can be any other shape such as stars, triangle, double-stars, rectangle, etc.

[0154] The outlet 30bo of the second oxidant conduit segment 30b can be an annular shaped opening that is positioned to output oxidant into the combustion chamber CC. The second oxidant conduit segment 30b can have its outlet 30bo positioned to provide an exit plane for oxidant passed out of the second oxidant conduit segment 30b via that second oxidant conduit segment outlet 30bo so that the oxidant flow output from the second oxidant conduit segment is ring-like in shape, for example.

[0155] The ignition chamber holes 25h can have a diameter P1 and also be arranged in multiple different spaced apart rows of oxidant pre-mixing feed holes 25h. In some embodiments, the total number of rows of concentrically aligned and spaced apart ignition chamber holes 25h can be a in the range of 1 row to 5 rows.

[0156] The angle between two immediately adjacent ignition chamber holes 25h measured at the center axis of the burner 5 can be an angle alpha (e.g., as shown in Figure 12). The diameter of downstream portion rows of such holes can be a pre-selected diameter P1 and the space between spaced apart rows of ignition chamber holes (wherein each row is in a ring shape or ring-like shape) can be a distance H (e.g. there is a pre-selected distance H between an immediately adjacent upstream row and an immediately adjacent row downstream of that row). In some embodiments, the ignition chamber holes 25h for these downstream portions of rows of holes 25h can be holes 80h of the bleed cup 80 of the ignition chamber 25.

[0157] A portion of the oxidant OX can be introduced into the ignition cup 70 of the ignition chamber and another portion of the oxidant can be introduced into the bleed cup 80 of the ignition chamber 25. The portion of the oxidant fed to the ignition cup 70 can be fed to vigorously mix with a portion of the fuel output from the first fuel conduit 20 (e.g. inner passageways 50a) and the amount of this oxidant can be such that a mixture composition of fuel and oxidant in the ignition cup 70 can be within the flammability limits

for the first fuel to allow ignition of the flame over a broad range of flow rates of the first fuel and oxidant.

[0158] The second portion of the oxidant of the first oxidant flow OX1 that enters the bleed cup 80 can mix with the fuel such that peak flame temperatures can be reduced as compared with typical diffusion flames, which can help minimize flame-generated NOx emissions. The oxidant feeding into the bleed cup 80 can also be provided to help keep the peripheral wall of the ignition chamber 25 cooled by protecting it from direct contact with the flame.

[0159] The fuel can be introduced through a series of holes (e.g. inner passageways 50a and outer passageways 50b) located at two different planes that can be recessed by a distance that is equal to $L_0+L_1+L_2$ or a distance that is equal to $L_{01}+L_1+L_2$ from hot face 5F of the burner 5 (e.g. from the burner output plane 5plane).

[0160] In some embodiments, the first portion of fuel in the ignition cup 70 can facilitate ignition while the second portion of fuel can be fed to the bleed cup via passageways 50b to help provide a sufficient length for fuel jets to fully or partially develop and partially-premix with the oxidant, which can help to stabilize the flame 7 over a broad range of equivalence ratio operation (e.g. an equivalence ratio of between 0.25 and 1.1 or between 0.25 and 1.0, etc.).

[0161] For example, the first distribution plate 72 can be recessed by a distance that is equal to $L_2+L_1+L_0$ from the exit plane 5plane of the burner 5 and the second distribution plate can be recessed a distance that is $L_2+L_1+L_{01}$ from the exit plane 5plane of the burner 5. For instance, a first fuel distribution plate 72 can be recessed from the exit plane 5plane by a distance of $L_2+L_1+L_{01}$ inwardly from the exit plane (e.g. in an axial direction inwardly away from the combustion chamber CC measured along the central axis of the burner 5 from the exit plane 5plane to that fuel distribution plate). A second fuel distribution plate 72 can be positioned to be staggered and even more recessed by a distance of $L_2+L_1+L_0$ from the exit plane 5 plane of the burner 5 (e.g. in an axial direction inwardly away from the combustion chamber CC the second fuel distribution plate 72 can be a distance of $L_2+L_1+L_{01}$ measured along the central axis of the burner 5 from the exit plane 5plane of the burner 5 to that fuel distribution plate).

[0162] A portion of oxidant can be introduced into the ignition cup 70 and oxidant bleed cup 80 via the peripheral wall of these cups of the ignition chamber 25, which can be oriented at right angles to the fuel exit plane 5plane (e.g. be oriented to extend perpendicular to the fuel exit holes 23). The portion of oxidant fed into the ignition cup can be a pre-selected portion of the oxidant (e.g. 20% of the total oxidant flow, between

5% and 20% of the oxidant flow, etc.). The first portion of the oxidant that enters the ignition cup 70 can vigorously mix with a portion of the fuel and function as "ignition" oxidant such that the mixture composition in the ignition cup 70 can allow for ignition of the first fuel to ignite the flame over a broad range of flow rates of the first fuel and oxidant.

[0163] The second portion of the oxidant that enters the bleed cup 80 can mix with the first fuel such that peak flame temperatures can be reduced compared with typical diffusion flames. This can help facilitate minimization of flame-generated NO_x emissions. Moreover, this type of oxidant introduction can also function to keep the peripheral wall(s) of the ignition chamber 25 cooled by protecting it from direct contact with the flame that is generated.

[0164] A first portion of first fuel in the ignition cup 70 can mix with the ignition oxidant. The mechanical mixture plate can be positioned to break the fuel jets in this first section to help the first fuel mix with the ignition oxidant in the ignition cup 70 and be output from holes 74h of a mixer plate 74 that can be positioned between the ignition cup 70 and the bleed cup 80. For instance, the mixer plate 74 can be located a recessed distance of $L_{01}+L_1+L_2$ from the exit plane 5plane of the burner 5. The second portion of the first fuel can pass through jets for passing out of a fuel distribution plate that is recessed by a distance of $L_1+L_2+L_{01}$ from the burner exit plane 5plane in order to give sufficient length for the fuel jets to fully or partially develop and partially-premix with the oxidant fed to the oxidant bleed cup 80. This can help to stabilize the flame over a broad range of equivalence ratios.

[0165] The angle alpha can be pre-selected to help to separate the ignition chamber holes 25h for the ignition chamber 25 of the burner 5 such that they are not too close to result in stream of oxidant with limited mixing with oxidant with the fuel while also preventing the holes from being too far apart to help provide enough coupling between adjacent jets to provide a desirable level of mixing of fuel-oxidant inside the ignition chamber 25. Each row of ignition chamber holes 25h may be symmetrically staggered to provide three dimensional mixing effects, which can be selected to help provide a reliable ignition of the burner 5 at lean equivalence ratio of as small as 0.25 in some embodiments.

[0166] The oxidant exit holes 32, second fuel exit hole 45h, and first fuel exit holes 23, can be arranged in ring or ring-like rows that are spaced apart from each other to define different pre-selected angles to help facilitate a pre-selected type of mixing for formation of a flame 7 within the ignition chamber.

[0167] For example, a circumferential angle defined by the main central axis of the burner and the centers of two immediately adjacent second fuel exit holes (45h) can be defined as angle gamma as shown in Figure 13. A circumferential angle defined by the central axis of the burner and the centers of two adjacent oxidant exit holes 32 can be defined as angle beta as shown in Figure 13. A circumferential angle defined by the central axis of the burner and the centers of two adjacent first fuel exit holes 23 can be defined as angle theta as shown in Figure 14.

[0168] The angle theta can be pre-selected to define holes to facilitate separation of the holes so they are not too close that they may result in fuel rich regions and prevent from oxidant-fuel mixing while also helping to prevent the holes from being too far apart to help provide sufficient coupling between immediately adjacent jets to provide coupling effect of heat release from each jet for stable combustion.

[0169] The angle beta can be pre-selected to help provide separation of the holes such that they are not too close to create oxidant rich regions while also preventing the holes from being too far apart to help provide sufficient coupling between immediately adjacent jets to provide enough oxidant for fuel-oxidant mixing and help facilitate formation of low velocity regions and recirculation zones to provide a flame anchoring zone for the flame 7.

[0170] The angle gamma can be pre-selected to be the same or to vary for holes located on each series of a concentric hole pattern. The total number of holes on each series of concentric hole pattern can be determined based on how the fuel amount is distributed to help reduce the NO_x formation across the different series of concentric holes.

[0171] In some embodiments, the first fuel conduit 20 can have holes 27 arranged in at least one row of spaced apart holes in a ring-like or ring alignment. Holes 27 can be in fluid communication with the oxidant conduit 30 so that oxidant from the oxidant conduit 30 can be passed into the first fuel conduit 20 upstream of the first oxidant conduit segment 30a and/or the upstream end of the partition plate 37 to facilitate additional pre-mixing of oxidant and fuel. These holes 27 (e.g., numbers of holes 27, their diameter, and the number of rows of holes) may be predetermined based on the area ratio of the holes 27 and oxidant exit area, as well as the pressures of the oxidant and first fuel flows. The pre-calculated ratio can also be dependent on the amount of oxygen within the oxidant or the amount of oxidant needed during startup for initiation of combustion and formation of a suitable flame 7.

[0172] In some operational states, the holes 27 can also facilitate some of the first fuel passing into the oxidant conduit 30 for mixing therein so that some fuel can be included in the oxidant passing through the oxidant conduit 30 and mixed therein.

[0173] Holes 27 of the first fuel conduit 20 can be arranged in one or more rows around the first fuel conduit 20. In some embodiments, there will no more than 5 rows of such holes 27 or no more than 3 rows of such holes. These holes 27 can be circular in shape or can have any other shape such as stars, triangles, double-stars, rectangles, etc.

[0174] The areas of different holes can also be sized in relation to each other. For example, the cross-sectional areas of ignition chamber holes 25h, oxidant exit holes 32, and the oxidant outlet for the oxidant conduit can be designated as area A0 (for the area of the ignition chamber holes 25), area A1 (for the area of the oxidant exit holes 32) and area A2 (for the oxidant outlet area of the oxidant conduit 30 that is aligned with the oxidant exit holes 32). In some embodiments, area A0 can be a pre-selected area value that is 5% to 25% of the sum of $A0+A1+A2$ (e.g. $A0 = 0.05*(A0+A1+A2)$ to $A0 = 0.25*(A0+A1+A2)$ in some embodiments).

[0175] Additionally, there can be other pre-selected dimensions specific to or related to use of an inner second fuel conduit 30c, examples of which can be appreciated from Figures 32-38 and 39-40, for instance. For example, the second fuel conduit 40 can include internal second fuel injection holes 40c having a pre-selected diameter P2 that are positioned to facilitate a diversion of a portion of fuel from the second fuel flow 2F to the inner second fuel conduit 30c for being passed through that conduit for being output at a location more inward relative to the center axis of the burner relative to the outlet of the second fuel output from the second fuel conduit 40.

[0176] In some embodiments, the inner second fuel conduit 30c can be in fluid communication with the oxidant conduit 30 so that a third flow of the oxidant OX3 that can be split from the second oxidant flow OX2 downstream of where this flow is split from the first oxidant flow OX1 can be fed into the inner second fuel conduit 30c for partial pre-mixing with this diverted portion of the second fuel. In other embodiments, the downstream end of the inner second fuel conduit 30c can be enclosed so that no mixing of oxidant with the fuel passing through this inner second fuel conduit 30c may occur (e.g. the third flow of the oxidant OX3 is not formed).

[0177] For instance, in some embodiments, the oxidant conduit 30 can include a second partition wall 37a that is positioned so its downstream end is upstream of the downstream end of the first partition wall 37 and extends to an outlet of the oxidant conduit 30 to define an inner wall of the inner second fuel conduit 30c and an outer wall

of the second oxidant conduit segment 30b. The outer wall of the inner second fuel conduit can be defined by the inner wall 40w of the second fuel conduit 40. In some embodiments, the second partition wall 37a can be a pipe or duct positioned within the oxygen conduit 30 and spaced apart from the first partition wall 37. An inlet into the inner second fuel conduit 30c can also be defined by a porous purge plate X1 connected to the second partition wall 37a and the second fuel conduit 40 to be positioned at an inlet end of the inner second fuel conduit 30c.

[0178] Alternatively, the plate X1 located at the upstream end of the inner second fuel conduit 30c can be connected to the second partition wall 37a and the inner side of the second fuel conduit 40 to enclose the inner second fuel conduit 30c and be non-porous such that the purge plate X1 can prevent oxidant from being fed into the inner second fuel conduit for pre-mixing with the second fuel passed into the inner second fuel conduit 30c via the internal second fuel injection holes 40c.

[0179] The first and second oxidant conduit segments 30a and 30b, and the inner second fuel conduit 30c can each have a respective diameter or width. For example, inner second fuel conduit 30c can have an outer width or diameter D12 that is larger than the width or diameter of the second oxidant conduit segment 30b and is also larger than the inner diameter D10 of the flame stabilization plate FSP.

[0180] The second partition wall 37a can have a length L7 to define a length of the inner second fuel conduit 30c. One or more second fuel injection holes 40c can be positioned in fluid communication between the second fuel conduit 40 and the inner second fuel conduit 30c so that second fuel can be fed therein. The one or more second fuel injection holes 40c can be located upstream of an outlet of the burner, or the burner outlet plane 5plane by a distance L8, which can be less than the length L7.

[0181] A flame stabilization plate FSP can be positioned adjacent to the outlet of the inner second fuel conduit 30c and the outlet 30bo of the second oxidant conduit segment 30b. The flame stabilization plate FSP can be positioned so that it is a recessed distance L6 from the output plane 5plane of the burner 5 (e.g. a distance axially inward from the combustion chamber CC that is measured linearly parallel to the central axis of the burner from the output plane 5plane to the flame stabilization plate FSP). The distance L6 can be less than the distance L8 and length L7 and can define an offset between an outlet of the inner second fuel conduit 30c and the outlet of second fuel exit holes 45 aligned with the holes 40o of the second fuel conduit 40.

[0182] For example, the flame stabilization plate FSP can be located at the exit of the inner second fuel conduit 30c and outlet 30bo of the second oxidant conduit segment

30b and can help define an exit through which the fuel is output from the inner second fuel conduit 30c for being passed into the combustion chamber CC and oxidant is output from the second oxidant conduit segment 30b for facilitating formation of a flame. The flame stabilization plate FSP can be an annular shaped plate (e.g. a ring-shaped plate, etc.) that has an inner diameter D10 and an outer diameter D11. Figure 34 illustrates an example of this diameter D11. In some embodiments, at least one swirler can be located before the exit of the inner second fuel conduit 30c (e.g. upstream of the exit of the inner second fuel conduit 30c) as well.

[0183] In some configurations, the flame stabilization plate FSP can have a porosity (defined by the total open area on the plate that allows the oxidant and diverted second fuel or the diverted second fuel to flow divided by the cross-sectional area of the plate) in the range of 1% to 20%. The porosity is distributed equally on the oxidizer side and the fuel side (secondary fuel or mixture of secondary/oxidizer mixture) of the flame stabilization plate. This flame stabilization plate FSP can be positioned and configured to create a low velocity region for the oxidant and fuel to mix to help create a stable flame. The porosity of the flame stabilization plate can be selected to help to keep the plate relatively cooler and also provide a fraction of oxidant and fuel in that low velocity region of the plate.

[0184] The flame stabilization plate FSP can have exit holes 38 that are aligned with the outlet end(s) of the inner second fuel conduit 30c for the outputting of the second fuel from the inner second fuel conduit 30c (or mixture of second fuel and oxidant in situations where the third oxidant flow OX3 is to be formed for feeding into the inner second fuel conduit 30c). The exit holes 38 of the flame stabilization plate FSP can have a diameter P3. Diameter P3 can have the same diameter as the oxidant holes 32.

[0185] The exit holes 38 of the flame stabilization plate FSP can include an inner ring of spaced apart exit holes 38o that can be positioned so that oxidant from the second oxidant conduit segment 30b is passable out of the exit holes 38 such that these exit holes function as oxidant exit holes 32. The exit holes 38 of the flame stabilization plate FSP can also include an outer arrangement of holes, or an outer ring of exit holes, that function as inner second fuel conduit exit holes 38f through which fuel output from the inner second fuel conduit 30c can pass. In embodiments where oxidant is also passed into the inner second fuel conduit 30c for at least partial pre-mixing with the second fuel within this conduit, the oxidant and second fuel output from the inner second fuel conduit 30c can pass out of these inner second fuel conduit exit holes 38f of the flame stabilization plate FSP.

[0186] The flame stabilization plate FSP can be recessed by a distance L_6 from the burner outlet plane 5plane as noted above. The distance L_6 can be selected to facilitate a secondary fuel flame anchoring to relatively be unaffected by the atmosphere within the combustion chamber CC.

[0187] The flame stabilization plate FSP (as well as the optional swirler that can be positioned in inner second fuel conduit 30c) can help generate a secondary fuel flame root in the region of the flame stabilization plate FSP. Embodiments of the burner 5 can also utilize another mechanism of flame stabilization at the exit of the inner second fuel conduit in combination with such feature(s) or as a substitute for such feature(s) as well.

[0188] In some embodiments, the second fuel injection holes 40c can be arranged in rows around the oxidant conduit 30 wherein each row is a set of spaced apart second fuel injection holes aligned in a concentric circle or concentric ring around the inner second fuel conduit 30c. The total number of rows of such concentric circles or rings of second fuel injection holes 40c can be in the range of 1-5 for some embodiments. The cross-sectional shape of the second fuel injection holes 40c can be circular shape or any other shape such as stars, triangle, double-stars, rectangle, etc. In some embodiments, there may be no more than 5 rows of second fuel injection holes 40c or no more than 3 rows of second fuel injection holes 40c.

[0189] As may best be seen from Figure 33, the innermost ring of second fuel exit holes 45h can be a row that is a ring of spaced apart angled holes 40h. These angled holes can extend from the outlet of the second fuel conduit towards the central axis at the outlet plane 5plane of the burner 5 at a pre-selected angle ω . This innermost ring of angled holes 40h can be spaced apart from each other so that the ring of spaced apart angled holes 40h has a diameter measured from the innermost edges of the holes 40h on opposite sides of the ring defined by the annular row of spaced apart angled holes 40h.

[0190] As may best be seen from Figures 25-26 and 39-40, embodiments of the burner 5 can be configured to facilitate flame development so the flame has flame stability as it is formed in the combustion chamber CC. For example, Figure 25 illustrates an example of flame stability that can be facilitated during a first mode of operation in which fuel from the first and second fuel conduits 20 and 40 can be fed to the burner. Initial flame development can be facilitated via the flows of the oxidant and fuels output from the different burner elements to provide fluid mixing that define a first stabilization surface 1A, a second stabilization surface 1B and a third stabilization surface 2 within a flame development region of the burner. These flame stabilization zones can be facilitated by

the features of the burner 5 to provide an anchoring point for flame development and stability that can permit a flame 7 to be sustained over a broad range of operating conditions. In some embodiments, the burner can be configured so that the formed and stabilized flame is established so that the flame is pre-defined to be relatively short while also being stable.

[0191] As may be appreciated from Figure 26, which illustrates an example of flame stabilization that can be facilitated during a second mode of operation in which a low rate of fuel from the first fuel conduit 20 can be fed to the burner such that the overall fuel rate of fuel fed to the burner is lower than in the first mode shown in Figure 25. In the example of Figure 26, at low firing rate under turndown conditions and low equivalence ratio, the flame can be anchored at an oxidant distribution plate 73 location without any blow-off via the recirculation zone setup in the area that can be created by staggered design of the oxidant distribution plate 73 and the burner's configuration permitting the use of multiple flame anchoring locations. This example of Figure 26 helps illustrate one example of how the presence of multiple flame anchoring locations can assist in maintaining a stable flame over a wide range of burner operating conditions.

[0192] This type of stable flame development and formation can also be provided via embodiments that utilize first and second oxidant conduit segments 30a and 30b as well as the inner second fuel conduit 30c (which may or may not include oxidant passed therein with some of the second fuel as discussed above). For example, Figure 39 illustrates an example of flame stabilization that can be facilitated during a first mode of operation in which fuel from the first and second fuel conduits 20 and 40 can be fed to the burner. Flame stabilization can be facilitated via the flows of the oxidant and fuels output from the different burner elements to provide fluid mixing that facilitate flame stabilization at multiple locations that can include a first stabilization surface 1A, a second stabilization surface 1B and a third stabilization surface 2. In addition, an additional flame front can be developed via the stabilized flame that can be from the region of the flame stabilization plate FSP, or flame stabilization plate region. In some embodiments, the burner 5 can be configured to facilitate formation of these flame front surfaces to provide at least one anchoring point for flame stabilization that can permit a flame 7 to be established that is stable.

[0193] As may be appreciated from Figure 40, which illustrates an example of flame stability that can be facilitated during a second mode of operation in which a flow rate of fuel only from the second fuel conduit 40 can be fed to the burner 5 (e.g. only the second fuel is fed to the burner 5 for formation of the flame within the combustion chamber CC and the flow rate of the first fuel is 0). In the example of Figure 40, flame stabilization

surface/zone 3 is developed via the burner 5 so that burner operation with a stable flame can be provided. The burner 5 configuration to help facilitate such a stable flame can include, for example, a ratio of the velocity of oxidant at the exit 30bo of the second oxidant conduit segment 30b and the fluid at the exit of the inner second fuel conduit 30c, as well as dimensional features of the flame stabilization plate FSP. These parameters can be helpful in developing the flame stabilization surface 3 in recirculation zones setup at the exit of the flame stabilization plate FSP, for example.

[0194] Figure 40 also illustrates in solid and dashed lines how the angled holes 40h of the innermost ring of second fuel exit holes 45h can facilitate improved stable flame formation and flame development. The angled holes 40h angled at angle omega have been found to help contribute to a much more stable flame that can provide improved radially out (e.g. a radial direction that extends perpendicular to the central axis of the burner) flame growth that can be established via the improved mixing of the fuel provided via the angled injection of the second fuel and the oxidant flow from the oxidant output from the burner. The directed fuel provided via the angled holes 40h can provide additional fuel to spatially sustain the second fuel flame that originates adjacent to the exit of the inner second fuel conduit 30c adjacent to the flame stability plate FSP. The energy release from the flame stability plate zone of combustion and combustion of fuel supplied from the angled holes 40h can provide heated combustion products and oxidant that can assist to initiate and consume or combust the second fuel from the non-angled outer row(s) of fuel exit holes 40o.

[0195] We have found that various combinations of pre-selected dimensions of many of the foregoing parameters (e.g., diameters, angles, lengths, etc.) can help provide improved flame formation, improved flame stability, and reduced NOx emissions. Below are a number of these parameters that can be utilized in different embodiments either alone or in any combination (e.g., all of these parameters can be used in combination, a subset of two or more of these parameters can be utilized in combination, only one of these parameters may be utilized, etc.). These parameters include:

- a. angle omega of between 2° and 80° (e.g., between 10° and 60° or between 20° and 55°);
- b. A ratio of D_{12}/D_4 of between 0.75 and 0.95
- c. A ratio of L_6/D_4 that is between 0.04 and 0.5 (e.g., between 0.05 and 0.3);
- d. A ratio of D_{10}/D_4 of between 0.70 and 0.85;
- e. A ratio of D_{11}/D_4 that is between 0.90 and 0.99;

- f. A ratio of $L7/D4$ of between 0.25 and 2.0 (e.g., between 0.3 and 1.0);
- g. A porosity of purge plate X1 of between 1% and 25%;
- h. A ratio of $P2/D2$ of between 0.06 and 0.5;
- i. A ratio of $L8/D4$ of between 0.1 and 2.0;
- j. A velocity of the second fuel flow 2F at the exit of the second fuel conduit 40 that is between 3.0 m/s and 91 m/s (e.g. between 6 m/s and 62 m/s);
- k. a ratio of the total number of the angled second fuel holes 40h that are angled at angle ω inwards towards the center axis of the burner to the total number of the second fuel exit holes 45h can be used in the burner can be between 0.1 and 0.5, or between .15 and .30 (e.g. $[\text{total number of angled holes } 40h]/[\text{total number of second fuel exit holes } 45h] = 0.01 \text{ to } 1.0, \text{ etc.}];$
- l. The fraction of the second fuel that is passed through the second fuel conduit that is diverted to the inner second fuel conduit segment 30c can be between 1% to 25% of the overall flow of the second fuel flow 2F (e.g. between 4% and 12% of the overall second fuel flow 2F is passed into the inner second fuel conduit segment 30c via internal second fuel injection holes 40c, etc.);
- m. The swirl angle of swirler(s) that can be utilized in one or more of the conduits or oxidant conduit segments can be between 5° and 70° (e.g., between 30° and 45° , between 5° and 60° , etc.);
- n. An angle θ of between 10° and 50° ;
- o. An angle β of between 10° and 40° ;
- p. An angle γ of between 10° and 90° ;
- q. An angle α of between 10° and 20° ;
- r. A ratio of $H/P1$ of between 1.25 and 2.5; and
- s. A porosity of the flame stabilization plate FSP adjacent the second oxidant conduit segment 30b and optional inner second fuel conduit 30c of between 1% and 20%;

[0196] Also, embodiments can also (or alternatively) use at least one of the following parameters (e.g., use only one of these parameters, use a combination of two or more or all of these parameters, use one or more of these parameters in combination with the parameters noted above, etc.):

- i. A value of P1 of between 0.12 cm and 0.51 cm;

- ii. A ratio of $P1/D2$ of between 0.06 and 0.6 (e.g., between 0.1 and 0.55 or between 0.06 and 0.5, etc.);
- iii. A value of $D7$ of between 0.12 cm and 0.762 cm;
- iv. A ratio of $D7/D2$ of between 0.05 and 0.6
- v. A value of $D0$ of between 0.12 cm and 0.64 cm;
- vi. A ratio of $D0/D2$ of between 0.05 and 0.6 (without intending to be bound by any particular theory, such sizing has been found to help significantly contribute to the ability to quickly mix first fuel with surrounding oxidant and/or combustion chamber gases);
- vi.. A value of $D1$ of between 0.12 cm and 0.381 cm;
- vii. A ratio of $D1/D2$ of between 0.06 and 0.15;
- viii. A ratio of $D3/D2$ of between 1.5 and 5 (e.g., between 1.9 and 3.5);
- ix. A ratio of $D4/D2$ of between 2 and 12 (e.g., between 3.5 and 10);
- x. A ratio of $D5/D2$ of between 5 and 25 (e.g., between 8 and 18);
- xi. A ratio of $D6/D2$ of between 1.5 and 6 (e.g., between 2.0 and 4.5);
- xii. A ratio of $D8/D4$ of between 1.1 and 1.4;
- xiii. A ratio of $D9/D4$ of between 1.6 and 2.5;
- xiv. A ratio of $L0/D3$ of between 0.2 and 2 (e.g., between 0.4 and 1.0);
- xv. A ratio of $(L1+L2)/D3$ of between 0.2 and 2 (e.g., between 0.4 and 0.7);
- xvi. A ratio of $L01/D3$ of between 0.1 and 1 (e.g., between 0.3 and 0.8);
- xvii. A ratio of $L4/L1$ of between 0.5 and 1.5 (e.g., between 0.7 and 1.1);
- xviii. A ratio of $L4/D3$ of between 0.05 and 1 (e.g., between 0.2 and 0.6);
- xix. A ratio of $L5/L01$ of between 0.2 and 1 (e.g., between 0.3 and 0.6);
- xx. A velocity of the second fuel flow (2F) of between 9.1 m/s and 152.4 m/s (e.g., between 30 m/s and 152.4 m/s);
- xxi. A velocity of the first fuel flow (1F) of between 6 m/s and 152.4 m/s (e.g., between 12 m/s and 122 m/s);
- xxii. A velocity of oxidant (OX) of between 3 m/s and 92 m/s (e.g., between 12 m/s and 61 m/s);

xxiii. A velocity of fluid (e.g. second fuel or second fuel mixed with third oxidant flow OX3) output from the inner second fuel conduit 30c that is between 3 m/s and 46 m/s (e.g. 3 m/s to 30.5 m/s, 6 m/s to 46 m/s, etc.); and

xiv. the diameter of the holes 27 of the first fuel conduit 20 can be defined as "P0" and $P0/D2$ is between 0.02 and 0.2.

[0197] We have found that the use of a swirl section 33 can provide a tangential flow to the oxidant and/or fuel exiting the burner 5 to create a recirculation zone at the center of the flame that can bring in hot combustion gases back towards the fuel to provide a continuous source of ignition to the flame 7. The upper and lower bound of the swirl angle for the swirler(s) of the swirler section 33 can be determined by the length or width of the combustion chamber, and burner firing rate. The burner configuration can be selected to avoid the flame 7 impinging on a combustion wall or at least one tube 2 in the combustion chamber CC doesn't impinge the tube(s) 2.

[0198] The oxidant velocity for the burner 5 can be selected based on the available pressure from a blower or compressor that may be used to help facilitate the flow of oxidant to and through the burner 5. We found that a pre-selected velocity for the oxidant can be determined to facilitate a good mixing of the oxidant with the fuel(s) output from the burner 5 to help maintain stable flame without straining or liftoff over a wide range of burner operations.

[0199] The velocity of the second fuel flow 2F can be determined such that it provides good mixing with the oxidant as well. A pre-selected velocity of the fuel can be selected to help avoid fuel collecting near a tube 2 in the combustion chamber or a combustion wall to help avoid the fuel combusting in such locations to avoid causing over-heating at such locations. In some embodiments, the velocity of the second fuel can be maximized within the constraints of stable and complete combustion to maximize entrainment of gases in the second fuel jets thereby diluting the combustion reactions. This can help to reduce tendency of the burner 5 to form thermal NO_x through lowering of the peak combustion temperature. A low velocity limit for the second fuel velocity can also be pre-selected to avoid the second fuel velocity being below the low velocity limit to avoid undesired weak mixing of the second fuel, which can lead to unreacted fuel collecting near a wall of the combustion chamber CC, which can contribute to over-heating of the wall via combustion of that fuel.

[0200] The velocity of first fuel flow 1F can be pre-selected so that the velocity of the fuel facilitates quick mixing of the fuel with surrounding oxidant. This velocity of this flow

of fuel can also be selected to facilitate formation of a stable flame without any lift-off or with minimal lift-off.

[0201] The burner 5 can be configured in such a way the velocity of the diverted second fuel or mixture of diverted second fuel and diverted third oxidant flow OX3 at the exit of the inner second fuel conduit 30c or the flame stabilization plate FSP is between 1.5 m/s and 30.5 m/s (e.g. between 6 m/s and 18.3 m/s). In some configurations, the burner 5 can be configured so that a ratio of velocity of the oxidant at the exit 30bo of the second oxidant conduit segment 30b and the fluid at the exit of the inner second fuel conduit 30c (e.g. adjacent the flame stabilization plate FSP) is between 1.5 and 5.0.

[0202] The fuel utilized for the first flow of fuel 1F can be a trim fuel that can be comprised of natural gas (e.g., methane), or other suitable fuel. The fuel of the second flow of fuel 2F can be a different type of fuel (e.g., tail gas, a gas that includes hydrogen, nitrogen, and ammonia, etc.). The fuels of the first and second flows of fuel can also include or alternatively include biogas, synthesis gas, hydrogen, ammonia, pressure swing adsorption waste gas (e.g. a gas that includes one or more of: hydrogen, natural gas, ammonia, liquid petroleum gas, a mixture of hydrogen, methane, carbon dioxide and carbon monoxide, a mixture of hydrogen, ammonia, and nitrogen, etc.) or other flammable gases (e.g. liquefied petroleum gas, etc.). The oxidant can be any suitable oxygen containing gas (e.g., air, oxygen enriched air, synthetic air, etc.). In some embodiments, the fuel of the first flow of fuel 1F can be natural gas, hydrogen, liquid petroleum gas or ammonia and the fuel of the second flow of fuel 2F can be a type of pressure swing adsorption waste gas (e.g. a gas that includes one or more of: hydrogen, natural gas, ammonia, liquid petroleum gas, a mixture of hydrogen, methane, carbon dioxide and carbon monoxide, a mixture of hydrogen, ammonia, and nitrogen, etc.).

[0203] Embodiments of the burner 5 can be utilized to facilitate combustion across various different operational modes and fuel combinations. For example, in some operational modes, the burner can utilize a single source of fuel (e.g., the first fuel of the first fuel flow 1F or the second fuel of the second fuel flow 2F) to provide 100% of the fuel for combustion of the fuel and formation of the flame. This can occur during a start-up condition or during normal operations, for example. After start-up, the burner can operate to utilize multiple sources of fuel (e.g., both the first fuel of the first fuel flow 1F and the second fuel of the second fuel flow 2F). In some situations, the first fuel can provide up to 40% of the total heating value for the formation of the flame 7 and the second fuel can provide at least 60% of the heating value. In some situations, the use of the fuel utilized for start-up can be minimized while the other fuel is maximized in its use during such an operational mode (e.g. the first fuel can range from 0% to 40% of the

overall heating value for the flame 7 while the second fuel can range from 100% to 60% of the overall heating value for the flame 7).

[0204] The use of oxidant can be provided to account for different operational modes as well. For example, the flow of oxidant can be provided to facilitate combustion of the fuel from an equivalence ratio range of between 1.0 and 0.25. The oxidant fed into the ignition chamber 25 of the burner 5 for pre-mixing or partial pre-mixing with fuel can range from 2-40% of the total oxidant flow rate or can range from 5% to 25% of the total oxidant flow rate in some embodiments. In some embodiments, the oxidant fed to the ignition cup 70 for mixing with fuel therein can be between 1% and 10% of the overall flow rate of the oxidant and the oxidant fed to the bleed cup 80 can be between 5% and 25% of the overall total oxidant flow rate.

[0205] The burner 5 can also be configured to accommodate a wide range of turndown ratios. For a fuel used for starting up of the burner to initiate formation of a flame, that fuel can then be turned down for subsequent use after a stable flame is formed at a turndown ratio of 1:30 or other suitable ratio, for example. For instance, if the first fuel or second fuel is considered a trim fuel, that trim fuel flow turndown ratio can be 1:30 in some embodiments.

[0206] Embodiments of the burner 5 can allow starting of the burner and ignition of the fuel to initially form the flame 7 during start-up to occur while the burner 5 operates at low equivalence ratio of as low as 0.25 (e.g. fuel lean start-ups). This can be advantageous in situations where it is not possible to reduce the oxidant flow rate below a particular set point while start-up fuel flow is simultaneously minimized for safety reasons. The equivalence ratio is defined as the ratio of the actual fuel/oxidant molar ratio to the stoichiometric fuel/oxidant molar ratio.

[0207] Embodiments of the burner 5 can also allow operating the combustion device 3 over a wide range of the ratio of primary to secondary fuel total heating value (i.e. firing rate ratio). Moreover, the oxidizer back pressure (e.g. air back pressure, oxygen-enriched air back pressure, etc.) can be provided for use with the burner 5 in some embodiments such that it is not required to have any external secondary compression device for the oxidant flow OX, which can help reduce the burner operating costs and any maintenance involved with such activities.

[0208] In some preferred embodiments, the burner further comprises a secondary fuel conduit 40 for supply of a second fuel, having a second fuel outlet 44 at its downstream end, particularly wherein the second fuel outlet 44 comprises a second fuel distribution plate 45 having a multiplicity of second fuel exit holes 45h. In some preferred

embodiments, the holes can be staggered in a series of concentric circle patterns around the outlet 30bo of the second oxidant conduit segment 30b. In some preferred embodiments, the porosity of the second fuel distribution plate 45 is in the range of 8% to 25%

[0209] The inner diameter of the second fuel conduit 40 can be defined as distance D5. Without intending to be bound by theory, the second fuel exit holes 45h can be arranged so that they are located on progressively larger concentric circle pattern or ring pattern to help provide a more distributed combustion by a) reducing the heat release per unit area of injection and b) diluting the combustion through the use of a relatively high velocity fuel injection. These factors can help provide lowering flame temperature of the second fuel combustion, which can lower thermal NOx emissions. NOx can be further reduced by maximizing the radial separation between the second fuel output from the second fuel exit holes 45h and first fuel combustion zones, represented by non-dimensional ratios $D9/D5$ and $D8/D5$.

[0210] Without intending to be bound by theory, the second fuel injection holes 45h located on the innermost circle (the innermost extension of which can be defined as D8) can facilitate flame stability for combustion of the second fuel to form the flame 7 over a wide range of second fuel compositions (e.g. over a wide range of hydrogen concentrations in the second fuel, which can be provided via a pressure swing adsorption (PSA) system output that is an off-gas stream of the PSA system utilized to provide a product hydrogen stream during ammonia cracking operations of reformer operations, etc.). This type of functionality can help provide flexibility to supply total thermal input from the burner divided in different ratios between primary and secondary fuels. In some embodiments, a maximum value of $D8/D4$ that can provide secondary flame stability under all conditions can be 1.4.

[0211] Without intending to be bound by theory, the location of the holes 45h on the outermost circle or outermost ring of holes 45h (the outermost extension of which can be defined as D9) can help lower the NOx emissions by enabling a distributed combustion. If the $D9/D5$ is too large, this can lead to incomplete fuel combustion in a cold furnace (below autoignition temperature of the fuels). A range of $D9/D4$ that can provide complete combustion of secondary fuel while maintaining low NOx emissions can be between 1.6 and 2.5 in some embodiments.

[0212] We have found that the lower range of the fraction of angled second fuel injection holes 40h (angled by angle ω) can help determine a minimum amount of second fuel that can be angled inwards to help sustain flame during operation in which

only the second fuel is fed to the burner for combustion and formation of the flame. This minimum amount of second fuel that can be angled inwards towards the flame centerline can be dependent on the fuel properties of the second fuel. These fuel properties can include lower and upper flammability limits, higher or lower heating value of the second fuel, and flame speed. The fuel properties that can contribute to the minimum amount of fuel to be output from the angled second fuel injection holes 40h can also include other properties of the second fuel as well.

[0213] The second fuel that is injected inwards via the angled holes 40h can help increase the NO_x formation tendency of the burner. To help limit NO_x emissions, it can be desired in some embodiments to define a minimal value of the second fuel to be passed through the angled holes 40h to help minimize the NO_x generation from the formation of the flame when the burner operates in a mode in which only the second fuel is combusted for formation of the flame. However, for second fuels that have relatively poor combustion properties, the burner 5 can be configured so that all the second fuel injection holes 45h can be angled inwards.

[0214] The particular angle omega by which the second fuel exit holes 40h are angled inwards can depend on which specific pitch diameter circles are the angled holes located. The angled holes can be configured so they do not direct the second fuel towards the secondary flame stabilization zone located at the exit of the flame stabilization plate FSP to help avoid impingement of the second fuel jets, which can potentially weaken the secondary fuel flame base/root.

[0215] Furthermore, the angled holes 40h can be configured so that they are not directing the second fuel further downstream of the burner 5 to help avoid formation of a continuous reaction sheet or brush, and prevent formation of self-sustained single-fuel operation using the second fuel. Lastly, multiple ways can be used to determine which specific holes can be angled inwards: it could include one series of innermost second fuel holes 45h, two series of such holes, all series of such holes, or some holes on one inner series of holes and other holes on other outer series' of holes.

[0216] We believe that embodiment that can utilize the third oxidant flow OX3 passed through the inner second fuel conduit 30c to premix with the second fuel diverted therein via the second fuel bleed holes 40c can help to improve the combustion and ignition properties of low measure of heat second fuel. (e.g. a low British Thermal Unit (BTU) value fuel that may be used as the second fuel)

[0217] We have also found that the lower range of the ratio L8/D4 can allow some burner configurations that utilize the diverted second fuel jets to develop or partially

develop (after impinging the inner second partition wall 37a and leave the exit plane of the inner second fuel conduit 30c in a uniform pattern or relatively uniform pattern to develop a symmetric flame structure at the exit plane of the inner second fuel conduit 30c.

[0218] Without intending to be bound by theory, the injection of the second fuel from second fuel injection holes 45h located on several different spaced apart circles or rings defined around the oxidant conduit 30 can help to achieve distributed combustion in the combustion chamber CC to help lower the NOx emissions from fuels that have tendency to form higher NOx (e.g. hydrogen and ammonia). Quantification of the degree of fuel distributedness can be given by the porosity parameter, Δ , where:

$$\Delta = A_{\text{secondary}} / [\pi (D9^2 - D8^2)/4]$$

(whereas the range of Δ can be between 0.1 and 0.2 in some embodiments based on the selection of values for D9 and D8).

[0219] Referring to the embodiment of the burner 5 shown in Figure 43, the burner 5 can have a downstream portion 5dp that can be configured so that there is a pilot fuel conduit for conveying a flow of pilot fuel PF at a location that is more central to the burner than the first fuel conduit 20. The first fuel conduit 20 can be positioned within the oxidant conduit 30 such that the oxidant conduit 30 is positioned between the first fuel conduit 20 and the second fuel conduit 40. In the embodiment of Figures 43 and 43, the oxidant flow OX can be split to form the first and second oxidant flows OX1 and OX2 such that a portion of the first oxidant flow OX1 is passed through a first oxidant conduit segment 30a for being injecting into the burner ignition chamber 25 for mixing with the first fuel flow 1F, and pilot fuel flow PF fed therein. The ignition chamber 25 can be positioned to receive fuel output from the first fuel conduit 20 and pilot fuel conduit and mix at least some of the oxidant of the first oxidant flow OX1 with that fuel. An ignition end of an ignition mechanism 5i can be positioned in or adjacent the ignition chamber 25 for facilitating spark and ignition of the fuel for formation of the flame 7 as well. The size of the first oxidant conduit segment 30a can be selected to facilitate splitting of the oxidant flow OX to form the first and second oxidant flows OX1 and OX2 and to be sufficiently sized to help prevent fuel from being passed upstream and into the oxidant conduit 30 during combustion.

[0220] In some embodiments, the first fuel of the first fuel flow 1F can be considered a pilot fuel and the second fuel of the second fuel flow 2F can be considered a trim fuel or other type of fuel.

[0221] For example, when the first fuel flow is ammonia or includes ammonia, initiating combustion at low temperatures may result in use of a pilot fuel flow PF. The pilot fuel can be a pilot fuel such as natural gas, hydrogen, fully or partially cracked ammonia, or propane to help facilitate ignition and/or combustion. Fig. 42 includes a schematic diagram showing a cross-sectional view of the inner portion of the burner 5 with the pilot fuel conduit surrounding the central ignition source wall to deliver pilot fuel as the first fuel flow 1F is also fed to the ignition chamber 25. In some embodiments the pilot fuel flow PF can be delivered to the ignition chamber 25 via nozzles to improve mixing. During start-up the flow of oxidant through an intermediate annular conduit can be provided to prevent the backflow of pilot fuel into the oxidant conduit 30.

[0222] Fig. 43 is a schematic diagram showing a cross-sectional view of the inner portion of the burner 5 that is structured similar to the embodiment of Figure 42 but wherein the ignition source is removed from the central ignition source wall and pilot oxidant OXP is delivered to the ignition chamber through the central conduit in place of the central ignition source. Pilot oxidant flow OXP can be supplied by diverting a portion of the oxidant supplied to the main oxidant conduit 30 upstream of the burner 5 or in an upstream portion of the burner 5. An ignition source may be positioned in the path of the pilot fuel or the pilot oxidant (not shown).

[0223] In some embodiments of the burners shown in Fig. 42 or Fig. 43, formation of a flame may be started by first starting the main oxidant supply, which initiates the flow of oxidant through the main oxidant conduit 30, and in the case of Fig. 43, the central pilot oxidant conduit. Next the flow of pilot fuel FP may be started through the pilot fuel conduit and the ignition source may be activated. Next the first fuel may be started through the first fuel conduit 20. If desired, the flow of pilot fuel PF may be stopped if no longer required for stable combustion, for example when the temperature of the combustion chamber CC is higher than the auto-ignition temperature of ammonia. Finally, when available flow of second fuel through the second fuel conduit 40 may be initiated. The ability to supply pilot fuel to the burner can permit the use of ammonia as a first fuel in a cold combustion device 3. Pilot fuel may also allow a higher degree of turndown when using ammonia as a first fuel, which can improve the overall operability of the combustion device 3.

[0224] Embodiments of our burner can be configured to provide any of a number of advantages as discussed above. For example, embodiments of the burner can provide improved mixing of an oxidant and a first fuel, which can be utilized as a primary fuel in some embodiments. For instance, partially premixing the first fuel with oxidant passed into the ignition chamber 25 via holes 25h of the ignition chamber 25 using at least one

mechanical mixer plate 74 in the ignition chamber 25 can help achieve better start-up of the burner in a cold combustion device 3 over a range of first fuel and oxidant flow rates.

[0225] Also, embodiments can be adapted so that the second fuel can be introduced into the combustion space radially away from the primary fuel/oxidant flame and in a distributed manner.

[0226] Embodiments of the burner can allow operating the burner over a wide range of second fuel composition (e.g. 1 mole percent (mol%) hydrogen (H₂) and 98 mol% nitrogen (N₂) to 98 mol% H₂ and 1 mol%N₂ with the remaining constituents including ammonia (NH₃) and/or water (H₂O). The total mol% of H₂ and N₂ could range from 50 mol% to 99 mol% of the total mixture of the fuel in some embodiments.

[0227] Some embodiments of the burner can be configured to utilize a first fuel turndown ratio of 1:30 (e.g. wherein the first fuel may be a primary fuel).

[0228] Embodiments of the burner can provide improved partial pre-mixing of a main oxidant and a first fuel. For example, embodiments of the burner can allow for more intimate mixing from combined swirl and pre-mixing holes leading to a shorter flame that can fit inside a compact combustion chamber (e.g. a short reformer, a short furnace, another type of short combustion chamber, etc.). Embodiments of the burner can be configured to provide a reduced flame length that can be able to accommodate such shorter or smaller combustion chamber sizes. This type of functionality can also permit the combustion device 3 to be designed to use a combustion chamber CC that has a shorter height or size.

[0229] Embodiments of the burner can be configured so that the burner can be fuel-flexible (e.g. allows use of natural gas, hydrogen, liquefied petroleum gas (LPG) as a first fuel and a lower BTU second fuel (e.g. ammonia, ammonia mixed with hydrogen and nitrogen and other constituents, etc.). Embodiments can be configured to allow the burner to facilitate a reliable start-up in a cold combustion device (e.g. in temperatures that are below the auto-ignition temperature of the fuel) using an air-fuel mode or oxidant fuel mode.

[0230] Embodiments of the burner can be configured so that no water cooling is required.

[0231] As discussed above, embodiments of the burner can also allow maintaining of low NO_x emissions via combustion of the fuel(s) e.g. keeping NO_x emissions within environmental limits). And embodiments of the burner can facilitate use of a fuel lean stable flame without flame blow-off at high excess oxidant (equivalence ratio of as low

as 0.25). For instance, in a first fuel mode the burner 5 can operate when the first fuel is reduced to 10% of maximum firing rating of the burner and the second fuel is cut-off (e.g. is not fed to the burner 5). The burner 5 can also enable stable and reliable ignition and combustion under cold conditions with equivalence ratio as low as 0.25.

[0232] Also as discussed above, embodiments of the burner 5 can be configured to provide flexibility in burner operation across a wide range of split of total heat/energy coming from the first fuel (which can be considered a primary fuel in some embodiments) and a second fuel (which can be considered a secondary fuel in some embodiments). For example, the burner can be operated so that only a second fuel is used to fuel combustion, only a first fuel is used to fuel combustion, only a first fuel and a pilot fuel are used to fuel combustion, or a mix of a first fuel and a second fuel is used to fuel combustion (e.g. a first mode of operation in which only the first fuel is used, a second mode of operation in which the first and second fuels are used, a third mode of operation in which only the second fuel is used, etc.). In some embodiments, 0% to 100% of the total thermal output can come from a first fuel, or primary fuel, and the balance can come from the second fuel, or secondary fuel. For instance, in some embodiments, the burner 5 can be configured to allow use of a low higher heating value secondary fuel and the thermal output from the secondary fuel at 100% of the total thermal power output of the burner in at least one type of operational mode of the burner.

[0233] A process combusting at least one fuel with a burner in a combustion chamber of a combustion device can also be appreciated from the above and is discussed herein. Embodiments of the process can include use of an exemplary embodiment of the burner 5, for example.

[0234] In certain embodiments, the process can include the steps of i) starting the burner using a first fuel, ii) ramping up the burner in firing rate, iii) starting the feeding of the second fuel to the burner, iv) further changing the flow rate of the first fuel and the second fuel and burner equivalence ratio in accordance with a pre-determined combustion scheme, v) cessation of feeding of the first fuel to the burner such that combustion via the burner is fueled by only the second fuel, and vi) restarting the feeding of the first fuel to the burner while the secondary fuel is still being fed to the burner.

[0235] In some embodiments, the starting of the burner using the first fuel can also include starting the main oxidant or starting a feed of oxidant to the burner (e.g. via the oxidant conduit 30) and starting an ignition mechanism (e.g. an igniter) along with starting of the first fuel, or primary fuel.

[0236] Embodiments of the process can also include other steps or be specific to operation of a specific embodiment of the burner 5 discussed herein. As can be appreciated from the above, embodiments of the process can facilitate improved mixing of a main oxidant and a primary fuel via the ignition chamber 25 and feeding of oxidant and first fuel to the ignition chamber 25, for example. As another example, embodiments of the process can facilitate low NO_x emissions, avoiding a need for secondary compression devices, and/or avoiding a need for water cooling.

[0237] We performed various different evaluations of embodiments of our burner 5 to evaluate how embodiments of the burners may be utilized in operation. The following examples are provided to help further illustrate aspects of different exemplary embodiments.

EXAMPLES

[0238] Example 1

[0239] An exemplary test burner with air as oxidant and natural gas as primary fuel (trim fuel) and a mixture of hydrogen, nitrogen, and ammonia (H₂, N₂, NH₃) as a low heat value tailgas for use as a secondary fuel was designed, manufactured, and tested in a laboratory test furnace. The trim fuel of natural gas was utilized as the first fuel flow 1F and the tailgas was utilized as the second fuel flow 2F in the conducted experimentation. Air was used as the oxidant.

[0240] The burners in this testing were operated over a wide range of operating conditions (Start-up, full load at heat-up, 100% design firing rate with both fuel, and 50% turndown condition with both fuel). The average furnace wall temperature under these conditions was in the range 450°F, or 232°C (during start-up and single fuel operation)-1600°F, or 871°C (dual fuel operation).

[0241] Burners designed as burners A, B, and C were utilized in this testing. Burner A had a burner design based on the embodiment shown in Figure 8, Burner B had a burner design based on the embodiment of Figure 9, and Burner C had a burner design based on the embodiment of Figure 4. Table 1 (below) compares the differences in the three burner designs.

[0242] The total burner firing rate, split of first and second fuel thermal output, burner equivalence ratio, and composition of the first fuel and second fuel were the same for all the three burners. The three burners in the experimental evaluation were identical except for the different ways the second fuel was injected through the burner.

[0243] In Burner A, the secondary fuel was injected in close coupled ($D8/D4 = 1.25$) condition next to the oxidant conduit 30. In Burner B, the secondary fuel was injected through second fuel exit holes 45h located on one series at a certain radial separation from the oxidant conduit 30. In Burner C, the second fuel was injected through second fuel exit holes 45h located on several series of concentric diameters and each concentric diameter was located at increasing radial separation from the oxidant conduit 30 and central axis.

[0244] The plot in Fig. 23 is comparison of normalized NO_x for three different type of burners 5 that were evaluated during this testing. The normalized NO_x value is defined as the ratio of NO_x (ppm, corrected at 3% oxygen in flue gas) produced by a burner type by the maximum NO_x (ppm, corrected at 3% O₂ in flue gas) produced from amongst the different burners. Here in the present example, the NO_x data has been normalized by the NO_x produced by Burner A as it produced the maximum NO_x (ppm, corrected at 3% O₂ in flue gas).

[0245] Fig. 23 shows that the NO_x emissions reduce by 63% in Burner C as compared to Burner A and by 27% in Burner C as compared to Burner B.

[0246] Quantification of the flux of Thermal energy from secondary fuel is defined by:
 Flux of secondary fuel thermal input = Thermal input secondary fuel / $[\pi (D9^2 - D8^2)/4]$

Table 1: Comparison of three burner types

	Flux of Thermal energy (Secondary Fuel MMBtu/hr/in ²)		D8/D4	D9/D4
Burner A	0.37		1.17	1.24
Burner B	0.30		1.39	1.54
Burner C	0.07		1.30	1.90

[0247] The fact that the Burner C was able to produce significantly lower NO_x as compared to Burner A and Burner B is believed to be due to multiple unique features of the former burner as follows. First, the second fuel exit holes 45h located on progressively larger concentric circle patterns or ring patterns can help to achieve a more distributed combustion by radially separating the second fuel injection holes away from the flame formed via combustion of the first fuel. The increasing radial separation away from the first fuel flame can allow some fraction (50%) of the second fuel to be injected

and combusted in a zone which is relatively lower temperature as compared to the flame temperature from combustion of the first fuel.

[0248] In burners B and A, all of the second fuel was injected in a space that has higher temperature due to its proximity to the first fuel flame. The design of Burner C was found to have a lower tendency to form thermal NO_x as compared to the other designs of Burners A and B. This effect is especially significant when second fuel has components like hydrogen or ammonia that have a tendency to form higher NO_x due to higher flame temperature and/or ability of the fuel to produce radical species that have chemical pathways to form NO_x.

[0249] The design exit velocity range for the second fuel may have allowed entrainment of the furnace gases in the fuel jets thereby diluting the fuel jets as well. The composition and temperature of entrained gases can change as the gas moves radially away from the oxidant conduit 30. Thermal NO_x formation can be primarily influenced by temperature and oxygen concentration. Temperature and oxygen concentration, in particular, can reduce as the gas moves radially out from the oxidant conduit 30 because of increased radial separation from the heat release region of the first fuel flame and also, the oxidant stream. As a result of this trend in temperature and gas composition, the fuel jets that are located on the outer series of exit holes would potentially entrain gases that have relatively lower temperature and oxygen concentration as compared to the inner series of holes. This feature of entraining furnace gases to dilute the second fuel stream can help to reduce tendency of the burner to form thermal NO_x by enabling distribution combustion, which helps to lower the peak combustion temperatures.

[0250] Lastly, the burner C was found to provide improved performance on NO_x emissions. The ignition chamber holes 25h can provide air in the ignition cup 70 that can be entrained by the fuel jets before the fuel leaves the exit plane 5plane of the burner 5. This enhanced mixing through a unique chamber design can allow for reducing peak temperatures relative to common characteristics of non-premixed burners. The lower peak temperature for this burner flame can mimic that of a partially-premixed air-fuel combustion rather than non-premixed combustion.

[0251] Additionally to compare Burner B and Burner C, there is a practical higher limit by which a single series of secondary fuel injection holes can be radially separated from the oxidant conduit (D8/D4). In Burner B, if the D8/D4 is increased to assist in NO_x reduction, at a certain radial separation limit the plant operation to start second fuel injection below auto-ignition temperature of the second fuel can be inhibited because it can lead to uncombusted fuel leaving the combustion device 3. In Burner C, the second

fuel exit holes 45h were located on progressively larger concentric circle patterns that allowed combustion from fuel injected from the inner series of holes to provide energy to initiate and combust the fuel injected from the outer series of holes. We believe this cascading combustion effect in Burner C can allow a plant operator to start the second fuel injection in a cold furnace (not above auto-ignition of second fuel) and still combust all the fuel.

[0252] Furthermore, this cascading effect of combustion from inner series of holes to outer series of holes can enable combustion of a wide range of low heat value fuel mixtures (e.g., low value British Thermal Unit, BTU, fuels). A single series of secondary fuel injection holes used in Burner B and/or Burner A would not allow such fuel-flexibility without sacrificing on NO_x emission based on our conducted testing. Burner C, however, was found to be able to allow operating the burner over a wide range of fuel composition in a cold furnace (e.g. fuel compositions having mole percentages (mol%) ranging from 5 mol%H₂ and 90 mol% N₂ to 90 mol% H₂ and 5mol% N₂, wherein remaining constituents could be NH₃, H₂O, etc.). The total mol% of H₂ and N₂ could range from 50% to 95% of the total mixture, for example. The second fuel exit holes 45h located on the innermost circle (D8) was found to be able to facilitate flame stability over a wide range of H₂ concentration in the secondary fuel.

[0253] The conducted evaluation work showed that Burner C was able to produce stable flame at high turndown of 1:30 and at equivalence ratio of 0.25. This performance can be due to the unique configuration of burner hardware that includes a specific configuration of the downstream portion 5dp of the burner 5. The burner 5 can provide multiple flame anchoring location based on the total firing rate of the burner as illustrated in Figures 25 and 26. At a high firing rate close to design firing rate of the burner, the flame 7 can be anchored at multiple locations: one near the oxidant distribution plate 73 and a second location at a periphery inside wall of the oxidant conduit 30. At low firing rate under turndown conditions and low equivalence ratio, the flame can be anchored at the oxidant distribution plate 73 location without any blow-off because of recirculation zone setup in the area created by step design of the oxidant distribution plate 73. Furthermore, the oxidant distribution plate 73 can be positioned so that it is recessed by distance L1 from the oxidant outlet plane, which can allow the flame anchoring to relatively be unaffected by the furnace atmosphere.

[0254] The burner C was also found to be able to produce a stable flame for a wide range of split of primary and secondary fuels. The primary fuel can supply 5% to 100% of the total burner thermal output and remaining balance coming from the secondary fuel. The main reason for this flexible performance can be due to the strong flame

anchoring zone for the primary fuel that can allow the primary fuel heat input to be reduced to as low as 5% of the total thermal output of the burner 5.

[0255] The design features of Burner C that can allow the oxidant to be radially and axially purged in the ignition chamber that keeps the peripheral wall of the chamber 25 cooled by protecting it from direct contact with the flame. The burner was operated in a plant setting reactor furnace and after one year of operation was found spotless without any damage to the burner hardware, in particular the ignition cup 70.

[0256] Finally, the Burner C was found to ignite well at equivalence ratios as low as 0.25, even at cold furnace conditions. This can be possible due to the unique design of ignition cup 70 that can provide a zone where local ignition can be initiated and sustained while the composite fuel-air mixture is still below the global burner lower flammability limit of natural gas (or other type of first fuel), which occurs at an equivalence ratio of approximately 0.48. This can be due to a portion of primary air being introduced into the ignition chamber 25, entering via the peripheral wall of the chamber, which is at right angles to the fuel distribution nozzle. This can serve to vigorously mix the fuel and "ignition" air, creating numerous "pockets" of local fuel-air mixture having equivalence ratio within the flammable region, thereby enabling ignition to reliably and repeatably occur in spite of the composite gas mixture having a non-flammable fuel concentration.

[0257] Example 2

[0258] Additional testing was conducted using Burners A, B, C, and an additional Burner D having a design of the embodiment of Figure 31 with angled holes 40h. Burner D had the same design as Burner C except that (i) the innermost ring of second fuel exit holes 45h were angled holes 40h, (ii) Burner D had the inner second fuel conduit 30 that received fuel from the second fuel conduit 40 and had the flame stabilization plate FSP, and (iii) there was no use of a swirler in the second oxidant conduit segment 30b. The graph of Figure 39 shows the results of this additional evaluation work. These results showed that changes in Design D provided a further improvement in low NO_x formation while also retaining the other advantages that were found to exist in the design of Burner C noted above. The NO_x emissions were reduced by 54% in Burner D as compared to Burner C.

Table 2: Comparison of four burner types

	Flux of Thermal energy (Secondary Fuel MMBtu/hr/in ²)	D8/D4	D9/D4

Burner A	0.37	1.17	1.24
Burner B	0.30	1.39	1.54
Burner C	0.07	1.30	1.90
Burner D	0.04	1.30	1.90

[0259] In the conducted experimentation, the design D was able to produce lower NO_x than design C because the non-swirl oxidant in design D delayed the mixing of fuel and oxidant; thereby assisting in reducing the high temperature regions in the combustion space as compared to design C. Additionally, the fraction of the secondary fuel that was diverted via the secondary fuel bleed holes 40c and via the angled secondary fuel injection holes 40h was optimized that helped minimize NO_x generated in the flame and also to initiate and sustain a continuous distributed combustion of the second fuel. Further, the presence of nitrogen in the second fuel that was diverted inwards towards the first fuel flame can potentially lower regions of peak temperature in combustion space of the first fuel flame, which would help lower thermal NO_x.

[0260] In burner D, the primary fuel can supply 0% to 100% of the total burner thermal output and remaining balance coming from the secondary fuel. When the primary fuel flow rate is shut-off or turndown to zero, the flame stabilization plate FSP located at the exit of the inner second fuel conduit 30c can provide a robust, low-velocity, stabilization zone (stabilization surface/zone 3) for the secondary fuel flame to initiate and sustain. The use of current velocity ratio of exit velocity from the inner second fuel conduit 30c and second oxidant conduit segment 30b, and appropriately sized flame stabilization plate (D10, D11 and porosity of the FSP) was able to allow the secondary fuel flame root or base to sustain itself without the assistance from the heat release from the combustion of primary fuel or the combusted hot combustion chamber gases. Furthermore, the flame stabilization plate FSP was recessed by recessed distance L6, which allowed the flame anchoring to be relatively unaffected by the atmosphere in the combustion chamber CC.

[0261] Furthermore, the secondary fuel from the angled secondary fuel injection holes 40h directed a fraction of fuel towards the flame front developed or originating from the exit of the inner second fuel conduit 30c through which some of the second fuel was passed via the internal second fuel injection holes 40c. This directed secondary fuel provided additional fuel to spatially sustain a continuous secondary fuel flame brush and the heat release from this zone of combustion provided heated combustion products and air that assisted in the initiation and combustion or consumption of the remaining

injected secondary fuel in the conducted experimentation. Lastly, the angled inward secondary fuel holes 40h allowed the flame brush to widen in width at the point of intersection of the secondary fuel jet and the oxidizer/combusted gases mixture. This widening of the flame brush in radially outward direction allowed a continuous distributed flame regime to develop in the combusted space in the conducted experimentation.

[0262] It should be appreciated that modifications to the embodiments explicitly shown and discussed herein can be made to meet a particular set of design objectives or a particular set of design criteria. For example, embodiments of the burner can be configured to that the size and shape of the flame generated via the burner is within a pre-selected size profile in a combustion chamber. As another example, type of suitable size and shape of different conduits of the burner can be adapted to meet a particular set of design criteria for the operational performance of a particular combustion device or combustion based system (e.g., remelt furnace operation, methane reforming, ammonia cracking, etc.). For instance, some embodiments may be quite large while others can be smaller to account for the size of the combustor in which it is to be utilized and the operational requirements for that combustor.

[0263] Embodiments of the combustion device and burner can be incorporated into a plant or industrial system. These embodiments can be configured to include process control elements positioned and configured to monitor and control operations (e.g. temperature and pressure sensors, flow sensors, an automated process control system having at least one work station that includes a processor, non-transitory memory and at least one transceiver for communications with the sensor elements, valves, and controllers for providing a user interface for an automated process control system that may be run at the work station and/or another computer device of the system, etc.).

[0264] As yet another example, it is contemplated that a particular feature described, either individually or as part of an embodiment, can be combined with other individually described features, or parts of other embodiments. The elements and acts of the various embodiments described herein can therefore be combined to provide further embodiments. Thus, while certain exemplary embodiments of a burner, combustion device, process for combustion of multiple fuels, and methods of making and using the same have been shown and described above, it is to be distinctly understood that the invention is not limited thereto but may be otherwise variously embodied and practiced within the scope of the following claims.

CLAIMS

1. A burner comprising:

a first fuel conduit positioned to pass a first fuel flow to an ignition chamber positioned in a downstream portion of the burner;

an oxidant conduit positioned to pass an oxidant flow to a combustion chamber of a combustion device, the oxidant conduit having a first oxidant conduit segment and a second oxidant conduit segment that is separated from the first oxidant conduit segment via a first partition wall such that the oxidant flow passable through the oxidant conduit is splitable into a first oxidant flow that is passed through the first oxidant conduit segment and a second oxidant flow that is passable through the second oxidant conduit segment; and

wherein the first oxidant conduit segment is configured so that a first portion of the first oxidant flow is passable to the ignition chamber for mixing with fuel therein via holes of the ignition chamber that are in fluid communication with the first oxidant conduit segment and a second portion of the first oxidant flow is outputable from the oxidant conduit via at least one oxidant exit hole in fluid communication with the first oxidant conduit segment; and

a second fuel conduit positioned to pass a second fuel flow to a combustion chamber of a combustion device.

2. The burner of claim 1, wherein the oxidant conduit is positioned between the first fuel conduit and the second fuel conduit and there is a fuel distribution plate having a plurality of second fuel exit holes in fluid communication with an outlet end of the second fuel conduit.

3. The burner of claim 1, wherein the oxidant conduit is positioned between the first fuel conduit and the second fuel conduit and there is an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall, the second fuel conduit having at least one internal second fuel injection hole in fluid communication with the inner second fuel conduit to divert a portion of second fuel passing through the second fuel conduit into the inner second fuel conduit for being output from the burner via an outlet of the inner second fuel conduit.

4. The burner of claim 3, wherein the inner second fuel conduit is in fluid communication with the second oxidant conduit segment such that the second oxidant flow is splitable to form a third oxidant flow that is passable through the inner second fuel conduit to mix with the portion of second fuel diverted into the second inner second fuel conduit via the at least one internal second fuel injection hole while a portion of the second oxidant flow is passed through the

second oxidant conduit segment for being output from at least one oxidant exit hole in fluid communication with the second oxidant conduit segment.

5. The burner of claim 3, wherein the second fuel conduit is in fluid communication with an inner row of spaced apart holes that each extend to an outlet of the burner inwardly towards a central axis of the burner at a pre-selected angle ω , the pre-selected angle ω being at between 2° and 80° .

6. The burner of claim 1, wherein:

the ignition chamber includes an ignition cup that is upstream of a bleed cup and a mixer plate positioned between the ignition cup and the bleed cup, the mixer plate having holes positioned so that jets of fuel output from the first fuel conduit are broken up and partially premix with oxidant feedable into the ignition cup via holes of the ignition cup that are in fluid communication with the first oxidant conduit segment so that the partially premixed fuel and oxidant are passable through the holes of the mixer plate into the bleed cup; and/or

a first oxidant distribution plate positioned between the ignition cup and the bleed cup, the first oxidant distribution plate having oxidant exit holes through which oxidant from the first oxidant conduit segment is outputable; and/or

a second oxidant distribution plate positioned adjacent an outlet of the bleed cup between the bleed cup and the first partition wall, the second oxidant distribution plate having oxidant exit holes through which oxidant from the first oxidant conduit segment is outputable.

7. The burner of claim 1, wherein:

the first fuel conduit has an inner diameter or width D3;

the oxidant conduit has an inner diameter or width D4;

the second fuel conduit has an inner diameter or width D5;

a downstream portion of the ignition chamber has a diameter or width D6;

second fuel exit holes through which the second fuel flow passed through the second fuel conduit is outputable have a diameter or width D7.

8. The burner of claim 7, wherein:

the second fuel exit holes include an inner row of spaced apart holes arranged in a ring pattern and an outer row of spaced apart holes arranged in a ring pattern that are in fluid communication with the second fuel conduit, a distance between the holes on opposite sides of the inner row of spaced apart holes being a distance D8 and a distance between the holes on opposite sides of the outer row of spaced apart holes being a distance D9 that is greater than distance D8; and

wherein at least one of:

D7 is between 0.12 cm and 0.762 cm;

a ratio of D8/D4 is between 1.1 and 1.3; and

a ratio of D9/D4 is between 1.6 and 2.2.

9. The burner of claim 8, wherein a diameter of the holes in a downstream portion of the ignition chamber have a pre-selected diameter P1 and a space between spaced apart rows of the holes of the ignition chamber is a distance H and wherein H/P1 is between 1.25 and 2.5.

10. The burner of claim 7, wherein the first fuel conduit is positioned around a receptacle having a diameter or width D2 and the first fuel conduit has an outlet in fluid communication with first fuel exit holes having a diameter D0;

the oxidant conduit being in fluid communication with oxidant exit holes having a diameter D1, and

the first partition wall positioned and configured so that the first oxidant conduit segment is defined to have a pre-selected diameter or width L4 and extends along a first portion L02 of an overall length L0 of the ignition chamber that extends from an upstream end of the ignition chamber to a downstream end of the ignition chamber and also has a pre-selected diameter or width L5 that extends along a second portion L01 of the overall length L0 of the ignition chamber such that mixing of oxidant within a downstream portion the ignition chamber occurs about a length L01 of the overall length L0 of the ignition chamber wherein L01 is less than L0;

wherein a diameter of the holes of the ignition chamber in the downstream portion of ignition chamber have a pre-selected diameter P1 and a space between spaced apart rows of the holes of the downstream portion of the ignition chamber is distance H; and

wherein at least one of:

- i. a value of $P1$ is between 0.12 cm and 0.51 cm;
- ii. a ratio of $P1/D2$ is between 0.06 and 0.6;
- iii. a value of $D7$ is between 0.12 cm and 0.762 cm;
- iv. a ratio of $D7/D2$ is between 0.05 and 0.6;
- v. a value of $D0$ is between 0.12 cm and 0.64 cm;
- vi. a ratio of $D0/D2$ is between 0.05 and 0.6;
- vi.. a value of $D1$ is between 0.12 cm and 0.381 cm;
- vii. a ratio of $D1/D2$ is between 0.06 and 0.15;
- viii. a ratio of $D3/D2$ is between 1.5 and 5;
- ix. a ratio of $D4/D2$ is between 2 and 12;
- x. a ratio of $D5/D2$ is between 5 and 25;
- xi. a ratio of $D6/D2$ is between 1.5 and 6;
- xii. a ratio of $D8/D4$ is between 1.1 and 1.3;
- xiii. a ratio of $D9/D4$ is between 1.6 and 2.2;
- xiv. a ratio of $L0/D3$ is between 0.2 and 2;
- xvi. a ratio of $L01/D3$ is between 0.1 and 1;
- xvii. a ratio of $L4/D3$ is between 0.05 and 1; and
- xviii. a ratio of $L5/L01$ is between 0.2 and 1.

11. The burner of claim 1, comprising:

an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall such that the inner second fuel conduit is between the second oxidant conduit segment and the second fuel conduit, the second fuel conduit having at least one internal second fuel injection hole in fluid communication with the inner second fuel conduit to divert a portion of second fuel passing through the second fuel conduit into the inner second fuel conduit for being output from the burner via an outlet of the inner second fuel conduit;

a flame stabilization plate (FSP) positioned adjacent to an outlet of the inner second fuel conduit.

12. The burner of claim 11, wherein the FSP is also positioned adjacent to an outlet of the inner second fuel conduit to provide a flame stability surface.

13. The burner of claim 12, wherein:

the oxidant conduit has an inner diameter or width D4 and the oxidant conduit is positioned between the first fuel conduit and the second fuel conduit;

wherein the second partition wall has a length L7; the at least one second fuel injection hole being located upstream of an outlet of the burner by a distance L8 that is less than L7;

the FSP being annular shaped and having an inner diameter D10 and an outer diameter D11 and the inner second fuel conduit having an inner width or diameter D12;

the FSP being positioned so that the FSP is recessed relative to an output plane of the burner a recessed distance L6, L6 being a distance axially inward from the output plane that is adjacent the combustion chamber to the FSP, L6 being less than L8 and L6 also being less than L7;

and wherein at least one of:

- a. a ratio of $D12/D4$ is between 0.75 and 0.95
- b. a ratio of $L6/D4$ is between 0.04 and 0.5;
- c. a ratio of $D10/D4$ is between 0.70 and 0.85;
- d. a ratio of $D11/D4$ is between 0.90 and 0.99; and
- e. a ratio of $L7/D4$ is between 0.25 and 2.0.

14. A process of combusting at least one fuel in a combustion chamber of a combustion device, the process comprising:

passing a first fuel flow through a first fuel conduit of a burner positioned to generate a flame in the combustion chamber,

passing an oxidant flow through an oxidant conduit of the burner such that the oxidant flow is split into a first oxidant flow that passes through a first oxidant conduit segment of the oxidant conduit that is separated from a second oxidant conduit segment via a first partition wall and a second oxidant flow that passes through the second oxidant conduit segment; and

passing a first portion of the first oxidant flow to an ignition chamber of the burner for mixing with fuel therein via holes of the ignition chamber that are in fluid communication with

the first oxidant conduit segment and passing a second portion of the first oxidant flow through the first oxidant conduit segment for being output out of the oxidant conduit via at least one oxidant exit hole in fluid communication with the first oxidant conduit segment.

15. The process of claim 14, comprising:

passing a second fuel flow through a second fuel conduit of the burner.

16. The process of claim 15, comprising:

diverting of a portion of the second fuel flow being passed through the second fuel conduit so that the diverted portion of the second fuel flow passes through at least one internal second fuel injection hole of the second fuel conduit that is in fluid communication with an inner second fuel conduit, the inner second fuel conduit being positioned between the second fuel conduit and the second oxidant conduit segment.

17. The process of claim 15, wherein the passing of the oxidant flow through the oxidant conduit of the burner also includes:

passing the second oxidant flow through the second oxidant conduit segment such that a portion of the oxidant is split from the second oxidant flow to form a third oxidant flow that passes through an inner second fuel conduit that is separated from the second oxidant conduit segment via a second partition wall, the second oxidant conduit segment being between the first oxidant conduit segment and the inner second fuel conduit, and the inner second fuel conduit being between the second fuel conduit and the second oxidant conduit segment; and

the passing of the second fuel flow through the second fuel conduit includes passing a portion of the second fuel flow through at least one internal second fuel injection hole of the second fuel conduit that is in fluid communication with the inner second fuel conduit to mix with the third oxidant flow passing through the third oxidant conduit segment.

18. The process of claim 15, comprising:

outputting a portion of the second fuel flow via second fuel exit holes in fluid communication with the second fuel conduit, the second fuel exit holes including an inner row of spaced apart angled holes that each extend to an outlet of the burner inwardly towards a central axis of the burner at a pre-selected angle ω at an angle of between 2° and 80° .

19. The process of claim 16, wherein the burner includes a flame stabilization plate (FSP) positioned adjacent an outlet of the inner second fuel conduit to provide a stabilization surface for the flame; the process also comprising:

ceasing of the passing of the first fuel flow through the first fuel conduit of the burner so that only the second fuel is passed through the burner to provide the flame within the combustion chamber.

20. The process of claim 19, comprising:

feeding the first fuel through the first fuel conduit of the burner after the ceasing of the passing of the first fuel flow through the first fuel conduit for a pre-selected time period so that the first fuel and the second fuel are combusted to form the flame in the combustion chamber.