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(54) FUEL NOZZLE ASSEMBLY FOR A BURNER INCLUDING A PERFORATED FLAME HOLDER

(71) Applicant: **CLEARSIGN TECHNOLOGIES CORPORATION**, Seattle, WA (US)

(72) Inventors: **DONALD KENDRICK**, BELLEVUE, WA (US); **CHRISTOPHER A. WIKLOF**, EVERETT, WA (US)

(21) Appl. No.: **16/557,840**

(22) Filed: **Aug. 30, 2019**

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(63) Continuation-in-part of application No. 15/498,124, filed on Apr. 26, 2017, now abandoned, Continuation-in-part of application No. PCT/US2018/020503, filed on Mar. 1, 2018.

(60) Provisional application No. 62/327,779, filed on Apr. 26, 2016, provisional application No. 62/466,123, filed on Mar. 2, 2017, provisional application No. 62/466,111, filed on Mar. 2, 2017.

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F23N 5/02	(2006.01)

(52) **U.S. Cl.**

CPC ***F23D 14/14*** (2013.01); ***F23D 14/24*** (2013.01); ***F23D 14/58*** (2013.01); *F23N 2027/02* (2013.01); *F23D 2212/103* (2013.01); *F23D 2213/00* (2013.01); *F23N 2033/06* (2013.01); ***F23N 5/02*** (2013.01)

(57) **ABSTRACT**

A fuel nozzle assembly includes one or more tapered fuel nozzles. Each tapered fuel nozzle includes an acute trailing edge or tip at a top portion of the fuel nozzle. One or more fuel orifices are arranged proximate the acute trailing edge or tip. A tapered fuel nozzle having a toroidal airfoil structure includes a fuel channel to distribute a fuel to the fuel orifice(s). The fuel nozzle assembly may be provided as part of a burner system, including a perforated flame holder, and associated method, in which the fuel nozzle assembly is oriented to direct fuel from the fuel orifices toward the perforated flame holder.

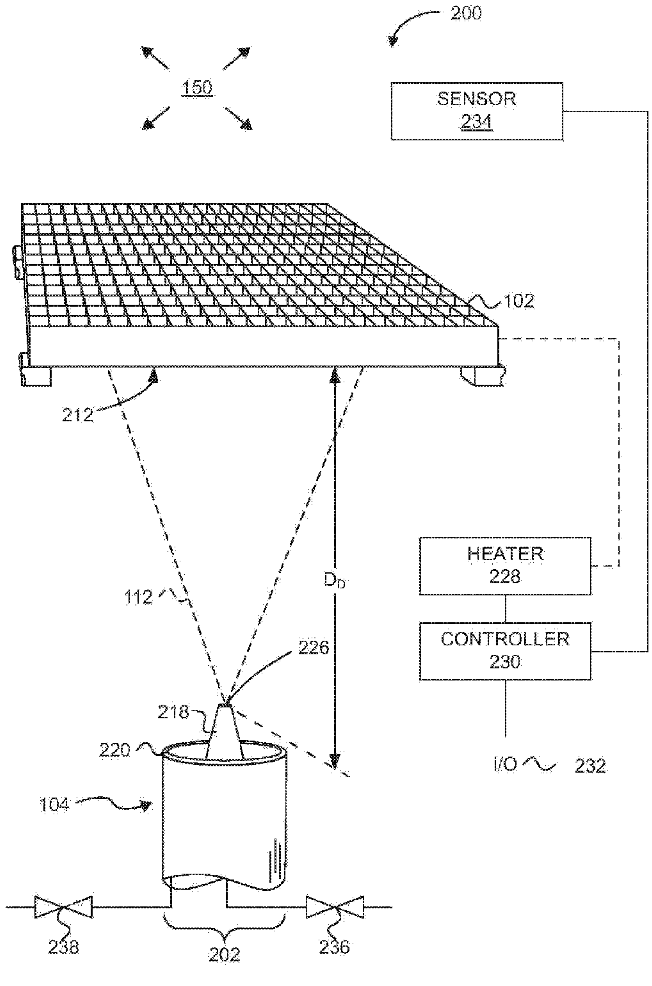


FIG. 1

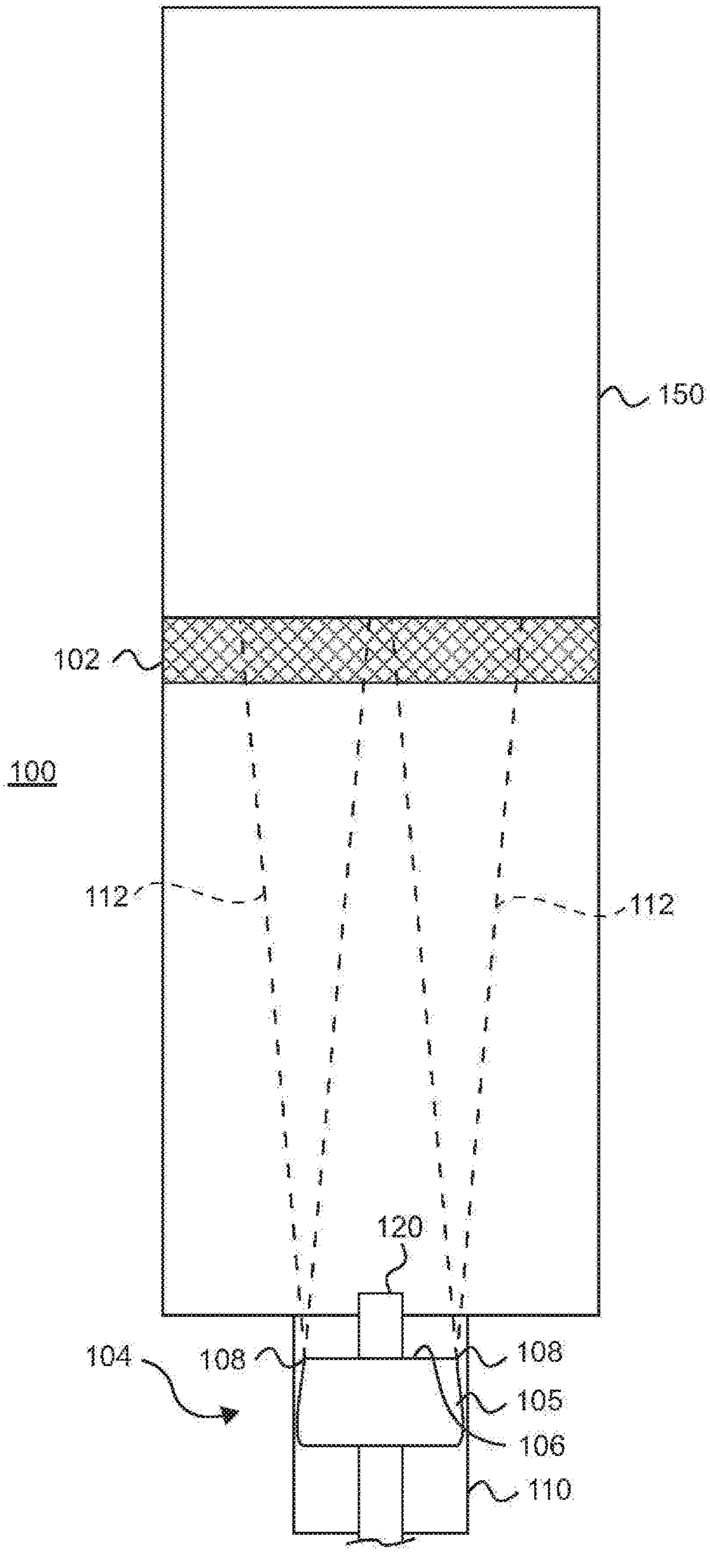


FIG. 2A

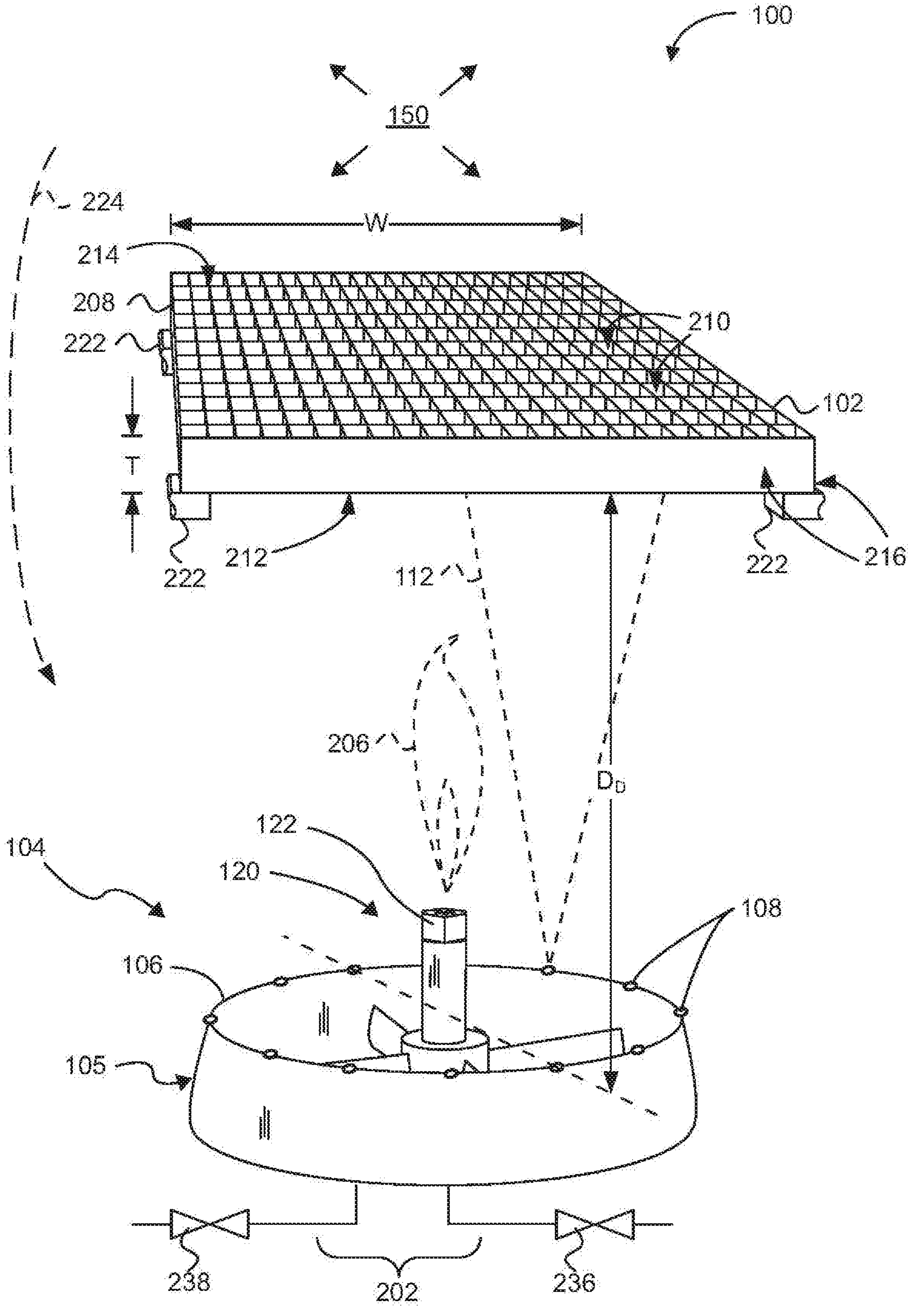

100
150
224
W
214
208
210
222
102
T
222
212
216
222
112
206
D_D
122
104
120
108
106
105
238
202
236

FIG. 2B

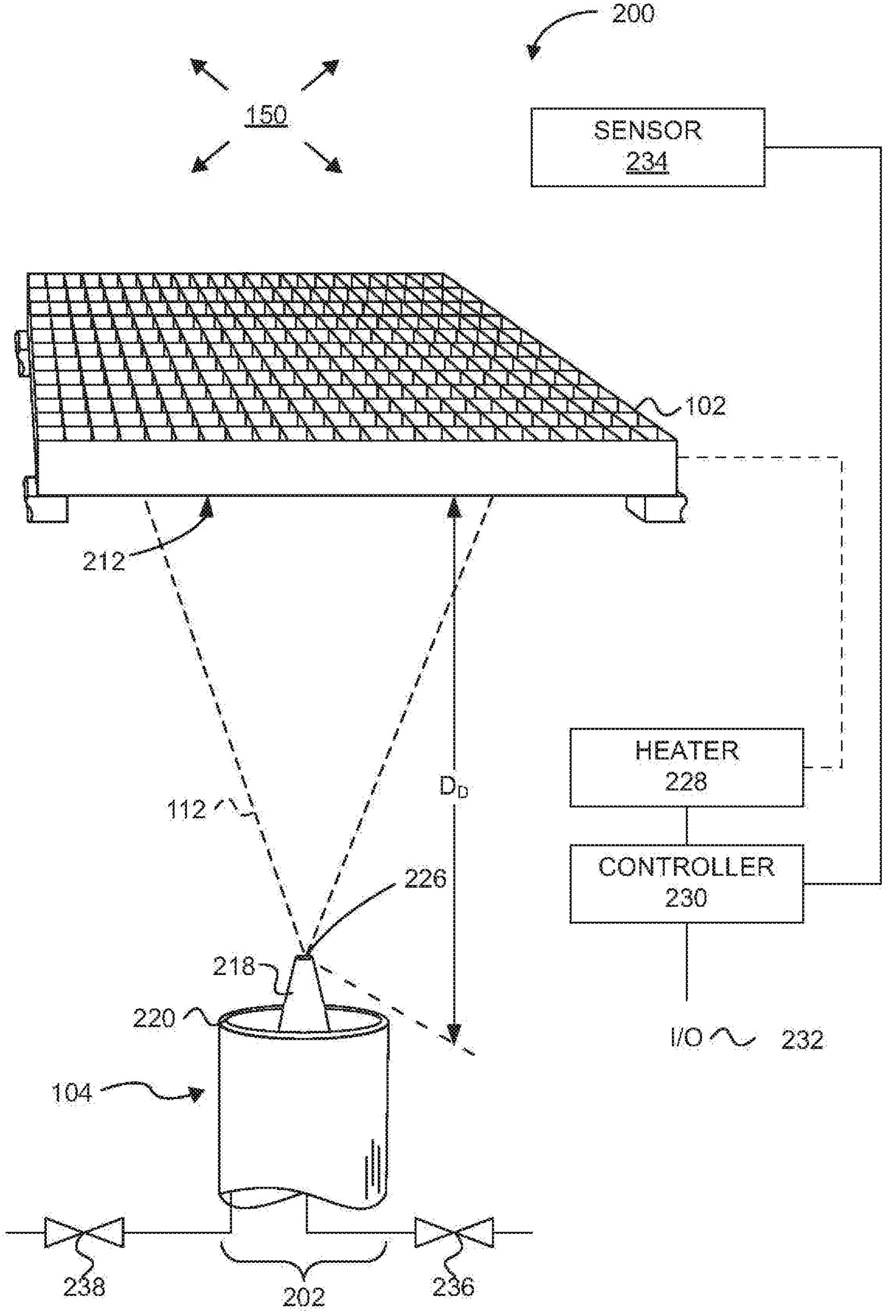

200
150
SENSOR
234
102
212
HEATER
228
CONTROLLER
230
D_D
112
226
218
220
104
I/O
232
238
202
236

FIG. 2C

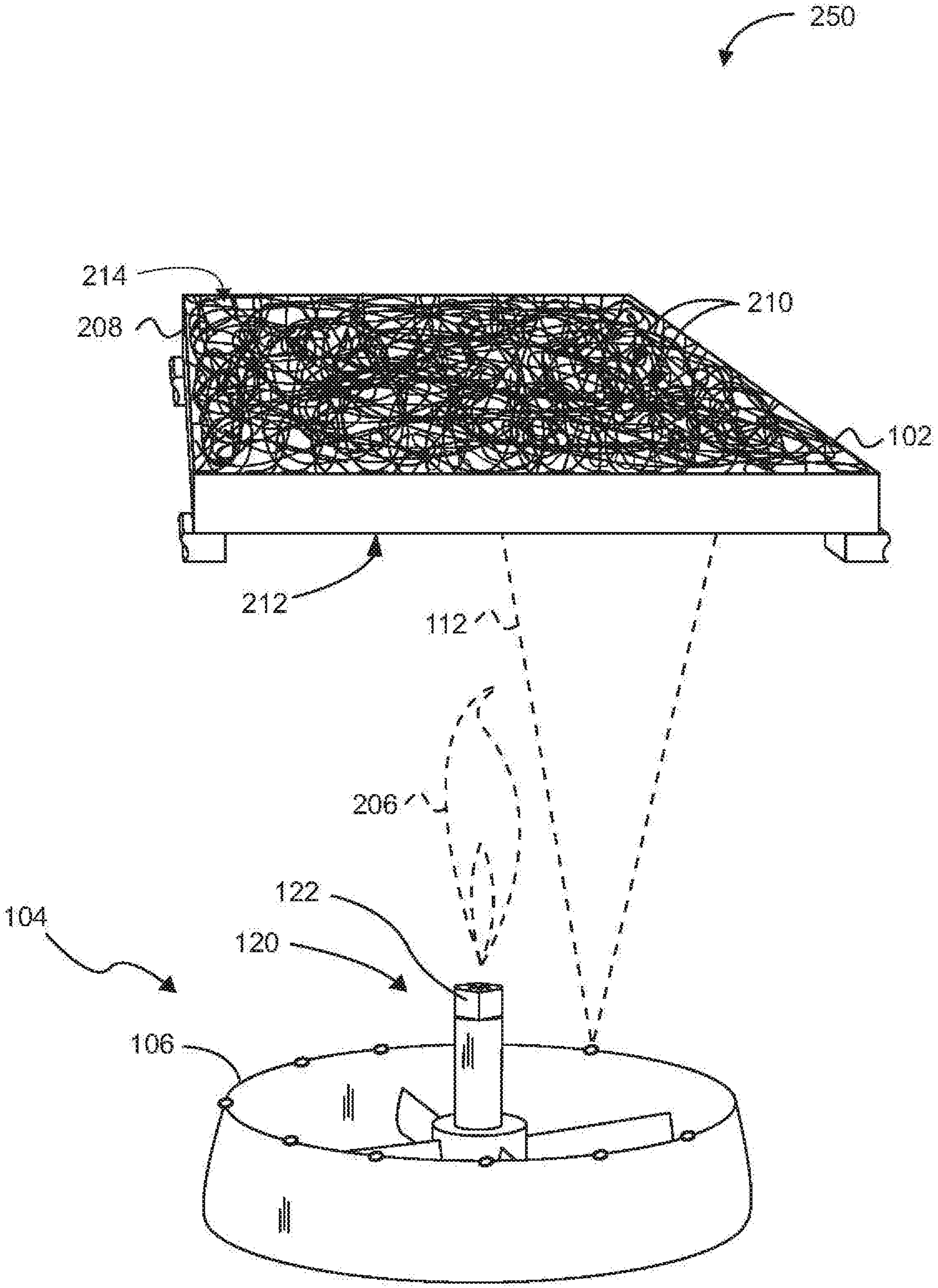
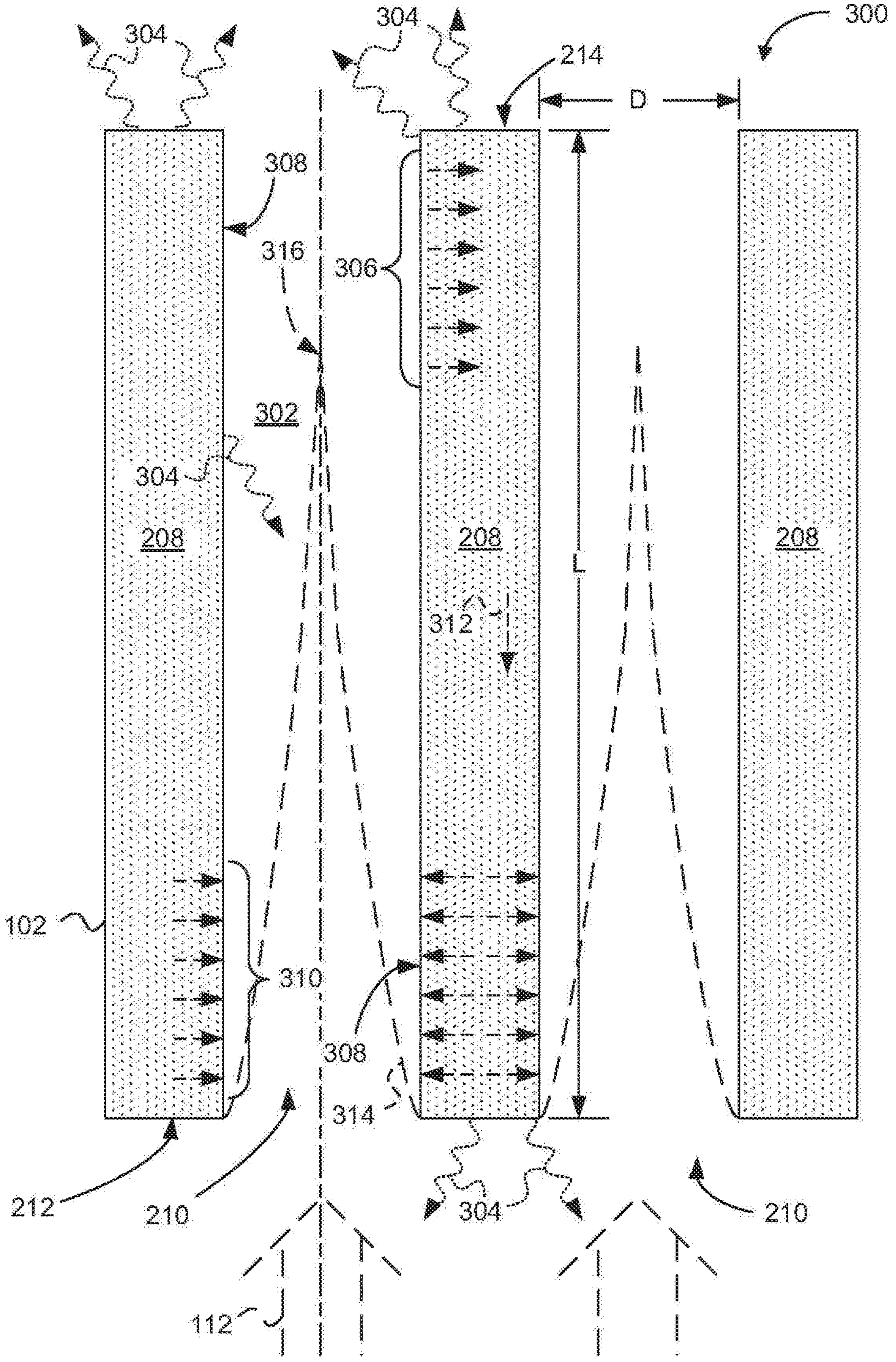


FIG. 3A



304
304
300
214
D
308
316
306
302
304
208
208
208
L
312
102
310
308
314
212
210
304
210
112

FIG. 3B

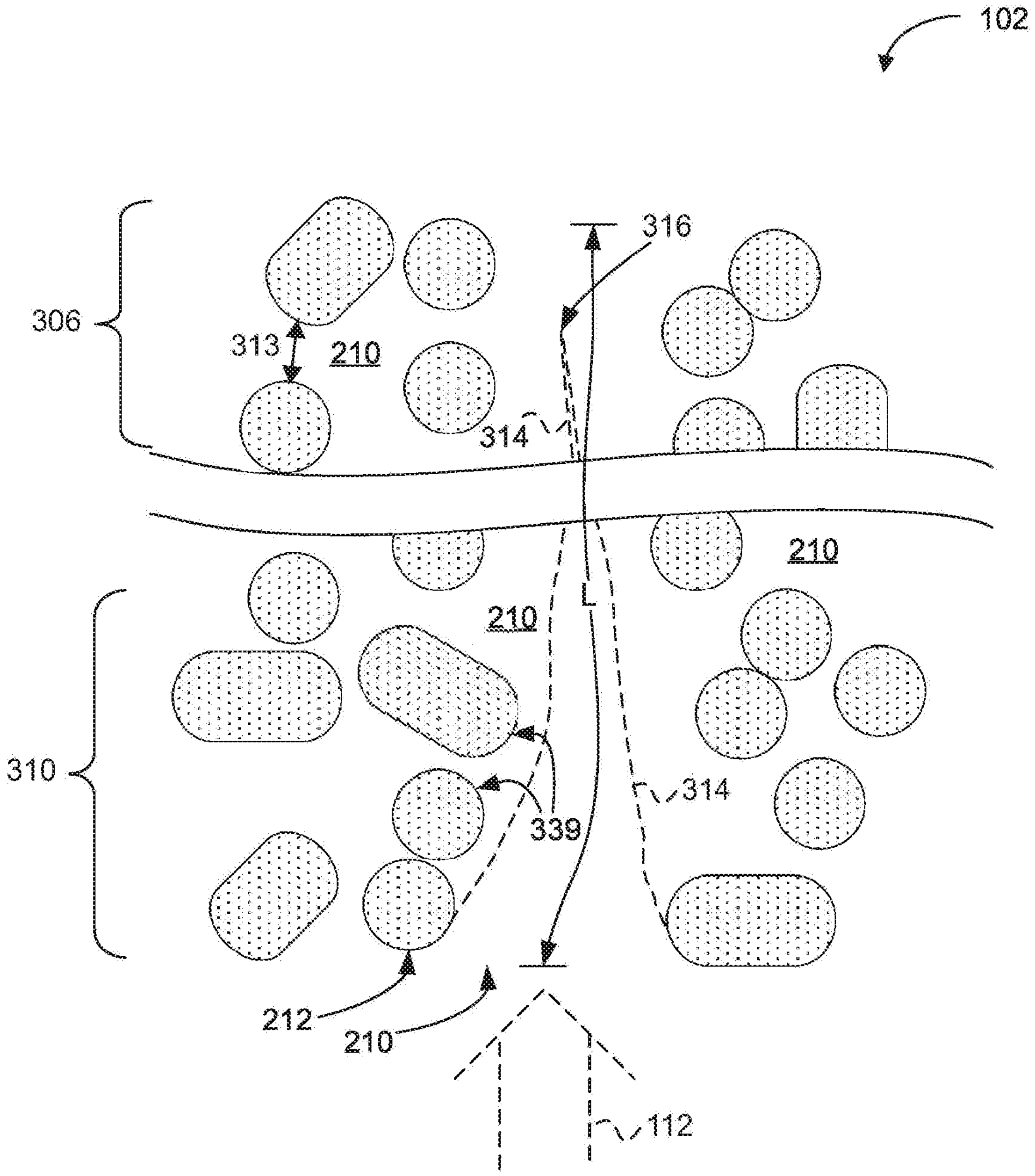


FIG. 4

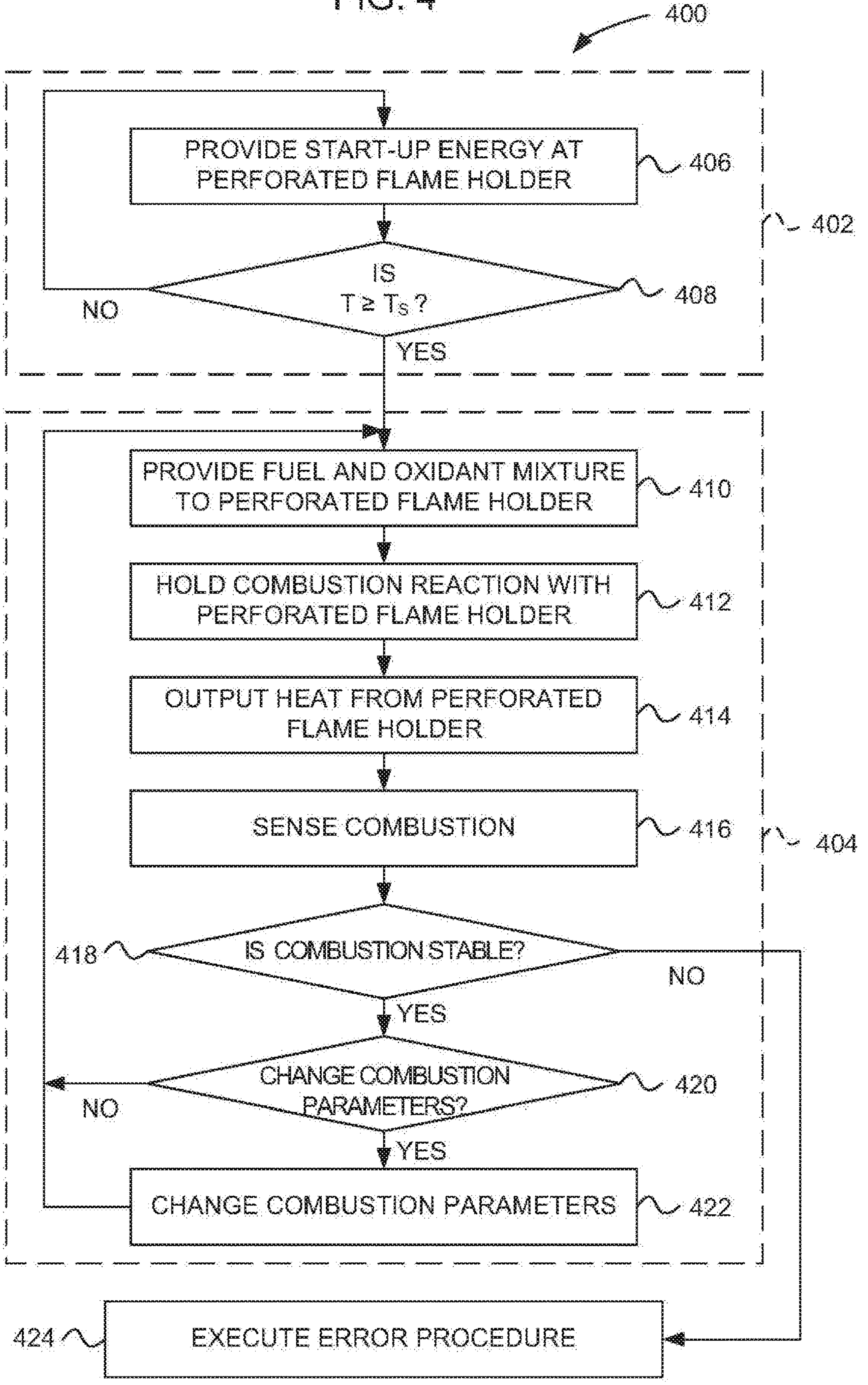

400
PROVIDE START-UP ENERGY AT PERFORATED FLAME HOLDER
406
402
IS T ≥ T_S ?
408
NO
YES
PROVIDE FUEL AND OXIDANT MIXTURE TO PERFORATED FLAME HOLDER
410
HOLD COMBUSTION REACTION WITH PERFORATED FLAME HOLDER
412
OUTPUT HEAT FROM PERFORATED FLAME HOLDER
414
SENSE COMBUSTION
416
404
418
IS COMBUSTION STABLE?
NO
YES
CHANGE COMBUSTION PARAMETERS?
420
NO
YES
CHANGE COMBUSTION PARAMETERS
422
424
EXECUTE ERROR PROCEDURE

FIG. 5A

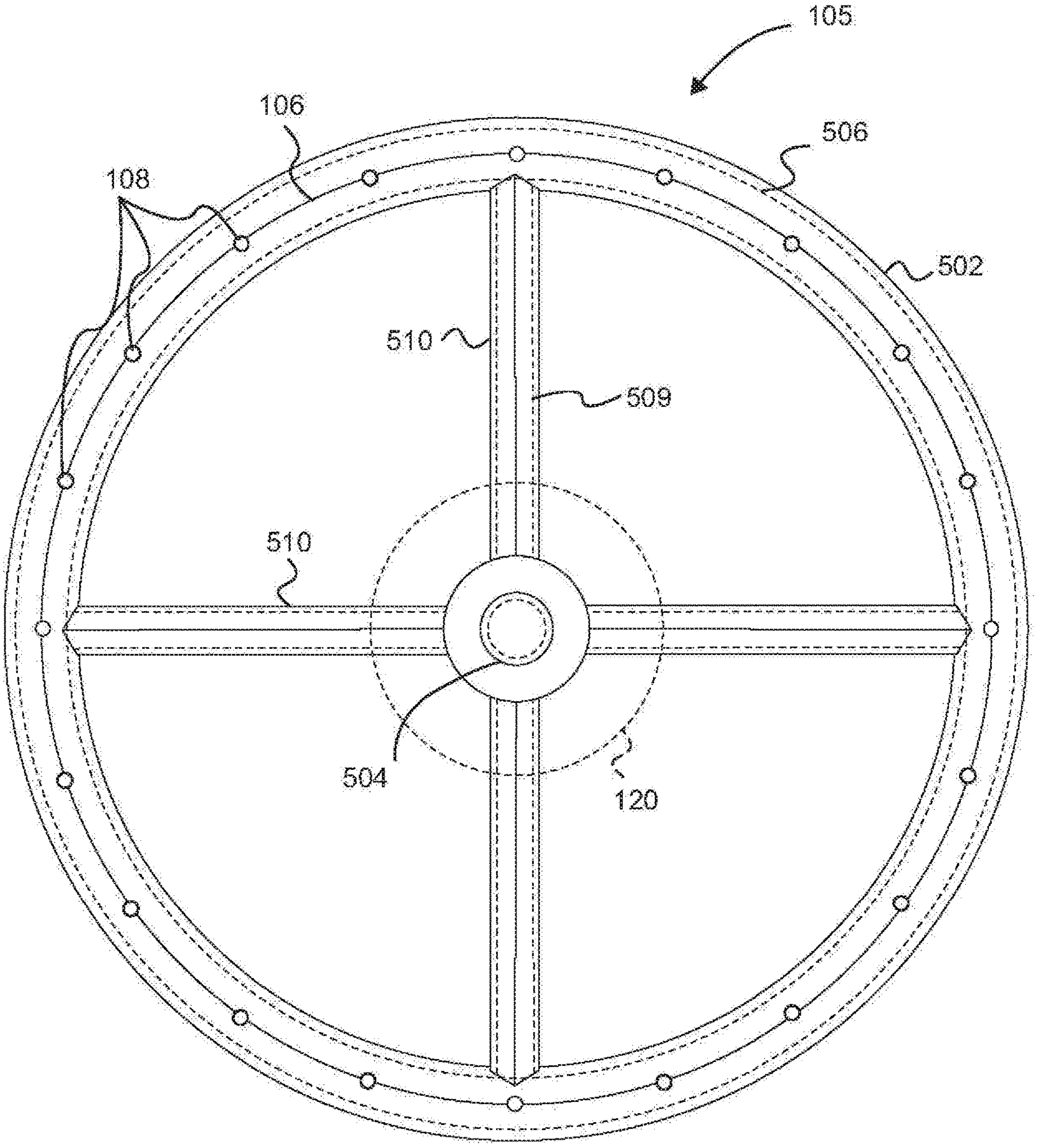
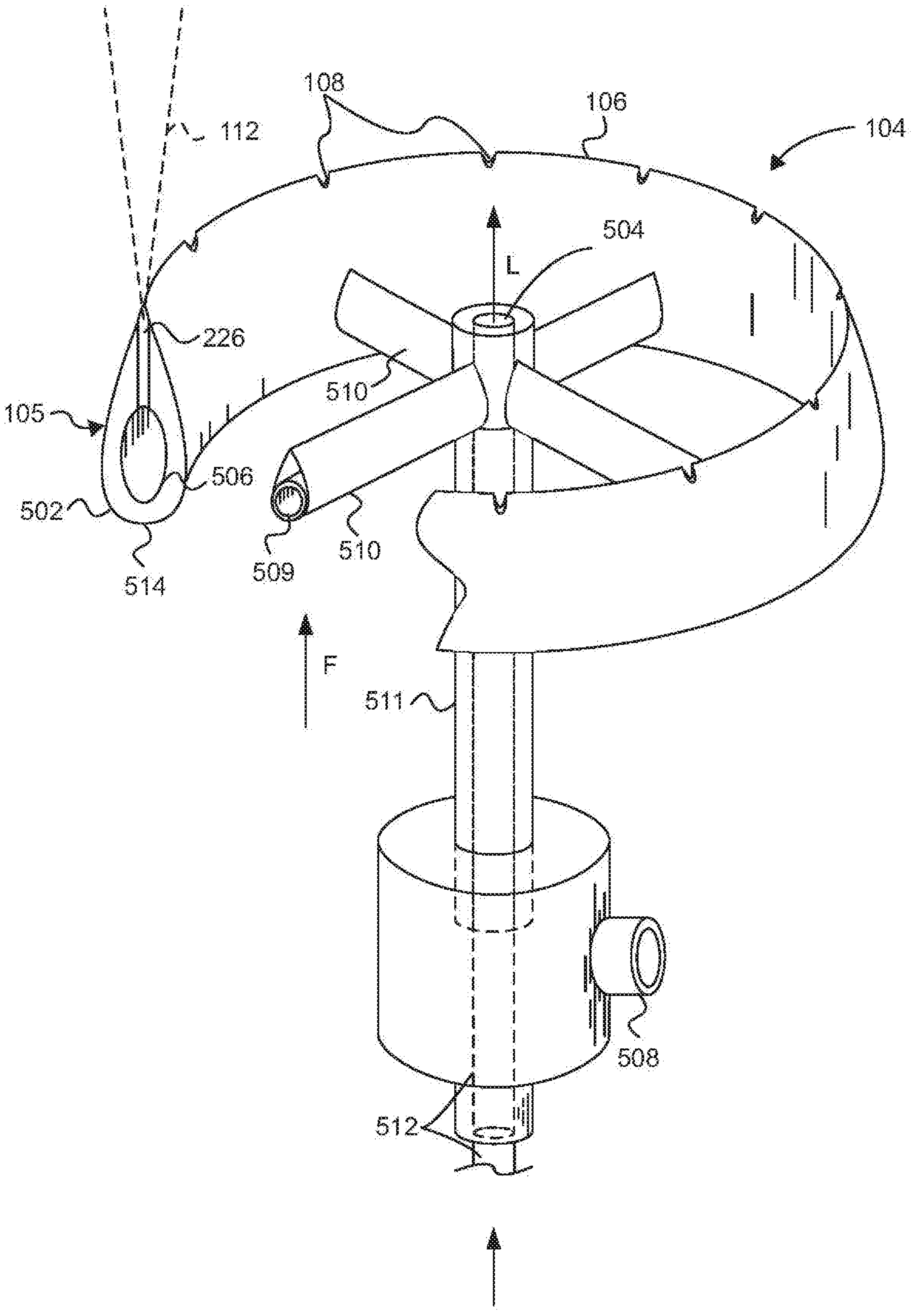


FIG. 5B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106
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504
L
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105
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502
510
509
514
F
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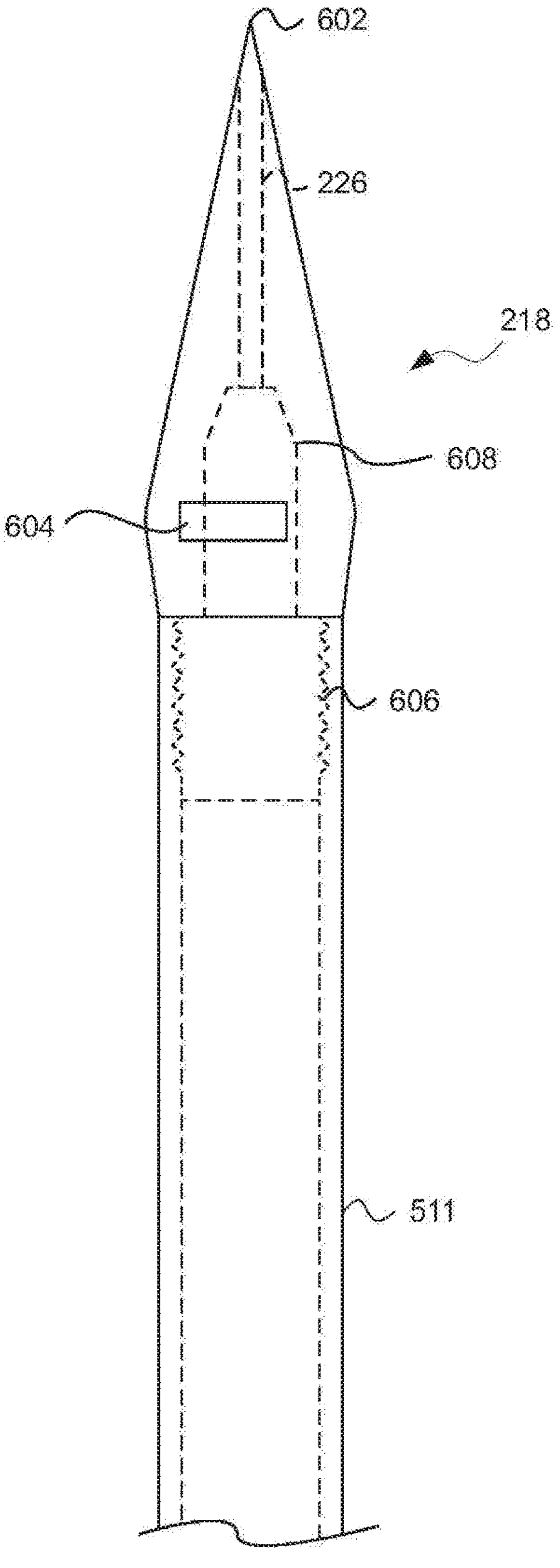
508
512

FIG. 6A



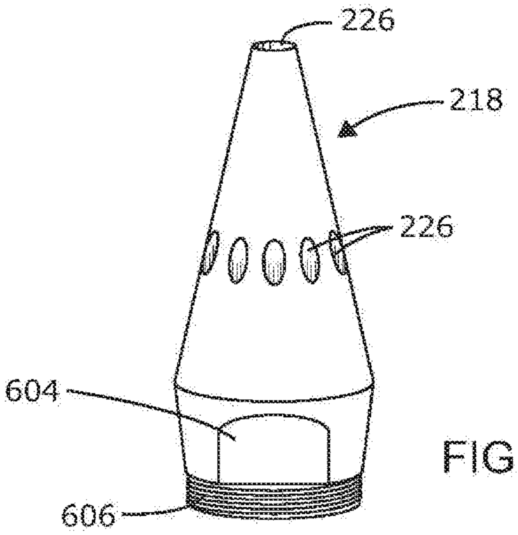


FIG. 6B

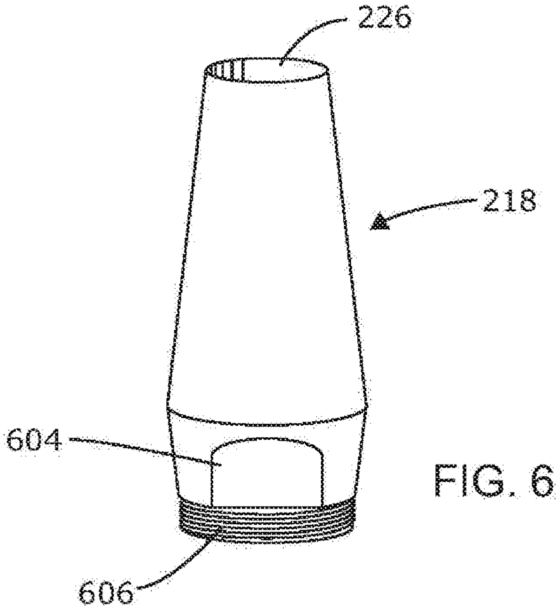


FIG. 6C

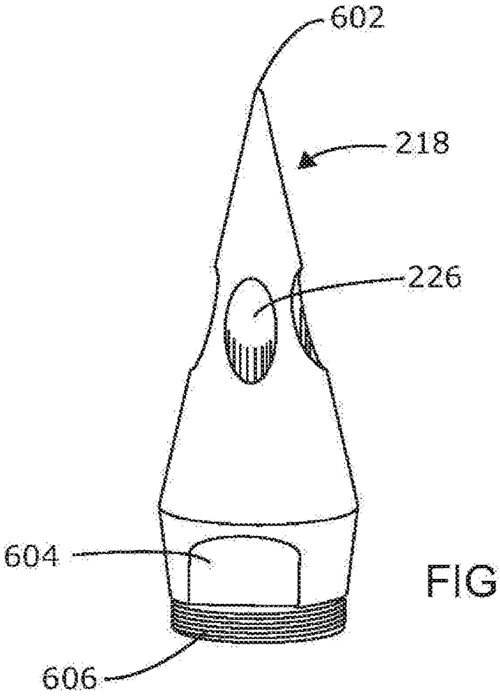


FIG. 6D

FIG. 6E

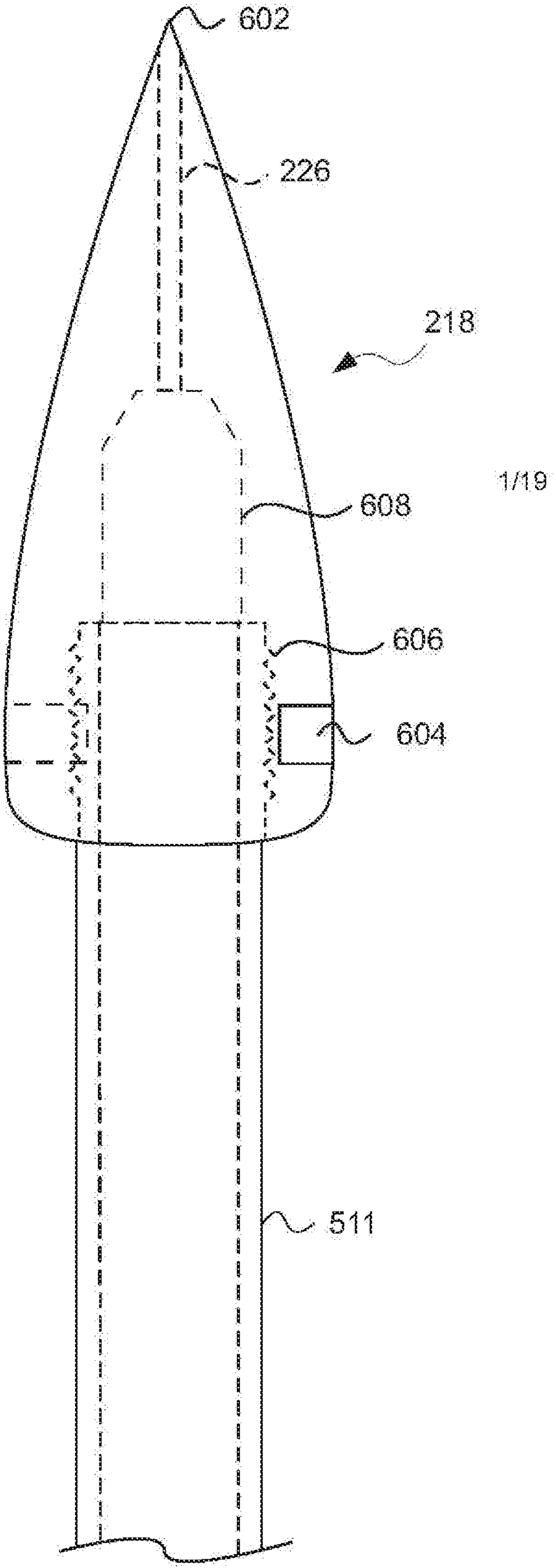


FIG. 7

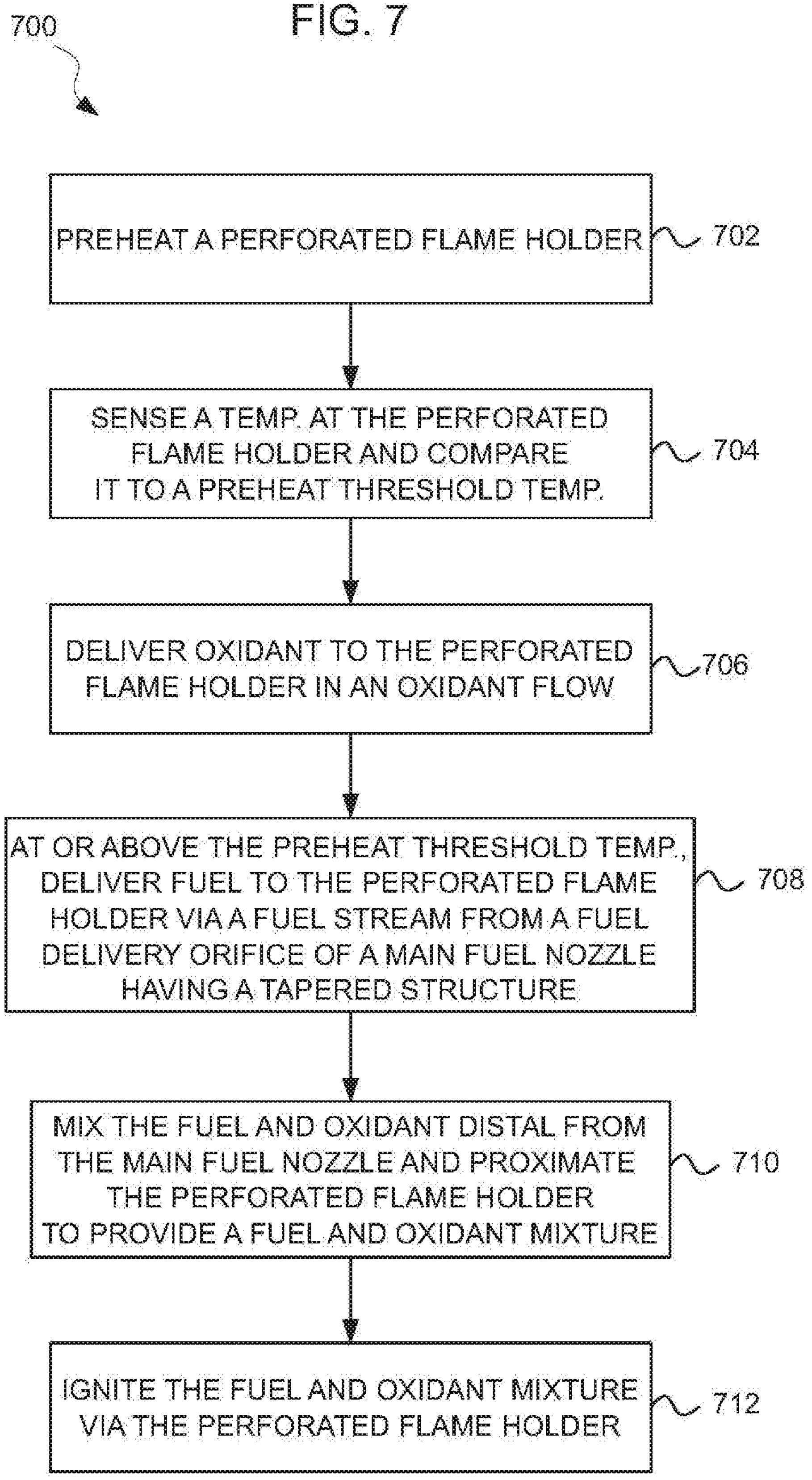

700
PREHEAT A PERFORATED FLAME HOLDER
702
SENSE A TEMP. AT THE PERFORATED FLAME HOLDER AND COMPARE IT TO A PREHEAT THRESHOLD TEMP.
704
DELIVER OXIDANT TO THE PERFORATED FLAME HOLDER IN AN OXIDANT FLOW
706
AT OR ABOVE THE PREHEAT THRESHOLD TEMP., DELIVER FUEL TO THE PERFORATED FLAME HOLDER VIA A FUEL STREAM FROM A FUEL DELIVERY ORIFICE OF A MAIN FUEL NOZZLE HAVING A TAPERED STRUCTURE
708
MIX THE FUEL AND OXIDANT DISTAL FROM THE MAIN FUEL NOZZLE AND PROXIMATE THE PERFORATED FLAME HOLDER TO PROVIDE A FUEL AND OXIDANT MIXTURE
710
IGNITE THE FUEL AND OXIDANT MIXTURE VIA THE PERFORATED FLAME HOLDER
712

FIG. 8

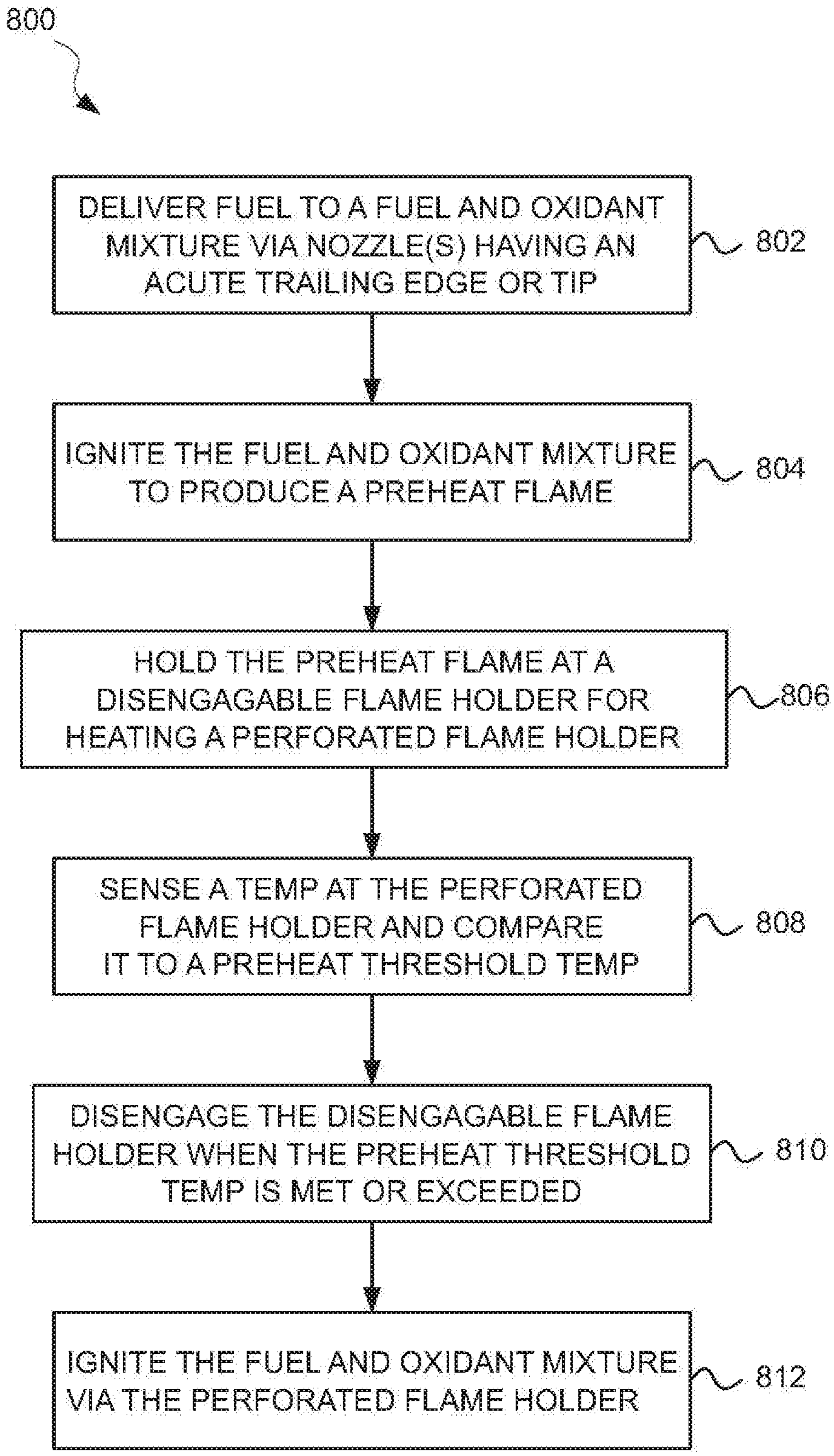

800
DELIVER FUEL TO A FUEL AND OXIDANT MIXTURE VIA NOZZLE(S) HAVING AN ACUTE TRAILING EDGE OR TIP
802
IGNITE THE FUEL AND OXIDANT MIXTURE TO PRODUCE A PREHEAT FLAME
804
HOLD THE PREHEAT FLAME AT A DISENGAGABLE FLAME HOLDER FOR HEATING A PERFORATED FLAME HOLDER
806
SENSE A TEMP AT THE PERFORATED FLAME HOLDER AND COMPARE IT TO A PREHEAT THRESHOLD TEMP
808
DISENGAGE THE DISENGAGABLE FLAME HOLDER WHEN THE PREHEAT THRESHOLD TEMP IS MET OR EXCEEDED
810
IGNITE THE FUEL AND OXIDANT MIXTURE VIA THE PERFORATED FLAME HOLDER
812

FIG. 9

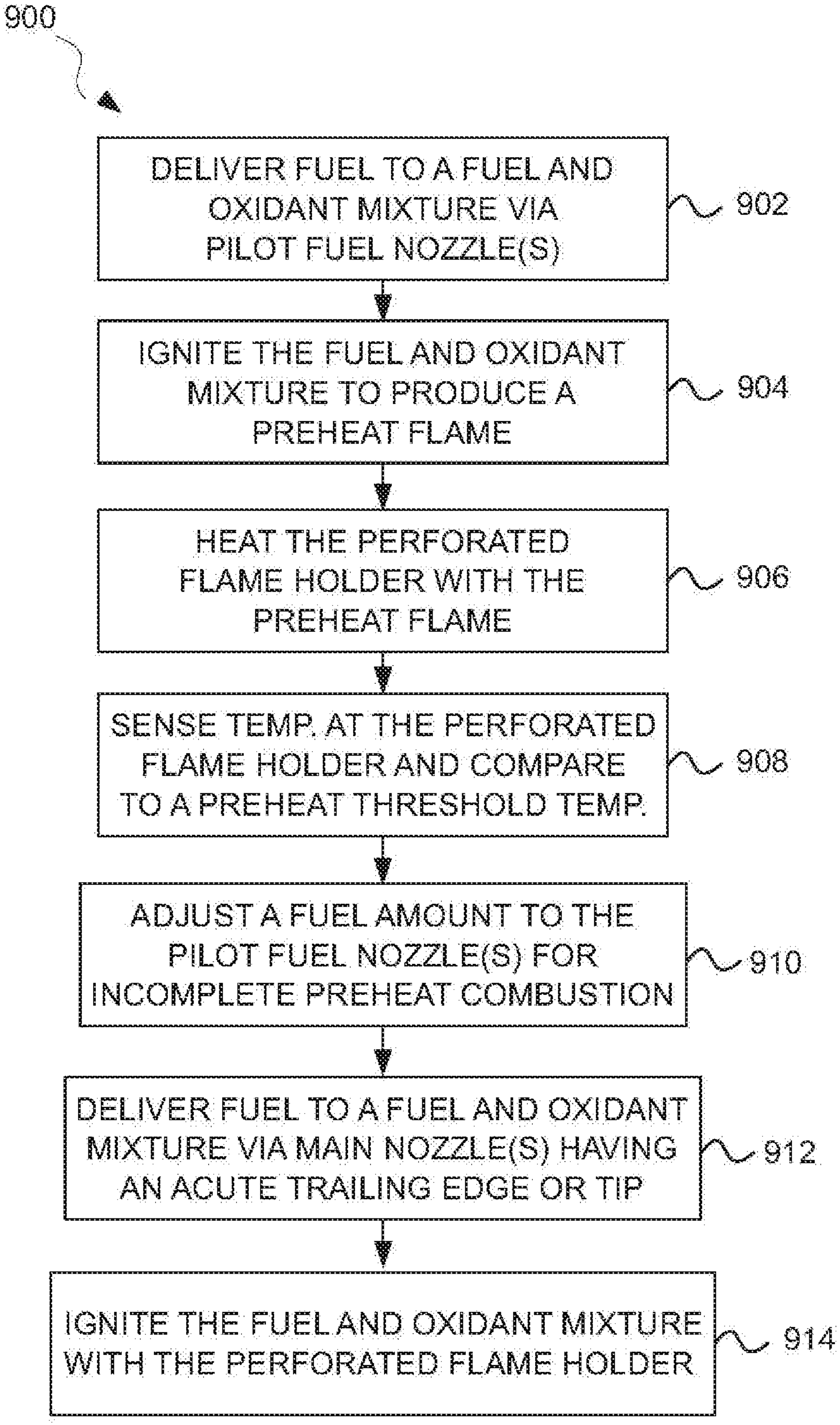

900
DELIVER FUEL TO A FUEL AND OXIDANT MIXTURE VIA PILOT FUEL NOZZLE(S)
902
IGNITE THE FUEL AND OXIDANT MIXTURE TO PRODUCE A PREHEAT FLAME
904
HEAT THE PERFORATED FLAME HOLDER WITH THE PREHEAT FLAME
906
SENSE TEMP. AT THE PERFORATED FLAME HOLDER AND COMPARE TO A PREHEAT THRESHOLD TEMP.
908
ADJUST A FUEL AMOUNT TO THE PILOT FUEL NOZZLE(S) FOR INCOMPLETE PREHEAT COMBUSTION
910
DELIVER FUEL TO A FUEL AND OXIDANT MIXTURE VIA MAIN NOZZLE(S) HAVING AN ACUTE TRAILING EDGE OR TIP
912
IGNITE THE FUEL AND OXIDANT MIXTURE WITH THE PERFORATED FLAME HOLDER
914

FIG.10A

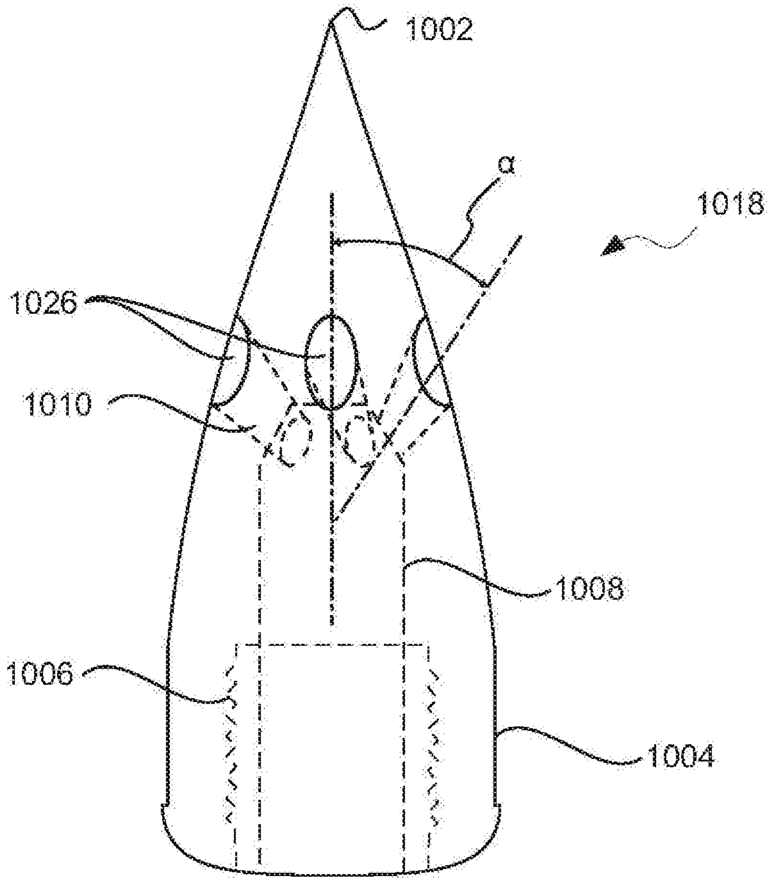


FIG. 10B

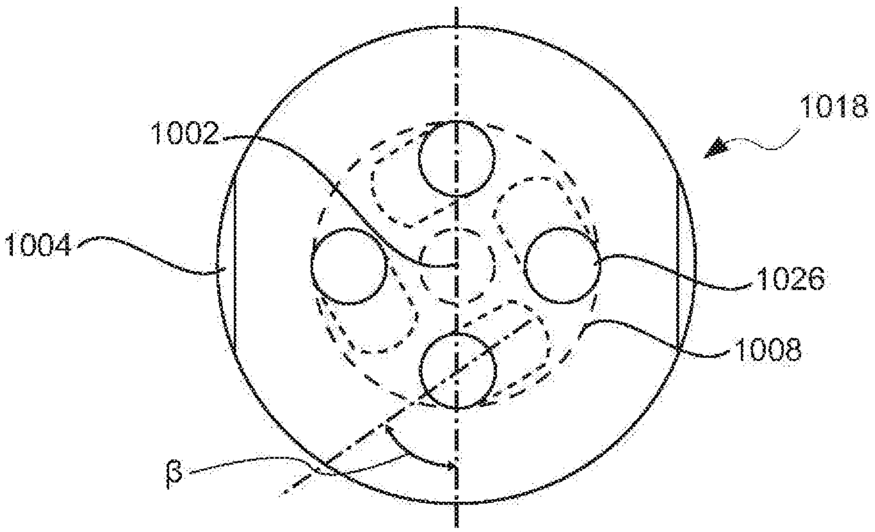


FIG. 11A

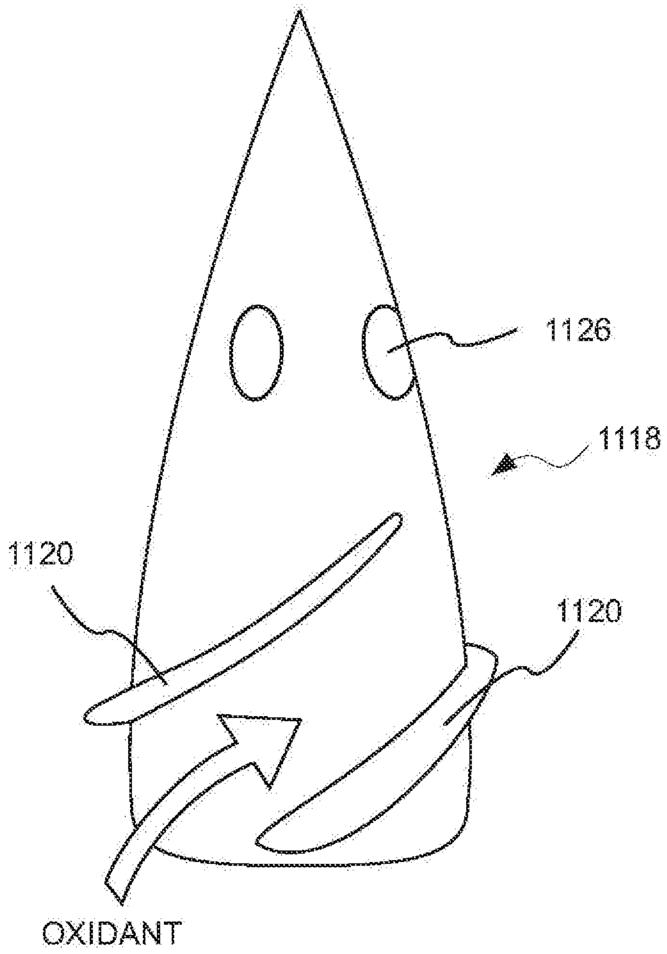


FIG. 11B

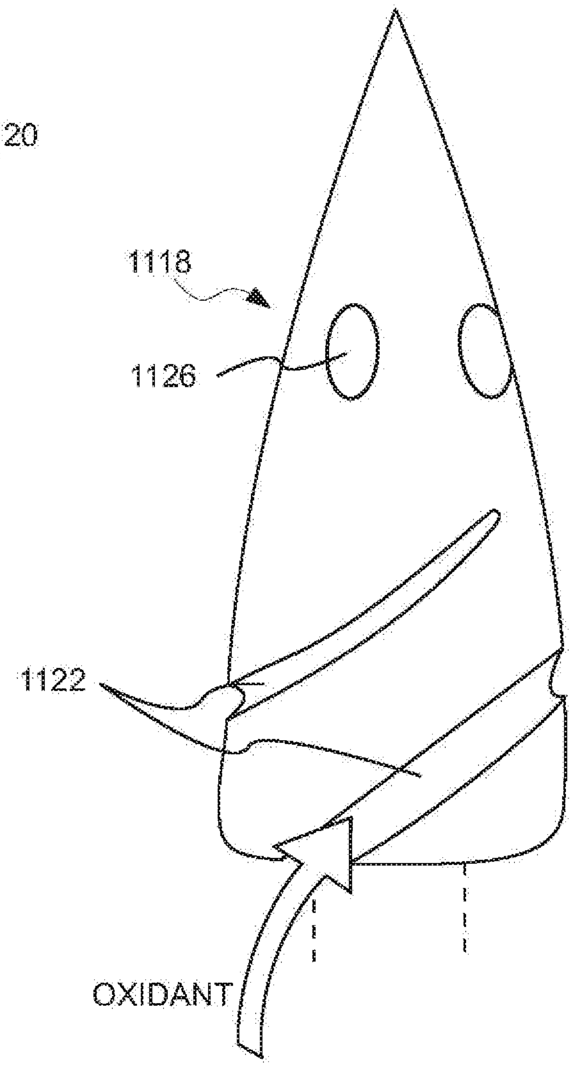


FIG.12

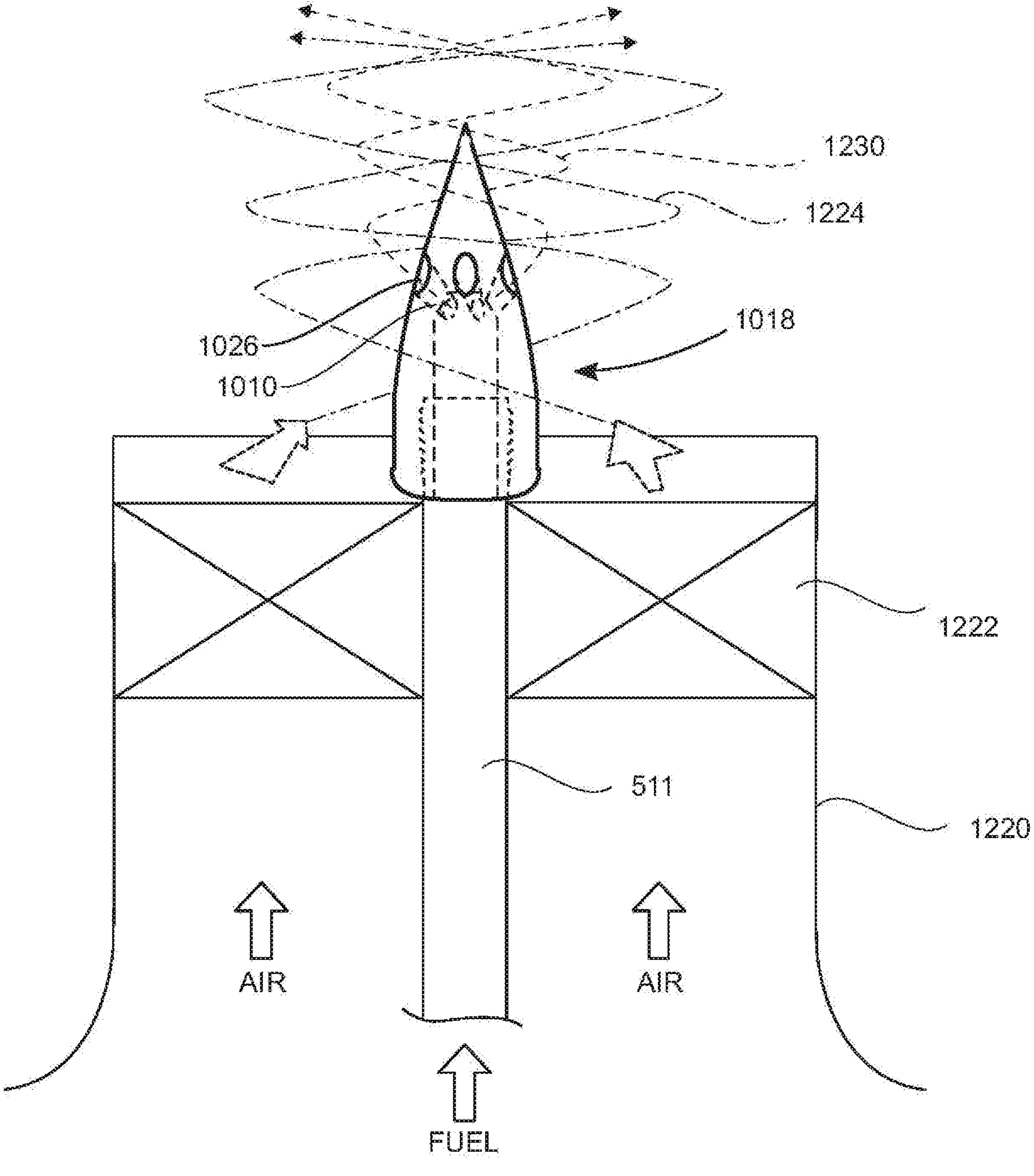


FIG. 13

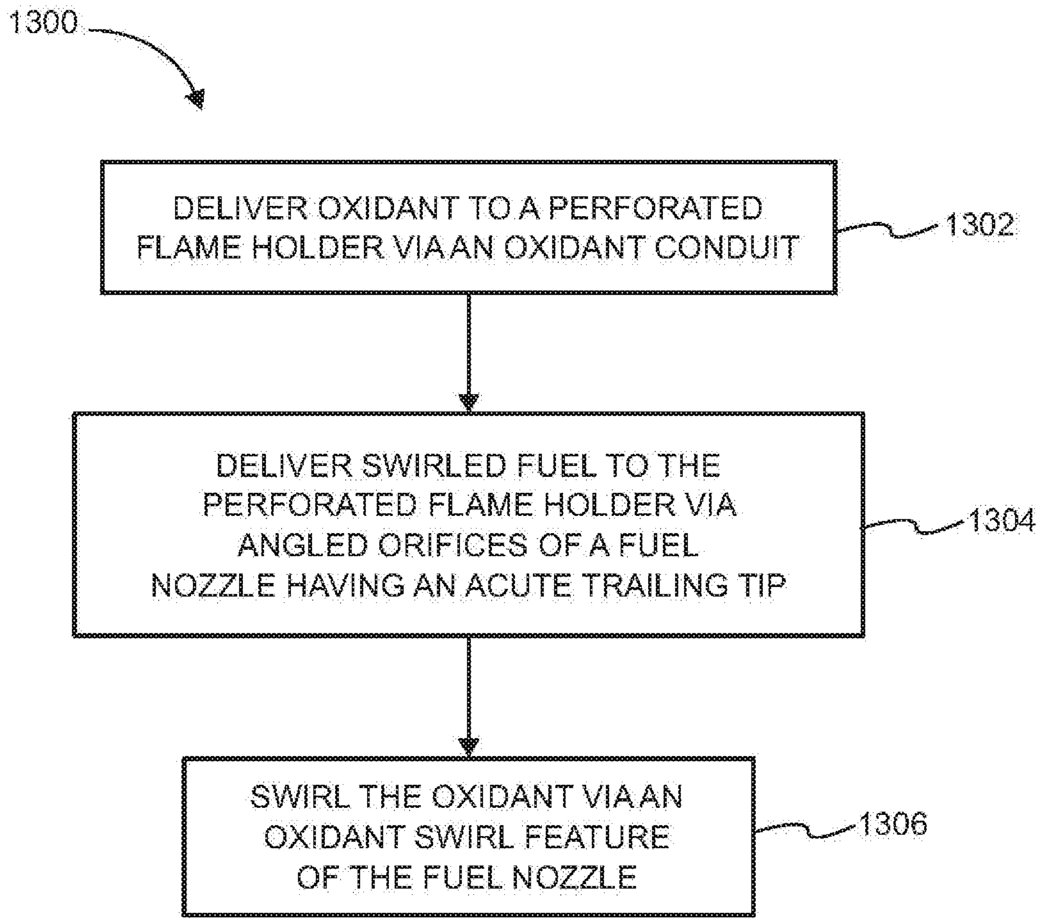

1300
DELIVER OXIDANT TO A PERFORATED FLAME HOLDER VIA AN OXIDANT CONDUIT
1302
DELIVER SWIRLED FUEL TO THE PERFORATED FLAME HOLDER VIA ANGLED ORIFICES OF A FUEL NOZZLE HAVING AN ACUTE TRAILING TIP
1304
SWIRL THE OXIDANT VIA AN OXIDANT SWIRL FEATURE OF THE FUEL NOZZLE
1306

FIG.14

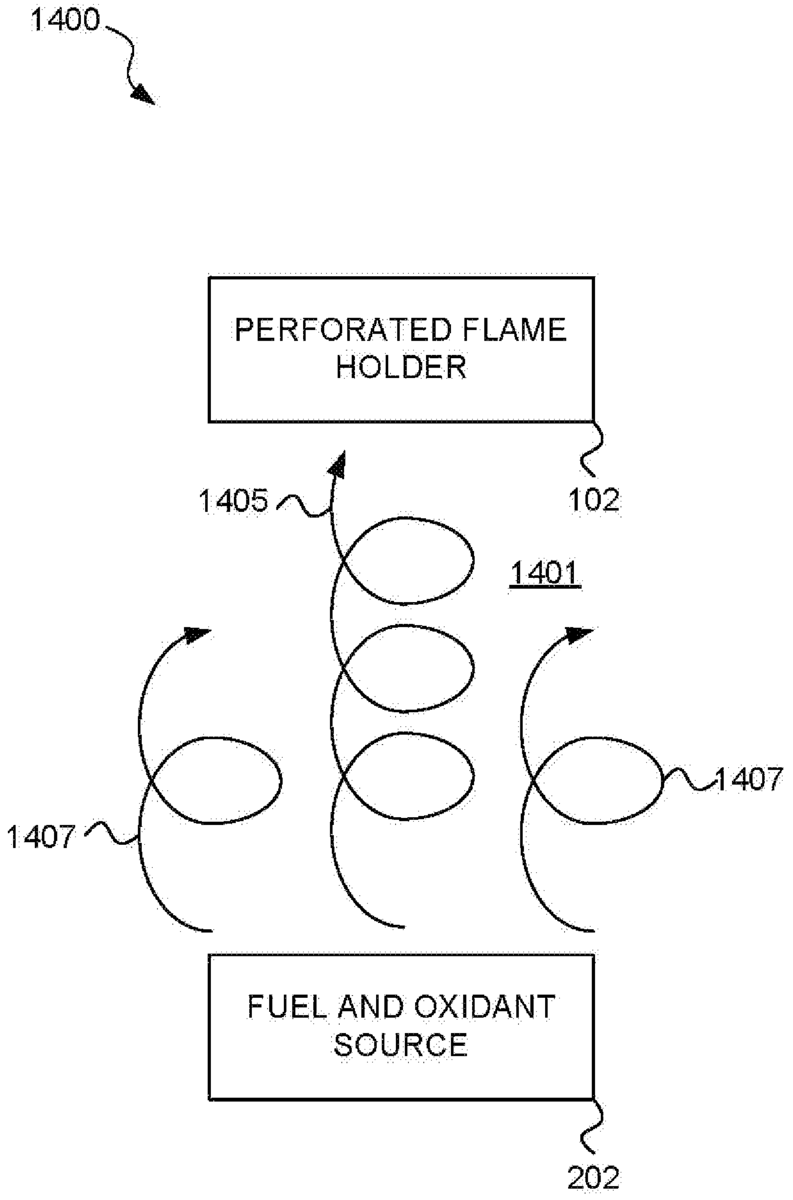

1400
PERFORATED FLAME HOLDER
102
1405
1401
1407
1407
FUEL AND OXIDANT SOURCE
202

FIG. 15

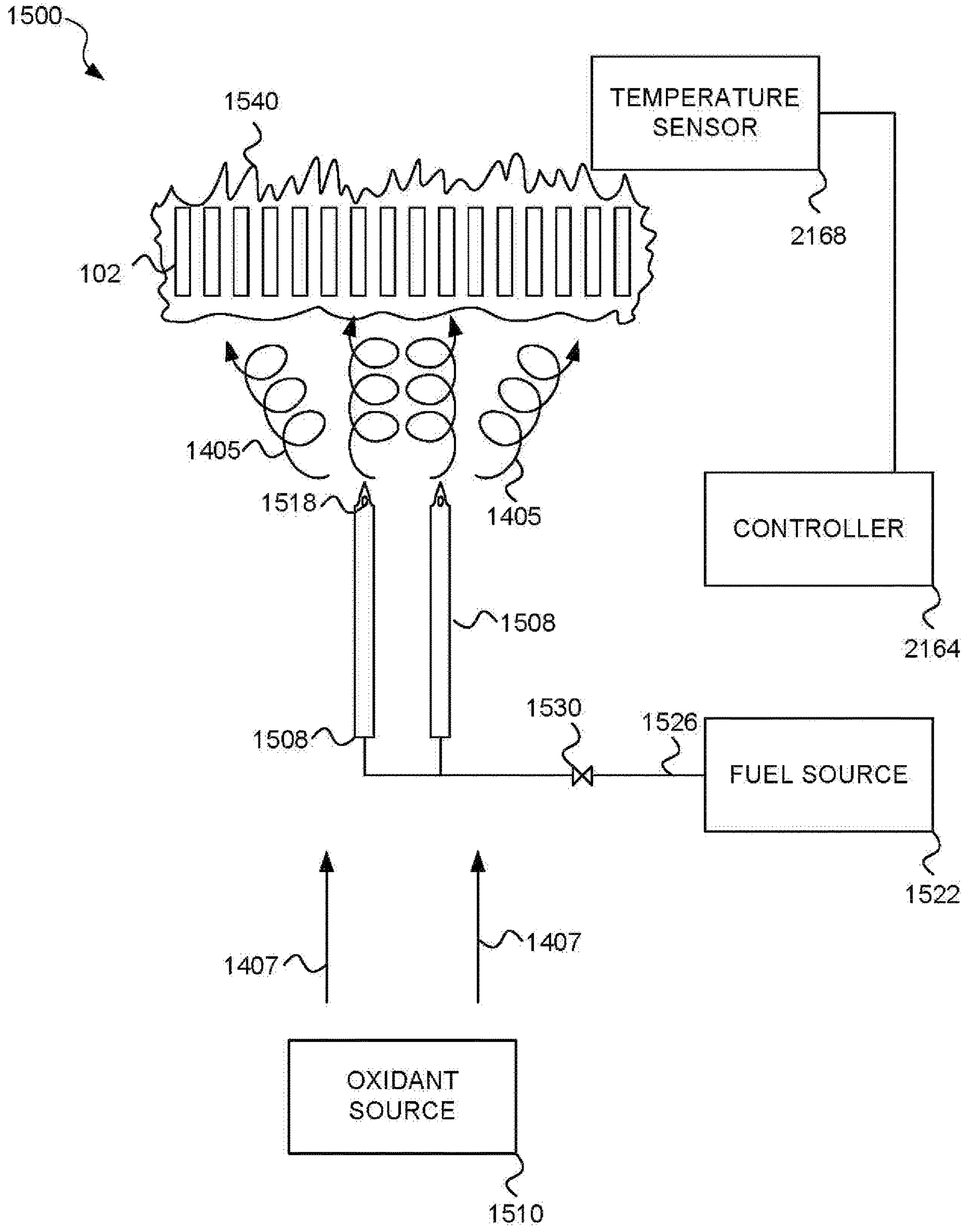

1500
1540
TEMPERATURE SENSOR
2168
102
1405
1518
1405
CONTROLLER
2164
1508
1530
1526
FUEL SOURCE
1508
1522
1407
1407
OXIDANT SOURCE
1510

FIG. 16

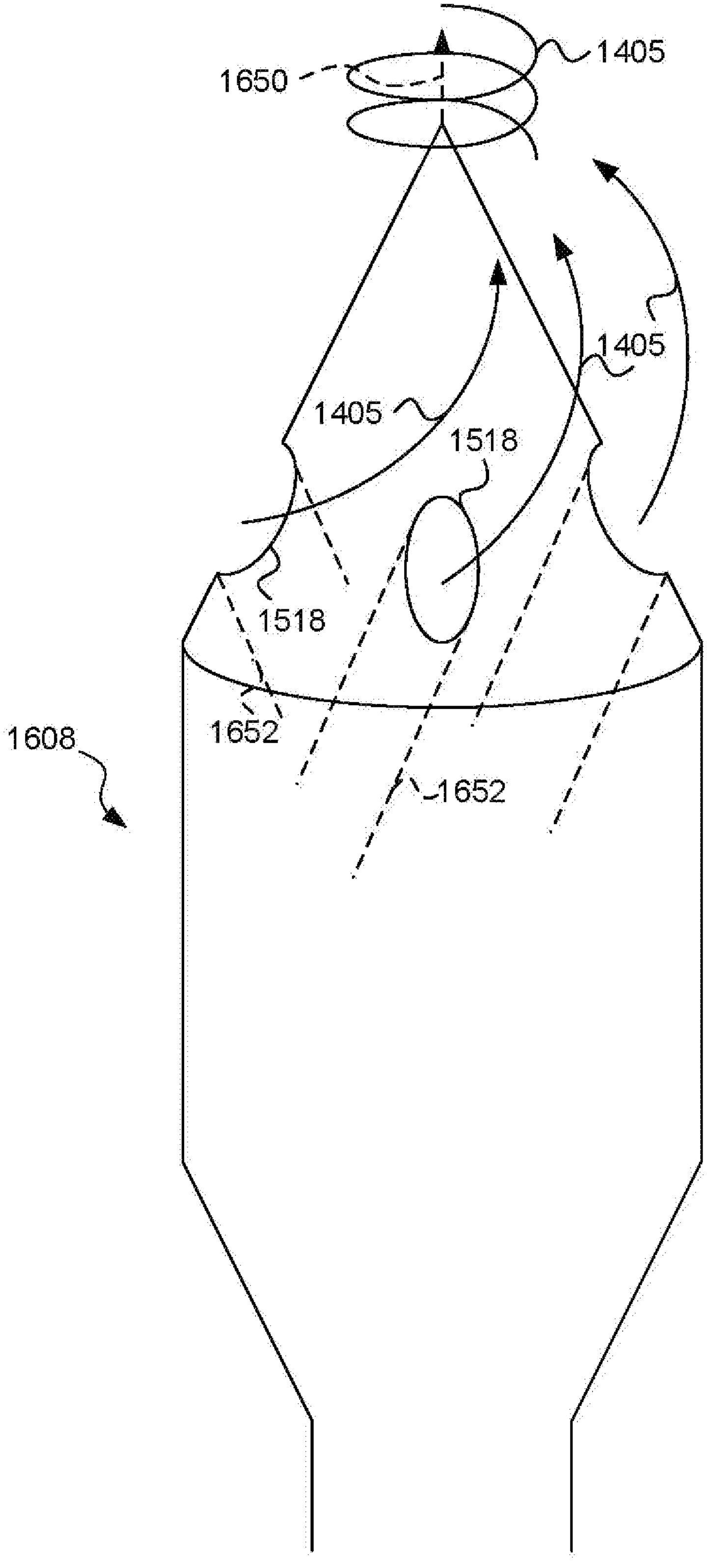


FIG. 17

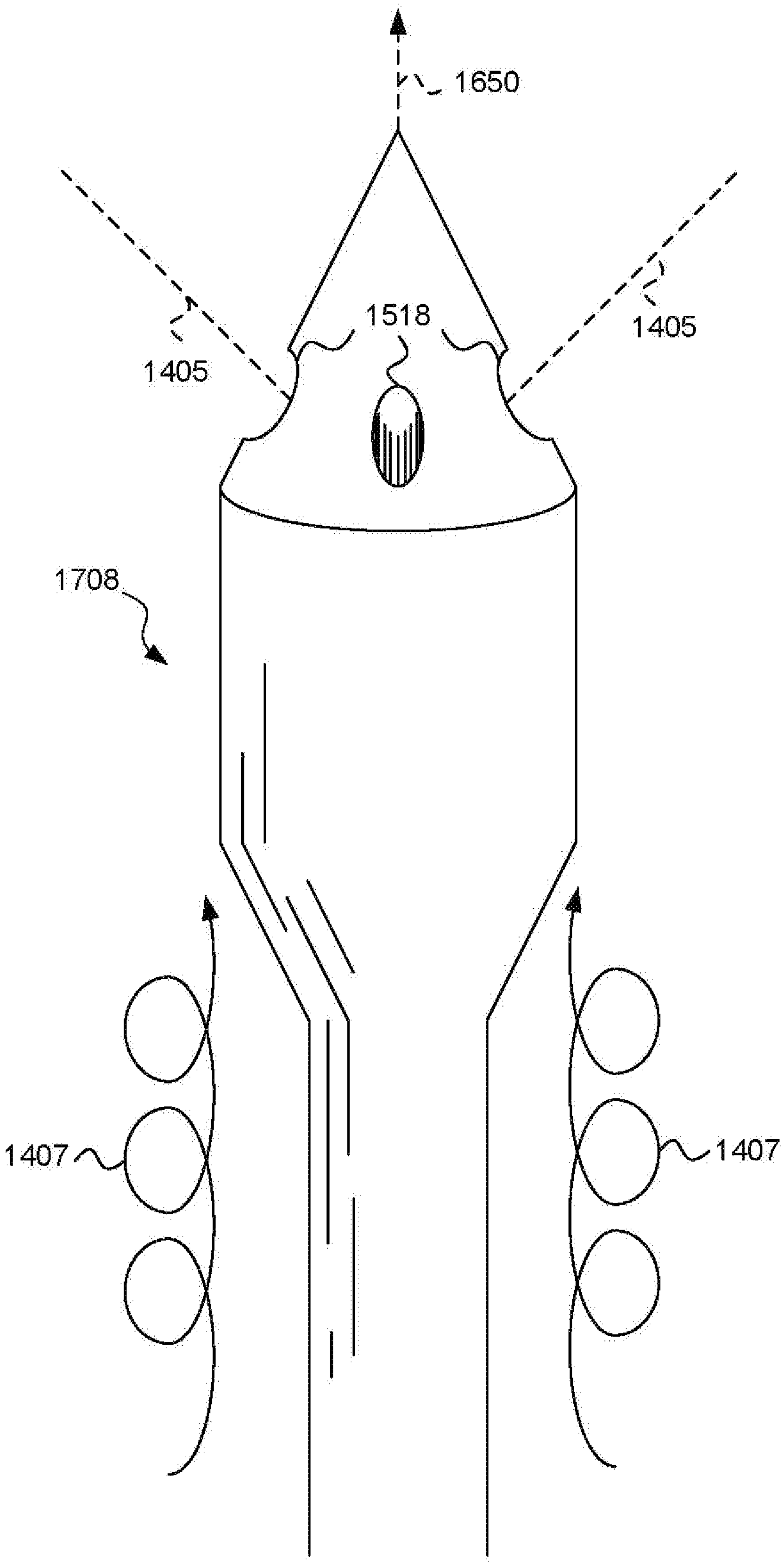


FIG. 18

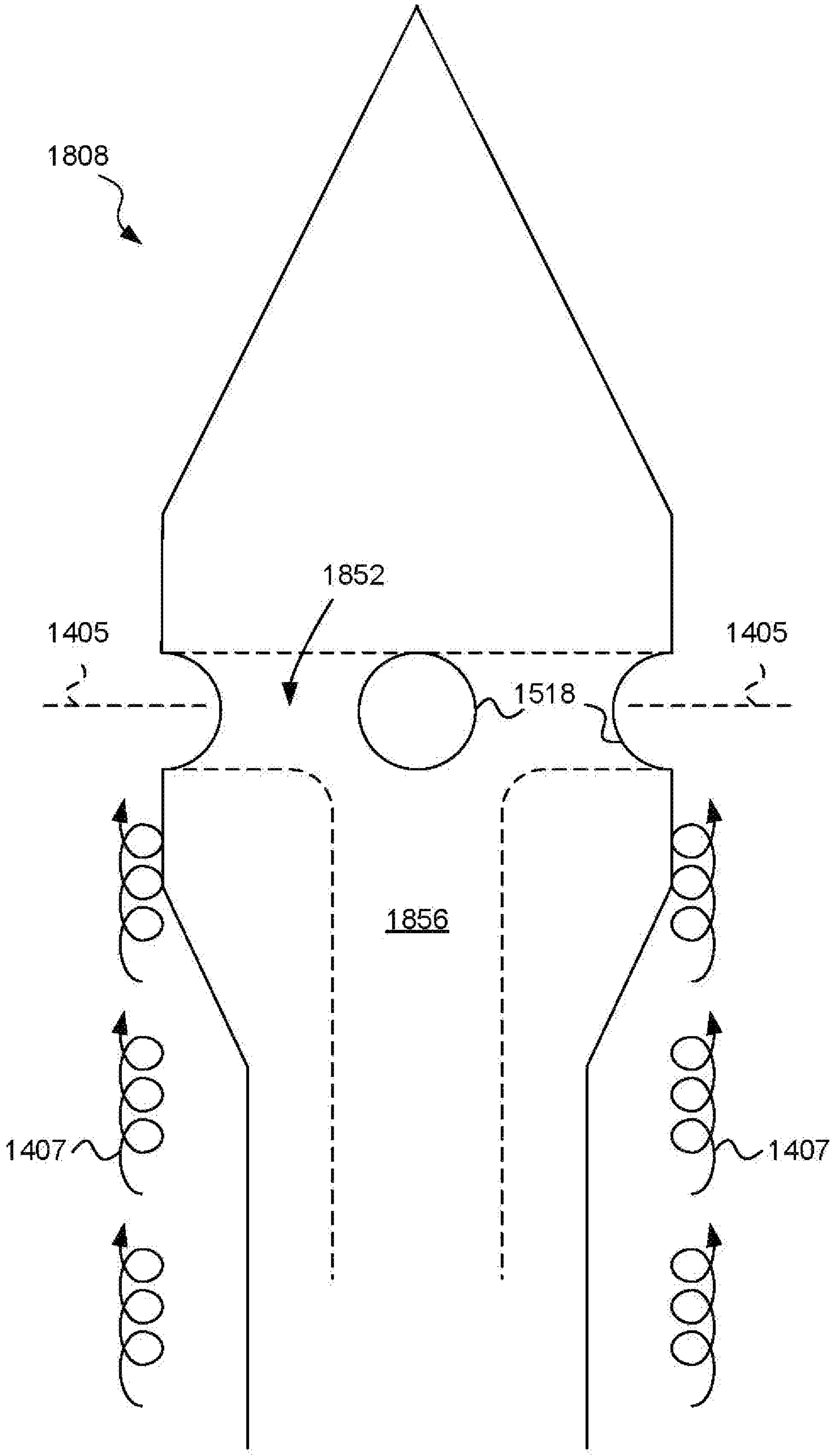


FIG. 19

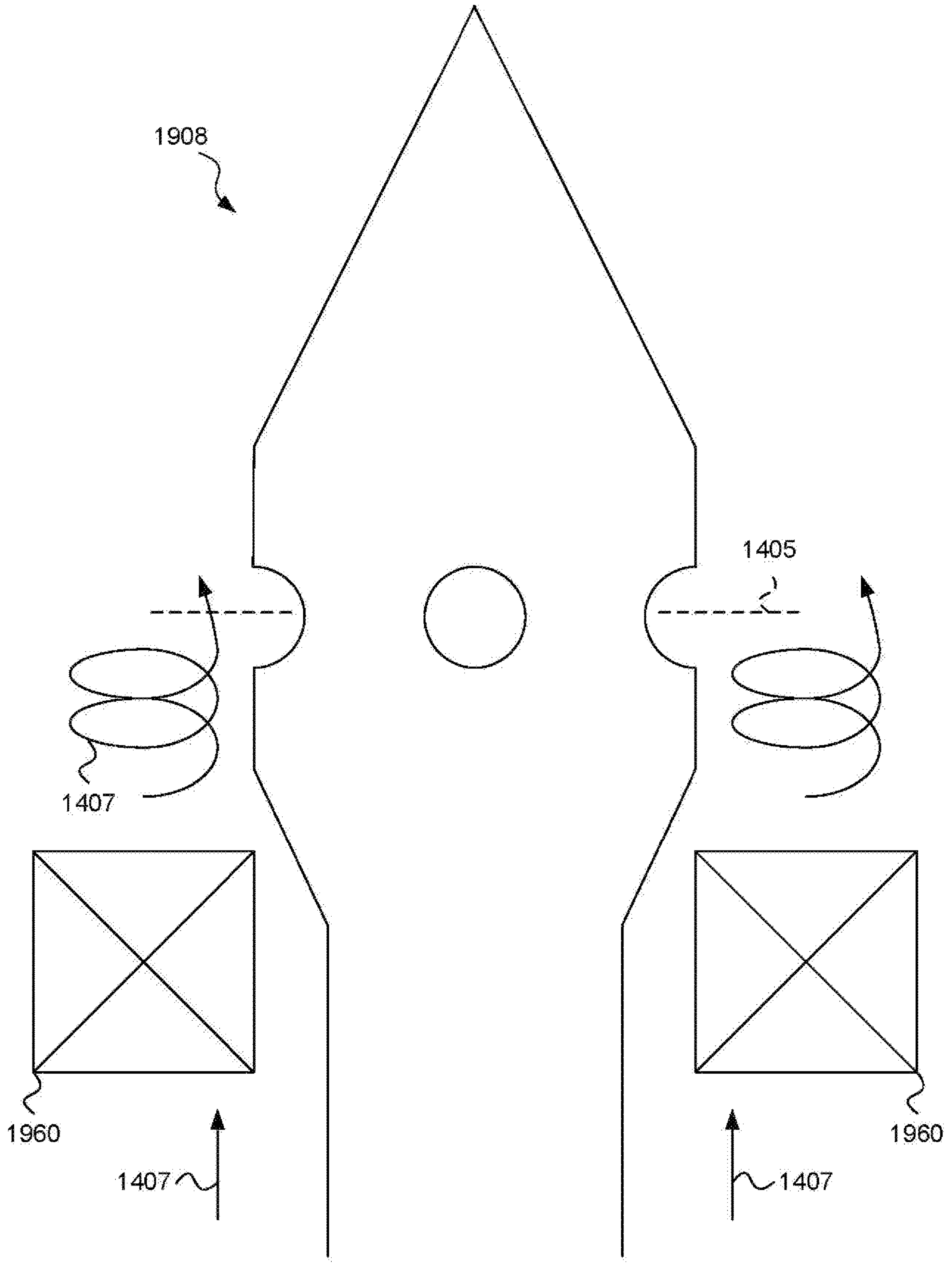
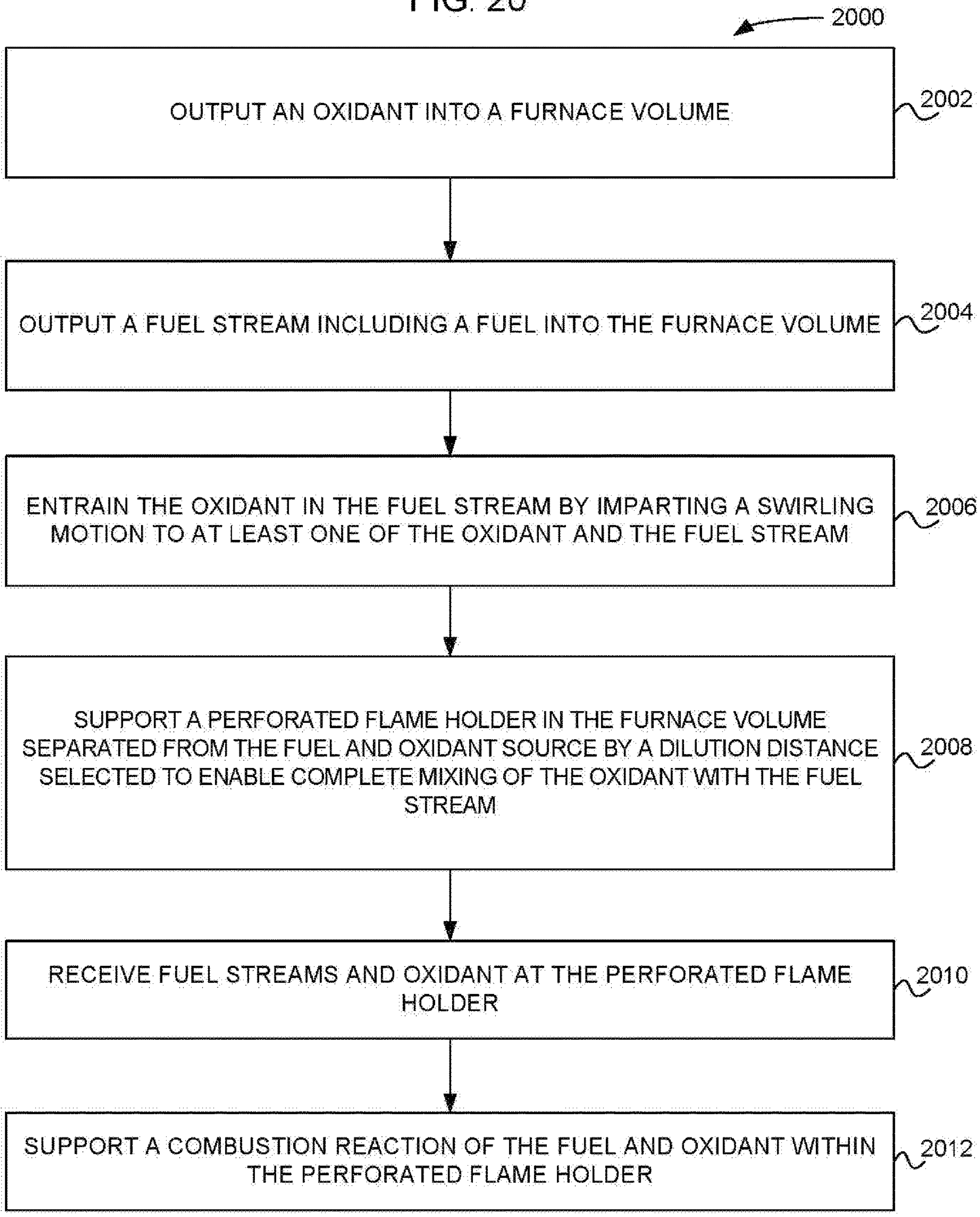


FIG. 20



OUTPUT AN OXIDANT INTO A FURNACE VOLUME

OUTPUT A FUEL STREAM INCLUDING A FUEL INTO THE FURNACE VOLUME

ENTRAIN THE OXIDANT IN THE FUEL STREAM BY IMPARTING A SWIRLING MOTION TO AT LEAST ONE OF THE OXIDANT AND THE FUEL STREAM

SUPPORT A PERFORATED FLAME HOLDER IN THE FURNACE VOLUME SEPARATED FROM THE FUEL AND OXIDANT SOURCE BY A DILUTION DISTANCE SELECTED TO ENABLE COMPLETE MIXING OF THE OXIDANT WITH THE FUEL STREAM

RECEIVE FUEL STREAMS AND OXIDANT AT THE PERFORATED FLAME HOLDER

SUPPORT A COMBUSTION REACTION OF THE FUEL AND OXIDANT WITHIN THE PERFORATED FLAME HOLDER

FIG. 21

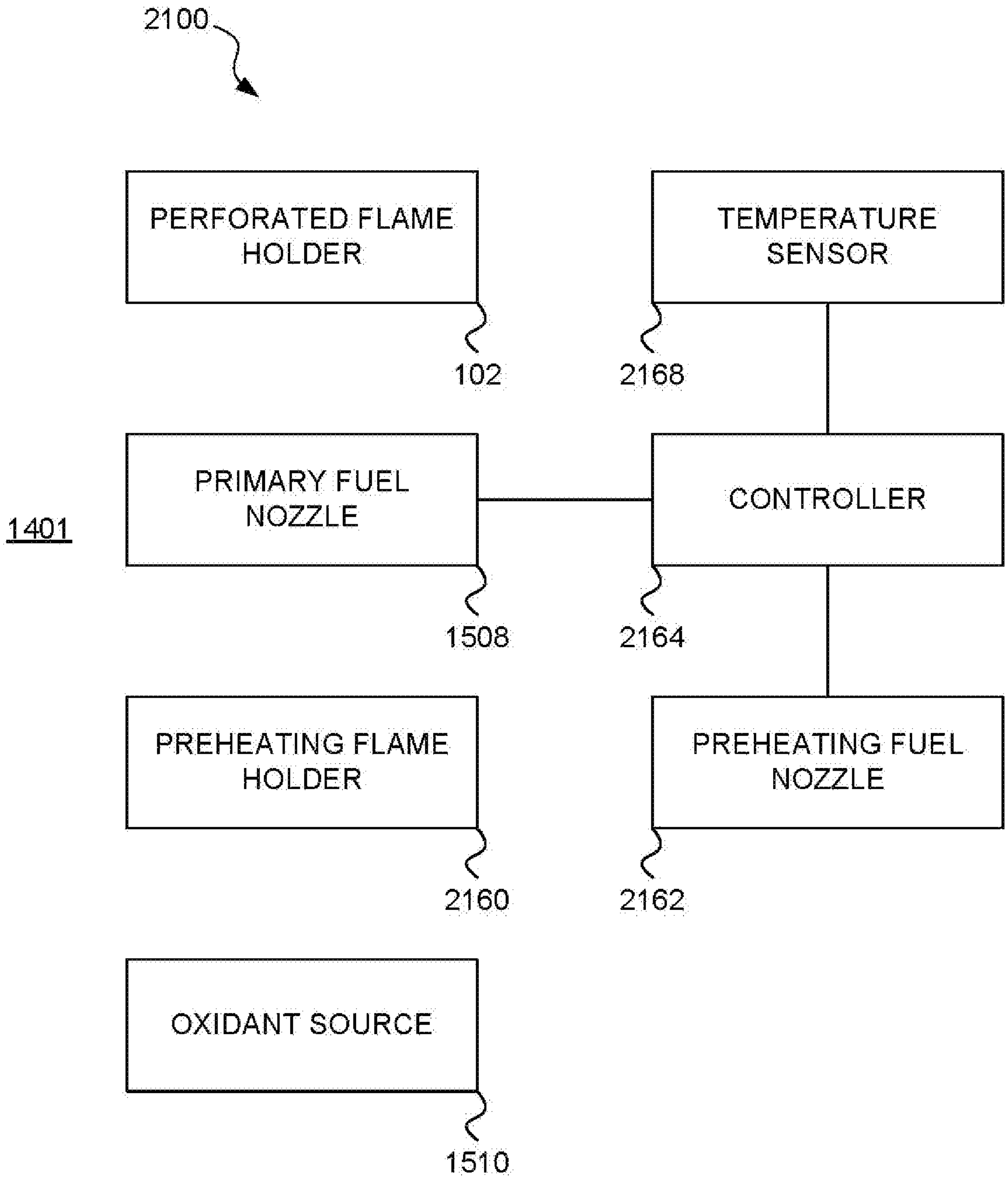

2100
PERFORATED FLAME HOLDER
102
TEMPERATURE SENSOR
2168
1401
PRIMARY FUEL NOZZLE
CONTROLLER
1508
2164
PREHEATING FLAME HOLDER
PREHEATING FUEL NOZZLE
2160
2162
OXIDANT SOURCE
1510

FIG. 22A

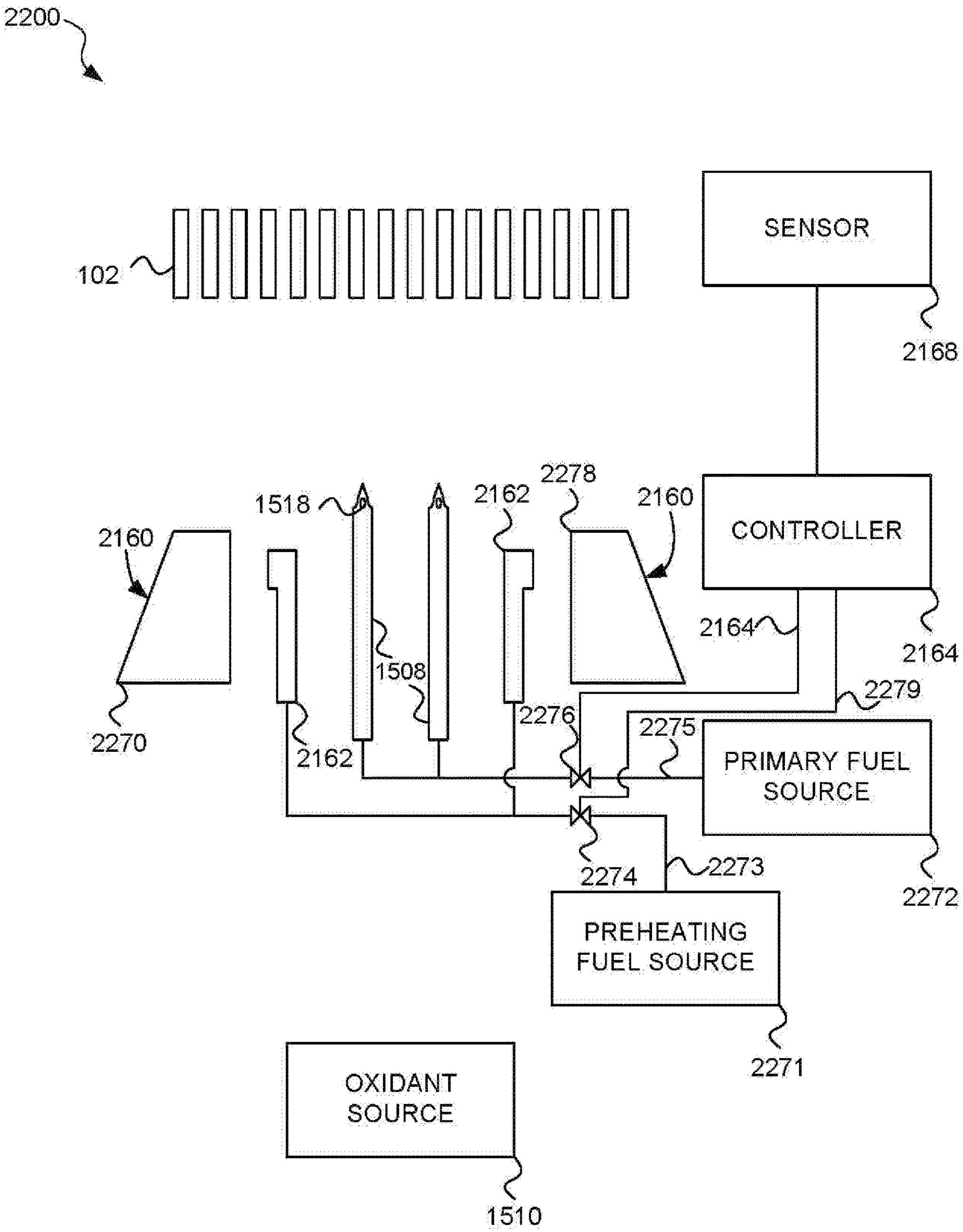

2200
102
SENSOR
2168
CONTROLLER
2164
2164
1518
2162
2278
2160
2160
2270
2162
1508
1508
2276
2275
2279
PRIMARY FUEL SOURCE
2272
2274
2273
PREHEATING FUEL SOURCE
2271
OXIDANT SOURCE
1510

FIG. 22B

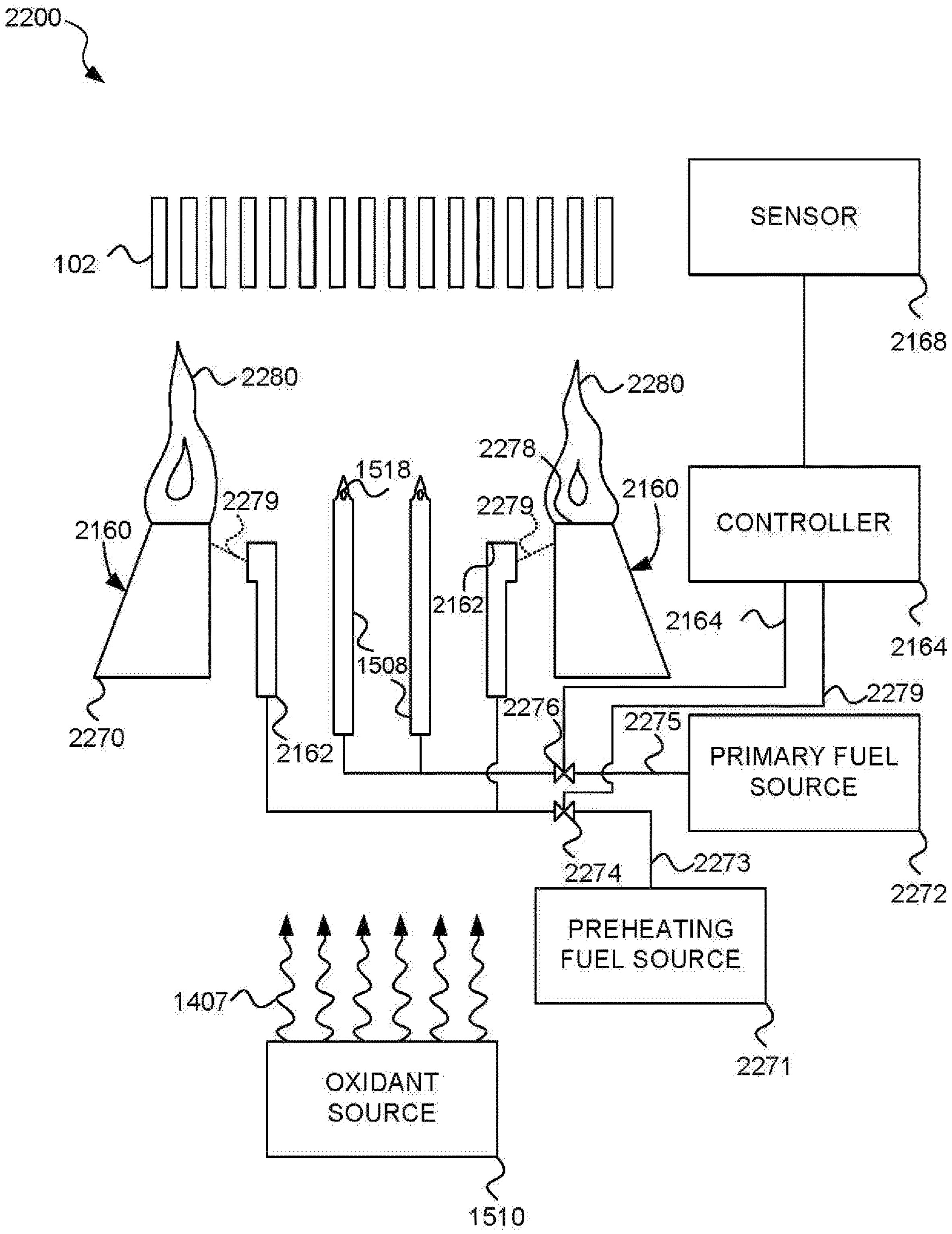
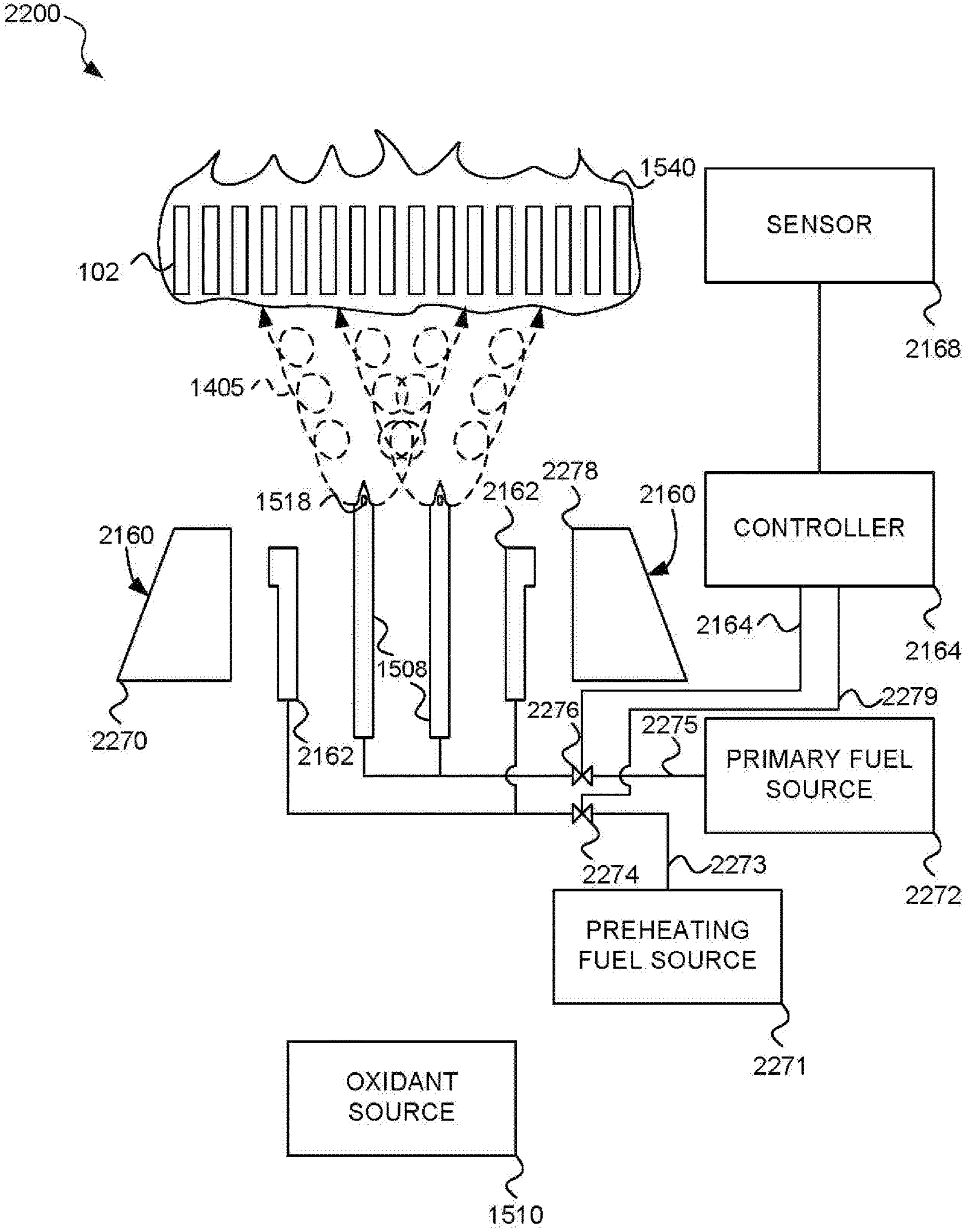

2200
SENSOR
2168
102
2280
2280
2278
1518
2279
2160
CONTROLLER
2160
2279
2162
2164
2164
1508
2270
2162
2276
2279
2275
PRIMARY FUEL SOURCE
2274
2273
2272
PREHEATING FUEL SOURCE
1407
2271
OXIDANT SOURCE
1510

FIG. 22C


2200
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SENSOR
102
2168
1405
2278
2160
1518
2162
CONTROLLER
2160
2164
2164
1508
2279
2276
2270
2275
PRIMARY FUEL SOURCE
2162
2273
2274
2272
PREHEATING FUEL SOURCE
2271
OXIDANT SOURCE
1510

FIG. 22D

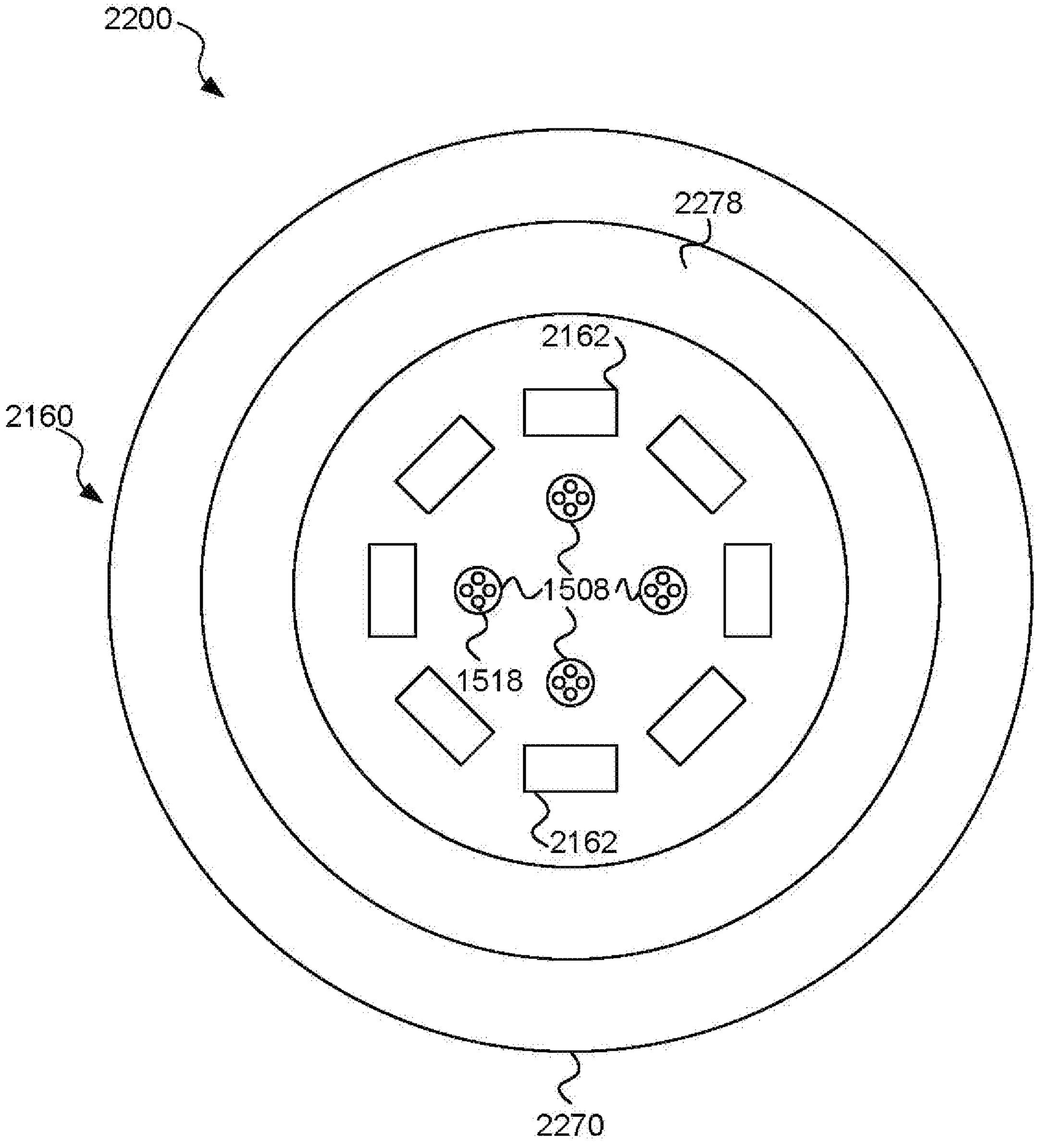
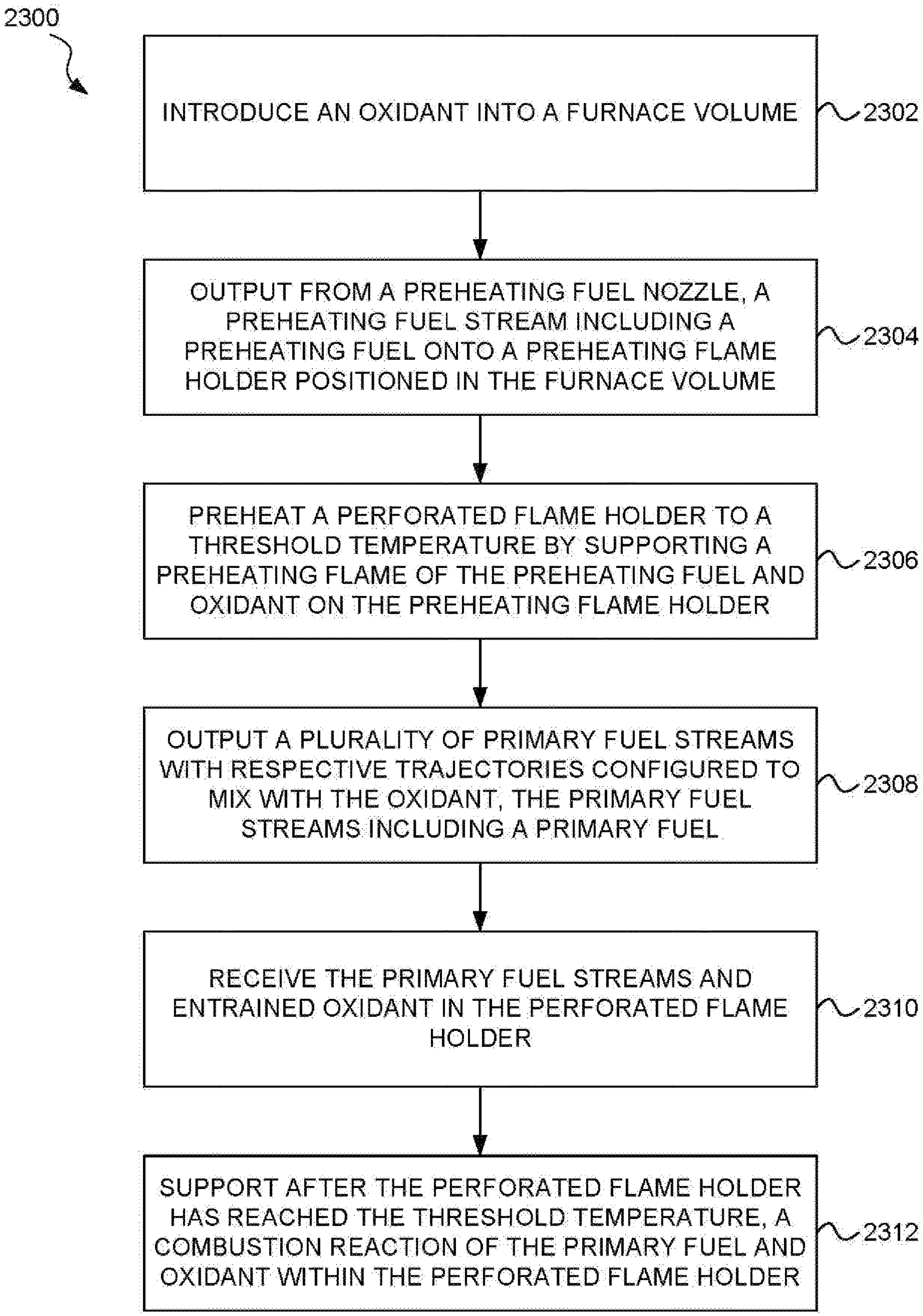


FIG. 23


2300
INTRODUCE AN OXIDANT INTO A FURNACE VOLUME
2302
OUTPUT FROM A PREHEATING FUEL NOZZLE, A PREHEATING FUEL STREAM INCLUDING A PREHEATING FUEL ONTO A PREHEATING FLAME HOLDER POSITIONED IN THE FURNACE VOLUME
2304
PREHEAT A PERFORATED FLAME HOLDER TO A THRESHOLD TEMPERATURE BY SUPPORTING A PREHEATING FLAME OF THE PREHEATING FUEL AND OXIDANT ON THE PREHEATING FLAME HOLDER
2306
OUTPUT A PLURALITY OF PRIMARY FUEL STREAMS WITH RESPECTIVE TRAJECTORIES CONFIGURED TO MIX WITH THE OXIDANT, THE PRIMARY FUEL STREAMS INCLUDING A PRIMARY FUEL
2308
RECEIVE THE PRIMARY FUEL STREAMS AND ENTRAINED OXIDANT IN THE PERFORATED FLAME HOLDER
2310
SUPPORT AFTER THE PERFORATED FLAME HOLDER HAS REACHED THE THRESHOLD TEMPERATURE, A COMBUSTION REACTION OF THE PRIMARY FUEL AND OXIDANT WITHIN THE PERFORATED FLAME HOLDER
2312

FUEL NOZZLE ASSEMBLY FOR A BURNER INCLUDING A PERFORATED FLAME HOLDER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a U.S. Continuation-in-Part Application of co-pending U.S. patent application Ser. No. 15/498,124, entitled “FUEL NOZZLE ASSEMBLY FOR A BURNER INCLUDING A PERFORATED FLAME HOLDER,” filed Apr. 26, 2017 (docket number 2651-296-03). U.S. patent application Ser. No. 15/498,124 claims priority benefit from U.S. Provisional Patent Application No. 62/327,779, entitled “FUEL NOZZLE ASSEMBLY FOR A BURNER INCLUDING A PERFORATED FLAME HOLDER,” filed Apr. 26, 2016 (docket number 2651-296-02), now expired.

[0002] The present application is also a U.S. Continuation-in-Part Application of co-pending International Patent Application No. PCT/US2018/020503, entitled “FUEL NOZZLE WITH AUGMENTED FUEL/AIR MIXING,” filed Mar. 1, 2018 (docket number 2651-290-04). International Patent Application No. PCT/US2018/020503 claims priority benefit from U.S. Provisional Patent Application No. 62/466,123, entitled “FUEL NOZZLE WITH AUGMENTED FUEL/AIR MIXING,” filed Mar. 2, 2017 (docket number 2651-290-02), now expired. International Patent Application No. PCT/US2018/020503 also claims priority benefit from U.S. Provisional Patent Application No. 62/466,111, entitled “COMBUSTION SYSTEM WITH PERFORATED FLAME HOLDER AND SWIRL STABILIZED PREHEATING FLAME,” filed Mar. 2, 2017 (docket number 2651-288-02).

[0003] Each of the foregoing applications, to the extent not inconsistent with the disclosure herein, is incorporated by reference.

BACKGROUND

[0004] Combustion systems are widely employed throughout society. There is a continual effort to improve the efficiency and reduce harmful emissions of combustion systems.

SUMMARY

[0005] In an embodiment, a combustion system includes a fuel nozzle, an oxidant supply, and a perforated flame holder. The fuel nozzle is configured to emit fuel in a fuel stream via at least one fuel orifice. The oxidant supply is configured to output oxidant in an oxidant flow adjacent to the fuel nozzle. The perforated flame holder is disposed a distance from the fuel nozzle and the oxidant source, and is oriented to receive mixed fuel and oxidant from the fuel nozzle and the oxidant supply. The perforated flame holder is configured to hold a combustion reaction of the mixed fuel and oxidant when the perforated flame holder is at an operating temperature. The fuel nozzle is defined by a tapered tip that decreases in width from a nozzle base to a nozzle end, where the decrease in width limits mixing of the fuel and the oxidant proximate the fuel nozzle.

[0006] According to an embodiment, a burner system includes a perforated flame holder and a fuel nozzle assembly. The perforated flame holder has an input face, an output face opposite the input face, and a plurality of perforations. The perforations are arranged between the input face and the output face. Each perforation is arranged to receive a portion of a fuel and oxidant mixture at the input face and may support a combustion reaction while the perforated flame holder is at an operating temperature. The fuel nozzle assembly includes a tapered fuel nozzle, which in turn includes an airfoil section and fuel orifices. The airfoil section has a toroidal structure arranged substantially perpendicular to an airflow direction. The airfoil section also has an acute trailing edge that is oriented in the airflow direction. The fuel orifices are arranged along the acute trailing edge.

[0007] According to another embodiment, a burner system includes a perforated flame holder and one or more tapered fuel nozzles. The perforated flame holder is arranged to receive a mixture of fuel and oxidant respectively from a fuel source and an oxidant source. The tapered fuel nozzles each have a circumferentially symmetric body that tapers from an attachment region to an acicular tip. The acicular tip is oriented toward the perforated flame holder, and at least one of the one or more tapered fuel nozzles is structured to contribute to a swirl number no greater than about 0.6 for oxidant flowing past. This limits formation of a heat-recirculating vortex proximate the respective tapered fuel nozzle.

[0008] According to an embodiment, a method for operating a burner system includes preheating a perforated flame holder, and delivering oxidant and fuel via structure that limits formation of fuel and oxidant mixing vortices proximate at least one main fuel nozzle. The oxidant is delivered to the perforated flame holder in an oxidant flow. The fuel is delivered to the perforated flame holder via a fuel stream from a fuel delivery orifice of the at least one main fuel nozzle, with the fuel stream being adjacent to the oxidant flow at least proximate to the at least one main fuel nozzle. The main fuel nozzle has a tapered structure that includes an acute trailing edge or tip, and the tapered structure limits generation of fuel and air vortices proximate the main fuel nozzle.

[0009] According to an embodiment a method for operating a burner system includes delivering oxidant and fuel to a perforated flame holder. The oxidant is delivered via an oxidant conduit, while the fuel is delivered via a tapered fuel nozzle, where the tapered fuel nozzle has one or more angled fuel orifices. The fuel becomes swirled by the angled fuel orifices. The fuel nozzle may include an oxidant swirling feature that engages oxidant flowing past the nozzle from the oxidant conduit.

[0010] According to an embodiment, a combustion system includes a perforated flame holder and a fuel and oxidant source configured to output an oxidant and a fuel stream including a fuel into a furnace volume. The fuel and oxidant source are configured to promote mixing of the oxidant with the fuel stream by imparting a swirling motion to at least one of the fuel stream and the oxidant. The combustion system further includes a perforated flame holder positioned to receive the fuel stream and is configured to support a combustion reaction of the fuel and oxidant within the perforated flame holder. The perforated flame holder is separated from the fuel and oxidant source by a dilution distance D_D selected to enable complete mixing of the oxidant with the fuel stream. The dilution distance D_D corresponds to a distance at which complete mixing of the fuel and oxidant would not occur in the absence of the swirling motion.

[0011] According to an embodiment, a method includes outputting an oxidant into a furnace volume, outputting a fuel stream including a fuel into the furnace volume, and mixing the oxidant with the fuel stream by imparting a swirling motion to at least one of the oxidant and the fuel stream. The method includes supporting a perforated flame holder in the furnace volume separated from the fuel and oxidant source by a dilution distance D_D selected to enable complete mixing of the oxidant with the fuel stream. The dilution distance D_D corresponds to a distance at which complete mixing of the fuel and oxidant would not occur in the absence of the swirling motion. The method also includes receiving the mixed fuel stream and oxidant at the perforated flame holder and supporting a combustion reaction of the fuel and oxidant within the perforated flame holder.

[0012] According to an embodiment, a combustion system includes a perforated flame holder and a preheating flame holder positioned in a furnace volume. The combustion system further includes a preheating fuel nozzle configured to output a preheating fuel stream including a preheating fuel onto the preheating flame holder. The preheating flame holder is configured to hold a preheating combustion reaction supported by the preheating fuel stream. The combustion system further includes an oxidant source configured to output an oxidant into the furnace volume. The combustion system further includes a fuel nozzle having a plurality of apertures each configured to output a respective fuel stream including a fuel, with a trajectory selected to mix with the oxidant before reaching the perforated flame holder. The perforated flame holder is configured to support a second combustion reaction of the fuel and the oxidant substantially within the perforated flame holder.

[0013] According to an embodiment, a method includes introducing an oxidant into a furnace volume, outputting from a preheating fuel nozzle a preheating fuel stream including a preheating fuel onto a preheating flame holder positioned in the furnace volume, and preheating a perforated flame holder to a threshold temperature by supporting a preheating flame of the preheating fuel and oxidant on the preheating flame holder. The method further includes outputting a plurality of fuel streams with respective trajectories configured to mix with the oxidant, the fuel streams including a fuel, and receiving the mixed fuel streams and oxidant in the perforated flame holder. The method further includes supporting, after the perforated flame holder has reached the threshold temperature, a combustion reaction of the fuel and oxidant within the perforated flame holder.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. **1** is a simplified diagram of a burner system including a perforated flame holder, according to an embodiment.

[0015] FIG. **2**A is a simplified perspective views of a burner system including a perforated flame holder, according to an embodiment.

[0016] FIG. **2**B is a simplified perspective views of a burner system including a perforated flame holder, according to an embodiment.

[0017] FIG. **2**C is a simplified perspective views of a burner system including a perforated flame holder, according to an embodiment.

[0018] FIG. **3**A is a side sectional diagram of a portion of the perforated flame holder of FIGS. **2**A and **2**B, according to an embodiment.

[0019] FIG. **3**B is a side sectional diagram of a portion of the perforated flame holder of FIG. **2**C, according to an embodiment.

[0020] FIG. **4** is a flow chart showing a method for operating a burner system including a perforated flame holder, according to an embodiment.

[0021] FIG. **5**A is a simplified top view of a fuel nozzle assembly for a burner system, according to an embodiment.

[0022] FIG. **5**B is a sectional side perspective view of the fuel nozzle assembly of FIG. **5**A, according to an embodiment.

[0023] FIG. **6**A is a simplified side view of a fuel nozzle for a burner system, according to an embodiment.

[0024] FIGS. **6**B-**6**D are side perspective views of fuel nozzle variations for a burner system, according to an embodiment.

[0025] FIG. **6**E is a simplified side view of a fuel nozzle for a burner system, according to an embodiment.

[0026] FIG. **7** is a flow chart showing a process for heating a burner system that includes a perforated flame holder, according to an embodiment.

[0027] FIG. **8** is a flow chart showing a method for preheating a burner system including a perforated flame holder, according to an embodiment.

[0028] FIG. **9** is a flow chart showing a method for preheating a burner system including a perforated flame holder, according to an embodiment.

[0029] FIGS. **10**A and **10**B illustrate side and top views, respectively, of a fuel nozzle having a fuel swirl structure, according to an embodiment.

[0030] FIGS. **11**A and **11**B illustrate side views of fuel nozzles having oxidant swirling features, according to an embodiment.

[0031] FIG. **12** is a side view of a burner system including a fuel nozzle having a fuel swirl structure and an oxidant conduit that includes an oxidant swirl feature, according to an embodiment.

[0032] FIG. **13** illustrates a method of delivering fuel and oxidant to a perforated flame holder, according to an embodiment.

[0033] FIG. **14** is a block diagram of a combustion system, according to an embodiment.

[0034] FIG. **15** is an illustration of a combustion system including a perforated flame holder, according to an embodiment.

[0035] FIG. **16** is an illustration of a fuel nozzle, according to an embodiment.

[0036] FIG. **17** is an illustration of a fuel nozzle, according to an embodiment.

[0037] FIG. **18** is an illustration of a fuel nozzle, according to an embodiment.

[0038] FIG. **19** is an illustration of a fuel nozzle, according to an embodiment.

[0039] FIG. **20** is a flow diagram of a process for operating a combustion system, according to an embodiment.

[0040] FIG. **21** is a block diagram of a combustion system including a perforated flame holder and a preheating flame holder, according to an embodiment.

[0041] FIGS. **22**A-**22**D are illustrations of a combustion system including a preheating flame holder and a perforated flame holder, according to an embodiment.

[0042] FIG. **23** is a flow diagram of a process for operating a combustion system, according to an embodiment.

DETAILED DESCRIPTION

[0043] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. Other embodiments may be used and/or other changes may be made without departing from the spirit or scope of the disclosure.

[0044] Fuel nozzles in a burner of a combustion system conventionally have a blocky structure. According to an interpretation, this blocky structure may contribute to formation of vortices downstream of the fuel nozzle. For example, according to an interpretation, oxidant flowing past the fuel nozzle may provide a pressure differential between the oxidant flow and a region directly downstream from the conventional, blocky fuel nozzle. The pressure differential may result in movement of fluid from a high pressure area to a low pressure area, which may result in vortices. These vortices may cause earlier than desired mixing of the fuel and oxidant, and may slow flow of the fuel and oxidant mixture downstream of the fuel nozzle. These effects can contribute to initiation or maintenance of a combustion reaction (e.g., a flame) in close proximity to the fuel nozzle. In conventional combustion systems, formation of a combustion reaction close to the fuel nozzle may be desirable or may be tolerated with minimal or no significant penalty.

[0045] However, combustion systems that implement a flame holder disposed a distance away from the fuel nozzle, such as a perforated flame holder (PFH), are intended to hold the combustion reaction substantially within the flame holder. Combustion of fuel and oxidant between the fuel nozzle and flame holder may decrease efficiency of the combustion system and is thus typically undesirable. Embodiments of fuel nozzles are described below that address the above-described problematic formation of vortices at the fuel nozzle(s).

[0046] FIG. **1** is a simplified diagram of a burner system **100** including a perforated flame holder **102** configured to hold a combustion reaction, according to an embodiment. The burner system **100** further includes a fuel nozzle assembly **104** having a tapered fuel nozzle **105**, an ignition and start-up flame source **120**, and a conduit **110**. The tapered fuel nozzle **105** may have an acute trailing edge **106** with one or more fuel orifices **108** arranged thereon. The tapered fuel nozzle **105** emits a fuel through the fuel orifices **108**. The conduit **110** provides an oxidant (e.g., air). The fuel nozzle assembly **104** thus may produce a fuel and oxidant mixture **112** that is directed to the perforated flame holder **102**. It may be noted that the dotted lines illustrating the fuel and oxidant mixture **112** in FIG. **1** illustrate paths of fuel ejected from the fuel orifices **108**, which fuel mixes between the trailing edge **106** and the perforated flame holder **102** with the oxidant flowing through the conduit **110**.

[0047] FIGS. **2**A-**2**B are simplified diagrams of the burner system **100** of FIG. **1** and an alternate burner system **200** each including a fuel nozzle assembly **104** and a perforated flame holder **102** configured to hold a combustion reaction, according to an embodiment. As used herein, the terms perforated flame holder, perforated reaction holder, porous flame holder, and porous reaction holder shall be considered synonymous unless further definition is provided. As described herein, the perforated flame holder **102** may be disposed a distance away from a fuel nozzle assembly **104**, and thus may be referenced herein as a distal flame holder or distal flame holding apparatus, particularly in embodiments described below that include more than one flame holder. In contrast, a burner system may also include a start-up flame holder, which may be referenced herein as a proximal flame holder, or distal flame holding apparatus.

[0048] A perforated flame holder **102** must be heated to an operating temperature range before its own radiant heat can maintain a stable combustion reaction. Various methods and structures are contemplated to initially attain such operating temperature. In an embodiment, a burner system may include multiple flame holders. A proximal flame holder may hold a flame between a fuel orifice and a distal flame holder. The proximal flame holder may be selectively engaged to hold a flame during a finite period until the distal flame holder reaches the operating temperature, and then may be removed when the operating temperature of the distal flame holder is reached. The proximal flame holder may be removed physically or virtually. For example, the proximal flame holder may be a physical object, such as a bluff body (not shown) that may be mechanically removed. Alternatively, the proximal flame holder may be implemented by an electrical interaction with the fuel and oxidant mixture **112** or products of pilot combustion and may thus be removed by simply changing the electrical characteristics or the fuel and oxidant mixture makeup. In an implementation that includes a dedicated start-up or pilot fuel supply, the pilot fuel nozzle may constitute a proximal flame holder, and may be made inoperative simply by cutting off or reducing fuel and/or oxygen supplied to the proximal flame holder. Although this embodiment describes use of two flame holders (i.e., distal, proximal), it is recognized that additional flame holder stages may be implemented. An alternative preheating configuration is described below with reference to a heater **228** illustrated in FIG. **2**B.

[0049] The burner system **100** illustrated in FIG. **2**A includes a fuel nozzle assembly **104** having a tapered fuel nozzle **105**. The tapered fuel nozzle **105** may include a transverse tube having one or more fuel orifices **108**. Such tube may take various shapes. For example, the transverse tube may be implemented as a toric or other toroidal structure as illustrated, or may include one or more linear or curved tubes (not illustrated) each having one or more orifices **108**. The toroidal structure of FIG. **2**A will be described in greater detail with respect to FIGS. **5**A-**5**B.

[0050] As shown in FIG. **2**B, the fuel nozzle assembly **104** may in an alternative embodiment include a single, unitary fuel nozzle **218** (e.g., fuel nozzles **218** described in detail with reference to FIGS. **6**A-**6**E). The fuel nozzle **218** may include one or more fuel orifices **226**. An array of unitary fuel nozzles **218** may be arranged to achieve desired fuel flow and distribution to a flame holder, such as perforated flame holder **102**. The fuel nozzle assembly **104** is configured to convey fuel and oxidant from a fuel and oxidant source **202** to the perforated flame holder **102**, which is described in detail below.

[0051] Experiments performed by the inventors have shown that perforated flame holders **102** described herein can support very clean combustion. Specifically, in experimental use of systems **100** ranging from pilot scale to full scale, output of oxides of nitrogen (NOx) was measured to range from low single digit parts per million (ppm) down to undetectable (less than 1 ppm) concentration of NOx at the stack. These remarkable results were measured at 3% (dry) oxygen (O_2) concentration with undetectable carbon monoxide (CO) at stack temperatures typical of industrial furnace applications (1400-1600° F.). Moreover, these results did not require any extraordinary measures such as selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), water/steam injection, external flue gas recirculation (FGR), or other extremes that may be required for conventional burners to even approach such clean combustion.

[0052] According to embodiments, the burner systems **100** and **200** include the fuel and oxidant source **202** disposed to output fuel via the fuel nozzle assembly **104** and oxidant via the conduit **110** (shown in FIG. **1**) into a combustion volume (e.g., combustion volume **150**) to form a fuel and oxidant mixture (e.g., mixture **112**). As used herein, the terms combustion volume, combustion chamber, furnace volume, and the like shall be considered synonymous unless further definition is provided.

[0053] A burner system may include a device for preheating the perforated flame holder **102**. For example, in some embodiments, as illustrated in FIG. **2**A, the fuel nozzle assembly **104** may include an ignition and start-up flame source **120** such as a pilot or start-up nozzle **122** which may have a separate fuel feed (described in greater detail below with respect to, e.g., FIG. **5**B). This pilot or start-up nozzle **122** may provide fuel for a pilot or start-up flame **206** to heat the perforated flame holder **102**, as described in greater detail below.

[0054] The ignition and start-up flame source **120** may include a fuel nozzle **122** the shape of which, according to an interpretation, conventionally causes fuel and/or oxidant vortices that mix fuel and oxidant sufficient to support a flame, and may impede release of a flame held proximate the fuel nozzle **122**. In other embodiments, the burner system **100**, **200** may include between the fuel nozzle assembly **104** and perforated flame holder **102** a permanent or retractable flame holder (not shown) that holds a pilot or start-up flame **206** as described above. The pilot or start-up flame **206** may emit heat from below the perforated flame holder **102** to heat the perforated flame holder **102** to a preheat threshold temperature.

[0055] Alternatively, e.g., as described with respect to FIG. **2**B, the perforated flame holder **102** may be preheated by a heater **228** operatively coupled to the perforated flame holder **102**. The heater **228**, a controller **230**, input/output **232** and a sensor **234** are illustrated in conjunction with the fuel nozzle assembly **104** employing one or more fuel nozzles **218**. The heater **228** and associated circuitry or controller **230** and sensor(s) **234** may in some embodiments be used in place of the ignition and start-up flame source **120** illustrated in FIG. **2**A for preheating the perforated flame holder **102**. However, it is recognized that certain embodiments may utilize both a pilot/start-up source (such as the ignition and start-up flame source **120**) and a heater **228** with associated controls or circuitry. Accordingly, although the description of the heater **228**, controller **230**, input/output **232** and sensor **234** herein is made in reference to the embodiment of FIG. **2**B, the description may be applied similarly to the burner system **100** described in reference to FIG. **2**A.

[0056] FIG. **3**A is a side sectional diagram **300** of a portion of the perforated flame holder **102** of FIGS. **2**A and **2**B, according to an embodiment. FIG. **3**B is a side sectional diagram **350** of a portion of the perforated flame holder **102** of FIG. **2**C. Referring to FIGS. **2**A, **2**B and **3**A, the perforated flame holder **102** includes a perforated flame holder body **208** defining a plurality of perforations **210** aligned to receive the fuel and oxidant mixture **112**. As used herein, the terms perforation, pore, aperture, elongated aperture, and the like, in the context of the perforated flame holder **102**, shall be considered synonymous unless further definition is provided. The perforations **210** are configured to collectively hold a combustion reaction **302** supported by the fuel and oxidant mixture **112**. Although FIG. **2**A shows the fuel and oxidant mixture **112** in association with a single fuel orifice **108**, this is merely representative of a fuel and oxidant mixture **112** associated with fuel from each fuel orifice **108**.

[0057] The fuel can include hydrogen, a hydrocarbon gas, a vaporized hydrocarbon liquid, an atomized hydrocarbon liquid, or a powdered or pulverized solid. The fuel can be a single species or can include a mixture of gas(es), vapor(s), atomized liquid(s), and/or pulverized solid(s). For example, in a process heater application, the fuel can include fuel gas or byproducts from the process that include CO, hydrogen (H_2), and methane (CH_4). In another application the fuel can include natural gas (mostly CH_4) or propane (C_3H_8). In another application, the fuel can include #2 fuel oil or #6 fuel oil. Dual fuel applications and flexible fuel applications are similarly contemplated by the inventors. The oxidant can include oxygen carried by air and/or can include another oxidant, either pure or carried by a carrier gas. The terms oxidant and oxidizer shall be considered synonymous herein.

[0058] According to an embodiment, the perforated flame holder body **208** can be bounded by an input face **212** disposed to receive the fuel and oxidant mixture **112**, an output face **214** facing away from the fuel and oxidant source **202**, and a peripheral surface **216** defining a lateral extent of the perforated flame holder **102**. The plurality of perforations **210** which are defined by the perforated flame holder body **208** extend from the input face **212** to the output face **214**. The plurality of perforations **210** can receive the fuel and oxidant mixture **112** at the input face **212**. The fuel and oxidant mixture **112** can then combust in or near the plurality of perforations **210** and combustion products can exit the plurality of perforations **210** at or near the output face **214**.

[0059] According to an embodiment, the perforated flame holder **102** is configured to hold a majority of the combustion reaction **302** within the perforations **210** during sustained operation. For example, on a steady-state basis, more than half the molecules of fuel output into the combustion volume **150** by the fuel and oxidant source **202** may be converted to combustion products between the input face **212** and the output face **214** of the perforated flame holder **102**. According to an alternative interpretation, more than half of the heat output by the combustion reaction **302** may be output between the input face **212** and the output face **214** of the perforated flame holder **102**. Under nominal operating conditions, the perforations **210** can be configured to collectively hold at least 80% of the combustion reaction **302** between the input face **212** and the output face **214** of the perforated flame holder **102**. In some experiments, the inventors produced a combustion reaction that was apparently wholly contained in the perforations **210** between the input face **212** and the output face **214** of the perforated flame holder **102**. According to an alternative interpretation, the perforated flame holder **102** can support combustion between the input face **212** and output face **214** when combustion is "time-averaged." For example, during transients, such as before the perforated flame holder **102** is fully heated, or if too high a (cooling) load is placed on the system, the combustion may travel somewhat downstream from the output face **214** of the perforated flame holder **102**.

[0060] While a "flame" is described in a manner intended for ease of description, it should be understood that in some instances no visible flame is present in or at the perforated flame holder **102**. Combustion occurs primarily within the perforations **210**, but the "glow" of combustion heat is dominated by a visible glow of the perforated flame holder **102** itself. In other instances, the inventors have noted transient flashback, or "huffing" wherein a visible flame momentarily ignites in a region lying between the input face **212** of the perforated flame holder **102** and a fuel nozzle assembly **104** or, in other embodiments, between the input face **212** of the perforated flame holder **102** and one or more fuel nozzles **218**, within the dilution region D_D.

[0061] Such transient flashback is generally short in duration such that, on a time-averaged basis, a majority of combustion occurs within the perforations **210** of the perforated flame holder **102**, between the input face **212** and the output face **214**. In still other instances, the inventors have noted apparent combustion occurring above the output face **214** of the perforated flame holder **102**, but still a majority of combustion occurred within the perforated flame holder **102** as evidenced by continued visible glow (a visible wavelength tail of blackbody radiation) from the perforated flame holder **102**.

[0062] The perforated flame holder **102** can be configured to receive heat from the combustion reaction **302** and output a portion of the received heat as thermal radiation **304** to heat-receiving structures (e.g., furnace walls and/or radiant section working fluid tubes) in or adjacent to the combustion volume **150**. As used herein, terms such as thermal radiation, infrared radiation, radiant heat, heat radiation, etc. are to be construed as being substantially synonymous, unless further definition is provided. Specifically, such terms refer to blackbody radiation of electromagnetic energy, primarily in infrared wavelengths.

[0063] Referring especially to FIG. 3A, the perforated flame holder **102** outputs another portion of the received heat to the fuel and oxidant mixture **112** received at the input face **212** of the perforated flame holder **102**. The perforated flame holder body **208** may receive heat from the (exothermic) combustion reaction **302** at least in heat receiving regions **306** of perforation walls **308**. Experimental evidence has suggested to the inventors that the position of the heat receiving regions **306**, or at least the position corresponding to a maximum rate of receipt of heat, can vary along the length of the perforation walls **308**. In some experiments, the location of maximum receipt of heat was apparently between ⅓ and ½ of the distance from the input face **212** to the output face **214** (i.e., somewhat nearer to the input face **212** than to the output face **214**). The inventors contemplate that the heat receiving regions **306** may lie nearer to the output face **214** of the perforated flame holder **102** under other conditions. Most probably, there is no clearly defined edge of the heat receiving regions **306** (or for that matter, the heat output regions **310**, described below). For ease of understanding, the heat receiving regions **306** and the heat output regions **310** will be described as particular regions **306**, **310**.

[0064] The perforated flame holder body **208** can be characterized by a heat capacity. The perforated flame holder body **208** may hold heat from the combustion reaction **302** in an amount corresponding to the heat capacity multiplied by temperature rise, and transfer the heat from the heat receiving regions **306** to heat output regions **310** of the perforation walls **308**. Generally, the heat output regions **310** are nearer to the input face **212** than are the heat receiving regions **306**. According to one interpretation, the perforated flame holder body **208** can transfer heat from the heat receiving regions **306** to the heat output regions **310** via thermal radiation, depicted graphically as **304**. According to another interpretation, the perforated flame holder body **208** can transfer heat from the heat receiving regions **306** to the heat output regions **310** via heat conduction along heat conduction paths **312**. The inventors contemplate that both radiation and conduction heat transfer mechanisms may be operative in transferring heat from the heat receiving regions **306** to the heat output regions **310**. In this way, the perforated flame holder **102** may act as a heat source to maintain the combustion reaction **302**, even under conditions where a combustion reaction would not be stable when supported from a conventional flame holder.

[0065] The inventors believe that the perforated flame holder **102** causes the combustion reaction **302** to occur within thermal boundary layers **314** formed adjacent to walls **308** of the perforations **210**. As the relatively cool fuel and oxidant mixture **112** approaches the input face **212**, the flow is split into portions that respectively travel through individual perforations **210**. The hot perforated flame holder body **208** transfers heat to the fluid, notably within thermal boundary layers **314** that progressively thicken as more and more heat is transferred to the incoming fuel and oxidant mixture **112**. After reaching a combustion temperature (e.g. the auto-ignition temperature of the fuel), the reactants continue to flow while a chemical ignition delay time elapses, over which time the combustion reaction **302** occurs. Accordingly, the combustion reaction **302** is shown as occurring within the thermal boundary layers **314**. As flow progresses, the thermal boundary layers **314** merge at a merger point **316**. Ideally, the merger point **316** lies between the input face **212** and output face **214** that defines the ends of the perforations **210**. At some point, the combustion reaction **302** causes the flowing gas (and plasma) to output more heat to the body **208** than it receives from the body **208**. The heat is received at the heat receiving region **306**, is held by the body **208**, and is transported to the heat output region **310** nearer to the input face **212**, where the heat recycles into the cool reactants (and any included diluent) to raise them to the combustion temperature.

[0066] In an embodiment, the plurality of perforations **210** are each characterized by a length L defined as a reaction fluid propagation path length between the input face **212** and the output face **214** of the perforated flame holder **102**. The reaction fluid includes the fuel and oxidant mixture **112** (optionally including nitrogen, flue gas, and/or other "non-reactive" species), reaction intermediates (including transition states in a plasma that characterizes the combustion reaction), and reaction products.

[0067] The plurality of perforations **210** can be each characterized by a transverse dimension D between opposing perforation walls **308**. The inventors have found that stable combustion can be maintained in the perforated flame holder **102** if the length L of each perforation **210** is at least four times the transverse dimension D of the perforation. In other embodiments, the length L can be greater than six times the transverse dimension D. For example, experiments have been run where L is at least eight, at least twelve, at least sixteen, and at least twenty-four times the transverse dimension D. Preferably, the length L is sufficiently long for thermal boundary layers **314** formed adjacent to the perforation walls **308** in a reaction fluid flowing through the perforations **210** to converge at merger points **316** within the perforations **210** between the input face **212** and the output face **214** of the perforated flame holder **102**. In experiments, the inventors have found L/D ratios between 12 and 48 to work well (e.g., to produce low NOx, produce low CO, and maintain stable combustion).

[0068] The perforated flame holder body **208** can be configured to convey heat between adjacent perforations **210**. The heat conveyed between adjacent perforations **210** can be selected to cause heat output from the combustion reaction portion **302** in a first perforation **210** to supply heat to stabilize a combustion reaction portion **302** in an adjacent perforation **210**.

[0069] According to an interpretation, the transient flashback or huffing phenomenon is at least in part a result of fuel and oxidant mixing in the dilution region D_D sufficient to support combustion. The nozzles described herein limit the mixing of fuel and oxidant near the fuel nozzles by limiting the formation of fuel and/or oxidant vortices that can result from conventional non-aerodynamic fuel nozzles. For example, a flat-topped fuel nozzle provides a low pressure area between a central orifice and a boundary such that when oxidant flows past the nozzle the oxidant is drawn toward the low pressure area, thus causing vortices that can mix the fuel and oxidant. In systems that do not utilize a perforated flame holder this mixing may be desirable. However, in systems that implement a perforated flame holder, the mixing near the fuel nozzles undesirably can support combustion if the mixture is ignited (such as with flashback).

[0070] Referring especially to FIGS. **2A-2B**, the fuel and oxidant source **202** can further include the fuel nozzle assembly **104**, configured to output fuel from orifices **108** (in the fuel nozzle assembly **104** shown in FIG. **2A**) or orifice **226** (in the fuel nozzle assembly **104** shown in FIG. **2B**), and an oxidant source configured to output a fluid including the oxidant (e.g., via conduit **110** of FIG. **1** or conduit **220** of FIG. **2B**). For example, the fuel nozzle assembly **104** can be configured to output pure fuel. The conduit **110**, **220** can be configured to output combustion air carrying oxygen.

[0071] The perforated flame holder **102** can be held by a perforated flame holder support structure **222** configured to hold the perforated flame holder **102** a distance D_D away from the fuel nozzle assembly **104**. The fuel nozzle assembly **104** can be configured to emit fuel jets selected to entrain the oxidant to form the fuel and oxidant mixture **112** as the fuel jet and oxidant travel along a path to the perforated flame holder **102** through the dilution distance D_D between the fuel nozzle assembly **104** and the perforated flame holder **102**. Additionally or alternatively (particularly when a blower or damper **238** is used in delivering oxidant or combustion air), the oxidant or combustion air conduit **220** can be configured to entrain the fuel as the fuel and oxidant travel through the dilution distance D_D. In some embodiments, a flue gas recirculation path **224** can be provided. Additionally or alternatively, the fuel nozzle assembly **104** can be configured to emit one or more fuel jets selected to entrain the oxidant and to entrain flue gas as the fuel jet travels through the dilution distance D_D between the fuel nozzle assembly **104** and the input face **212** of the perforated flame holder **102**. The fuel nozzle **105** may be configured to emit the fuel through one or more fuel orifices **108** having a dimension that is referred to as "nozzle diameter."

[0072] The perforated flame holder support structure **222** can support the perforated flame holder **102** to receive the fuel and oxidant mixture **112** at a distance D_D away from the tapered fuel nozzle **105** greater than 20 times the nozzle diameter. In another embodiment, the perforated flame holder **102** is disposed to receive the fuel and oxidant mixture **112** at a distance D_D away from the tapered fuel nozzle **105** between 100 times and 1100 times the nozzle diameter. Preferably, the perforated flame holder support structure **222** is configured to hold the perforated flame holder **102** about 200 times the nozzle diameter or more away from the tapered fuel nozzle **105**. When the fuel and oxidant mixture **112** travels about 200 times the nozzle diameter or more, the mixture is sufficiently homogenized to cause the combustion reaction **302** to output minimal NOx.

[0073] The fuel and oxidant source **202** can alternatively include a premix fuel and oxidant source, according to an embodiment. A premix fuel and oxidant source can include a premix chamber (not shown), a fuel nozzle configured to output fuel into the premix chamber, and an air channel configured to convey combustion air into the premix chamber. A flame arrestor (not shown) can be disposed between the premix fuel and oxidant source and the perforated flame holder **102** and be configured to prevent flame flashback into the premix fuel and oxidant source.

[0074] The combustion air conduit **220**, whether configured for entrainment in the combustion volume **150** or for premixing can include a blower or damper **238** configured to force air through the fuel and air source **202** and/or to control an amount of the air being forced through the fuel and air source **202**.

[0075] The perforated flame holder support structure **222** can be configured to support the perforated flame holder **102** from a floor or wall (not shown) of the combustion volume **150**, for example. In another embodiment, the support structure **222** supports the perforated flame holder **102** from the fuel and oxidant source **202**. Alternatively, the support structure **222** can suspend the perforated flame holder **102** from an overhead structure (such as a flue, in the case of an up-fired system). The support structure **222** can support the perforated flame holder **102** in various orientations and directions.

[0076] The perforated flame holder **102** can include a single perforated flame holder body **208**. In another embodiment, the perforated flame holder **102** can include a plurality of adjacent perforated flame holder sections that collectively provide a tiled perforated flame holder **102**.

[0077] The perforated flame holder support structure **222** can be configured to support the plurality of perforated flame holder sections. The perforated flame holder support structure **222** can include a metal superalloy, a cementatious, and/or ceramic refractory material. In an embodiment, the plurality of adjacent perforated flame holder sections can be joined with a fiber reinforced refractory cement.

[0078] The perforated flame holder **102** can have a width dimension W between opposite sides of the peripheral surface **216** at least twice a thickness dimension T between the input face **212** and the output face **214**. In another embodiment, the perforated flame holder **102** can have a width dimension W between opposite sides of the peripheral surface **216** at least three times, at least six times, or at least nine times a thickness dimension T between the input face **212** and the output face **214** of the perforated flame holder **102**.

[0079] In an embodiment, the perforated flame holder **102** can have a width dimension W less than a width of the combustion volume **150**. This can allow the flue gas recirculation path **224** from above to below the perforated flame holder **102** to lie between the peripheral surface **216** of the perforated flame holder **102** and a combustion volume wall (not shown).

[0080] Referring again to FIGS. **2A-2B** and **3A**, the perforations **210** can include elongated squares, each of the elongated squares has a transverse dimension D between opposing sides of the squares. In another embodiment, the perforations **210** can include elongated hexagons, each of the elongated hexagons has a transverse dimension D between opposing sides of the hexagons. In another embodiment, the perforations **210** can include hollow cylinders, each of the hollow cylinders has a transverse dimension D corresponding to a diameter of the cylinders. In another embodiment, the perforations **210** can include truncated cones, in which each of the truncated cones has a transverse dimension D that is rotationally symmetrical about a length axis that extends from the input face **212** to the output face **214**. The perforations **210** can each have a transverse dimension D equal to or greater than a quenching distance of the fuel based on standard reference conditions.

[0081] In one range of embodiments, each of the plurality of perforations has a transverse dimension D between 0.05 inch and 1.0 inch. Preferably, each of the plurality of perforations has a transverse dimension D between 0.1 inch and 0.5 inch. For example the plurality of perforations can each have a transverse dimension D of about 0.2 to 0.4 inch.

[0082] The void fraction of a perforated flame holder **102** is defined as the total volume of all perforations **210** in a section of the perforated flame holder **102** divided by a total volume of the perforated flame holder **102** including the body **208** and perforations **210**. The perforated flame holder **102** should have a void fraction between 0.10 and 0.90. In an embodiment, the perforated flame holder **102** can have a void fraction between 0.30 and 0.80. In another embodiment, the perforated flame holder **102** can have a void fraction of about 0.70. Using a void fraction of about 0.70 was found to be especially effective for producing very low NOx.

[0083] The perforated flame holder **102** can be formed from a fiber reinforced cast refractory material and/or a refractory material such as an aluminum silicate material. For example, the perforated flame holder **102** can be formed from mullite or cordierite. Additionally or alternatively, the perforated flame holder body **208** can include a metal superalloy such as Inconel or Hastelloy. The perforated flame holder body **208** can define a honeycomb.

[0084] The inventors have found that the perforated flame holder **102** can be formed from VERSAGRID® ceramic honeycomb, available from Applied Ceramics, Inc. of Doraville, S.C.

[0085] The perforations **210** can be parallel to one another and normal to the input and output faces **212**, **214**. In another embodiment, the perforations **210** can be parallel to one another and formed at an angle relative to the input and output faces **212**, **214**. In another embodiment, the perforations **210** can be non-parallel to one another. In another embodiment, the perforations **210** can be non-parallel to one another and non-intersecting. In another embodiment, the perforations **210** can be intersecting. The body **208** can be one piece or can be formed from a plurality of sections.

[0086] FIG. **2C** is a simplified perspective view of a combustion system **250**, including an alternative perforated flame holder **102**, according to an embodiment. The perforated flame holder **102** in this embodiment is a porous ceramic tile. In particular, the perforated flame holder **102** of FIG. **2C** is a reticulated ceramic perforated flame holder, according to an embodiment. FIG. **3B** is a simplified side sectional diagram of a portion of the perforated flame holder **102** of FIG. **2C**, according to an embodiment. The perforated flame holder **102** of FIGS. **2C**, **3B** can be implemented in the various combustion systems described herein, according to an embodiment. According to an embodiment, the perforated flame holder **102** is configured to support a combustion reaction of the fuel and oxidant at least partially within the perforated flame holder **102**. According to an embodiment, the perforated flame holder **102** can be configured to support a combustion reaction of the fuel and oxidant **206** upstream, downstream, within, and adjacent to the perforated flame holder **102**.

[0087] Referring to FIGS. **2C** and **3B**, the perforated flame holder body **208** can include fibers **339** including reticulated fibers. The fibers **339** can define branching perforations **210** that weave around and through the fibers **339**. According to an embodiment, the perforations **210** are formed as passages through the reticulated fibers **339**.

[0088] According to an embodiment, the reticulated fibers **339** can include alumina silicate. According to an embodiment, the reticulated fibers **339** can be formed from extruded mullite or cordierite. According to an embodiment, the reticulated fibers **339** can include Zirconia. According to an embodiment, the reticulated fibers **339** can include silicon carbide.

[0089] The term "reticulated fibers" refers to a netlike structure. According to an embodiment, the fibers **339** are formed from an extruded ceramic material. In reticulated fiber embodiments, the interaction between the fuel and oxidant, the combustion reaction, and heat transfer to and from the perforated flame holder body **208** functions similarly to the embodiment shown and described above with respect to FIGS. **2A-2B**, **3A**, and **4**. One difference in activity is a mixing between openings (or perforations) **210**, because the fibers **339** form a perforated flame holder body **208** that allows flow back and forth between neighboring perforations.

[0090] According to an embodiment, the network of reticulated fibers **339** is sufficiently open for downstream fibers **339** to emit radiation for receipt by upstream fibers **339** for the purpose of heating the upstream fibers sufficiently to maintain combustion of a lean fuel and oxidant mixture. Compared to a continuous perforated flame holder body **208** (e.g., as in FIG. **2A**), heat conduction paths (e.g., **313**) between fibers **339** are reduced owing to separation of the fibers. This may cause relatively more heat to be transferred from the heat-receiving region **306** (heat receiving area) to the heat-output region **310** (heat output area) of the perforation "wall" via thermal radiation.

[0091] It will be acknowledged that the fuel nozzle assembly **104** illustrated in FIG. **2**C is one of several fuel nozzles that may be alternatively utilized in a burner system **100** or **200** with the perforated flame holder **102**. For example, a fuel nozzle assembly such as found in FIG. **2**B may be implemented, and/or fuel nozzles such as are illustrated in FIGS. **6**A-**6**E and FIGS. **10**A-**10**B may be implemented for use with a perforated flame holder **102** having reticulated fibers as described above.

[0092] According to an embodiment, individual perforations **210** may extend from an input face **212** to an output face **214** of the perforated flame holder **102**. Perforations **210** may have varying lengths L. According to an embodiment, because the perforations **210** branch into and out of each other, individual perforations **210** may not be clearly defined by a length L.

[0093] According to an embodiment, the perforated flame holder **102** is configured to support or hold a combustion reaction or a flame at least partially between the input face **212** and the output face **214**. According to an embodiment, the input face **212** corresponds to a surface of the perforated flame holder **102** proximal to the fuel nozzle **218** or to a surface that first receives fuel. According to an embodiment, the input face **212** corresponds to an extent of the reticulated fibers **1239** proximal to the fuel nozzle **218**. According to an embodiment, the output face **214** corresponds to a surface distal to the fuel nozzle **218** or opposite the input face **212**. According to an embodiment, the input face **212** corresponds to an extent of the reticulated fibers **1239** distal to the fuel nozzle **218** or opposite to the input face **212**.

[0094] According to an embodiment, the formation of boundary layers **314**, transfer of heat between the perforated reaction holder body **208** and the gases flowing through the perforations **210**, a characteristic perforation width dimension, and the length L can be regarded as related to an average or overall path through the perforated reaction holder **102**. In other words, the width dimension can be determined as a root-mean-square of individual width dimension values determined at each point along a flow path. Similarly, the length L can be a length that includes length contributed by tortuosity of the flow path, which may be somewhat longer than a straight line distance from the input face **212** to the output face **214** through the perforated reaction holder **102**. According to an embodiment, the void fraction (expressed as (total perforated reaction holder **102** volume−fiber volume)/total volume)) is about 70%.

[0095] According to an embodiment, the reticulated ceramic perforated flame holder **102** is a tile about 1"×4"×4". According to an embodiment, the reticulated ceramic perforated flame holder **102** includes about 10 pores per square inch of surface area. Other materials and dimensions can also be used for a reticulated ceramic perforated flame holder **102** in accordance with principles of the present disclosure.

[0096] According to an embodiment, the reticulated ceramic perforated flame holder **102** can include shapes and dimensions other than those described herein. For example, the perforated flame holder **102** can include reticulated ceramic tiles that are larger or smaller than the dimensions set forth above. Additionally, the reticulated ceramic perforated flame holder **102** can include shapes other than generally cuboid shapes.

[0097] According to an embodiment, the reticulated ceramic perforated flame holder **102** can include multiple reticulated ceramic tiles. The multiple reticulated ceramic tiles can be joined together such that each ceramic tile is in direct contact with one or more adjacent reticulated ceramic tiles. The multiple reticulated ceramic tiles can collectively form a single perforated flame holder **102**. Alternatively, each reticulated ceramic tile can be considered a distinct perforated flame holder **102**. In another embodiment (not shown), the perforated flame holder **102** can include a plurality of tubes or pipes bundled together. The plurality of perforations **210** can include hollow cylinders and can optionally also include interstitial spaces between the bundled tubes. In an embodiment, the plurality of tubes can include ceramic tubes. Refractory cement can be included between the tubes and configured to adhere the tubes together. In another embodiment, the plurality of tubes can include metal (e.g., superalloy) tubes. The plurality of tubes can be held together by a metal tension member circumferential to the plurality of tubes and arranged to hold the plurality of tubes together. The metal tension member can include stainless steel, a superalloy metal wire, and/or a superalloy metal band.

[0098] The perforated flame holder body **208** can alternatively include stacked perforated sheets of material, each sheet having openings that connect with openings of subjacent and superjacent sheets, the connected openings forming the perforations **210**. The perforated sheets can include perforated metal sheets, ceramic sheets and/or expanded sheets. In another embodiment, the perforated flame holder body **208** can include discontinuous packing bodies such that the perforations **210** are formed in the interstitial spaces between the discontinuous packing bodies. In one example, the discontinuous packing bodies may include structured packing shapes. In another example, the discontinuous packing bodies may include random packing shapes. For example, the discontinuous packing bodies can include ceramic Raschig rings, ceramic Berl saddles, ceramic Intalox saddles, and/or metal rings or other shapes (e.g. Super Raschig Rings) that may be held together by a metal cage.

[0099] The inventors contemplate various explanations for why burner systems including the perforated flame holder **102** provide such clean combustion.

[0100] In one aspect, the perforated flame holder **102** acts as a heat source to maintain a combustion reaction even under certain conditions where a combustion reaction would not be stably supported by a conventional flame holder. This capability can be leveraged to support combustion using a leaner fuel-to-oxidant mixture than is typically feasible. Thus, according to an embodiment, at the point where the fuel and oxidant mixture **112** contacts the input face **212** of the perforated flame holder **102**, an average fuel-to-oxidant ratio of the fuel and oxidant mixture **112** is below a (conventional) lower combustion limit of the fuel component of the fuel stream−lower combustion limit defines the lowest concentration of fuel at which a fuel/air mixture will burn when exposed to a momentary ignition source under normal atmospheric pressure and an ambient temperature of 25° C. (77° F.).

[0101] According to one interpretation, the fuel and oxidant mixture(s) **112** supported by the perforated flame holder **102** may be more fuel-lean than mixtures that would provide stable combustion in a conventional burner. Combustion near a lower combustion limit of fuel generally burns at a lower adiabatic flame temperature than mixtures near the center of the lean-to-rich combustion limit range. Lower flame temperatures generally evolve a lower concentration of NOx than higher flame temperatures. In conventional flames, too-lean combustion is generally associated with high CO concentration at the stack. In contrast, the perforated flame holder **102** and systems including the perforated flame holder **102** described herein were found to provide substantially complete combustion of CO (single digit ppm down to undetectable, depending on experimental conditions), while supporting low NOx. In some embodiments, the inventors achieved stable combustion at what was understood to be very lean mixtures (that nevertheless produced only about 3% or lower measured O_2 concentration at the stack). Moreover, the inventors believe perforation walls **308** may act as a heat sink for the combustion fluid. This effect may alternatively or additionally reduce combustion temperature.

[0102] According to another interpretation, production of NOx can be reduced if the combustion reaction **302** occurs over a very short duration of time. Rapid combustion causes the reactants (including oxygen and entrained nitrogen) to be exposed to NOx-formation temperature for a time too short for NOx formation kinetics to cause significant production of NOx. The time required for the reactants to pass through the perforated flame holder **102** is very short compared to a conventional flame. The low NOx production associated with perforated flame holder combustion may thus be related to the short duration of time required for the reactants (and entrained nitrogen) to pass through the perforated flame holder **102**.

[0103] Since CO oxidation is a relatively slow reaction, the time for passage through the perforated flame holder (perhaps plus time passing toward the flue from the perforated flame holder **102**) is apparently sufficient and at sufficiently elevated temperature, in view of the very low measured (experimental and full scale) CO concentrations, for oxidation of CO to carbon dioxide (CO_2).

[0104] FIG. **4** is a flow chart showing a method **400** for operating a burner system including the perforated flame holder shown and described herein. To operate a burner system including a perforated flame holder, the perforated flame holder is first heated to a temperature sufficient to maintain combustion of the fuel and oxidant mixture.

[0105] According to a simplified description, the method **400** begins with step **402**, wherein the perforated flame holder is preheated to a start-up temperature, T_S. After the perforated flame holder is raised to the start-up temperature, the method proceeds to step **404**, wherein fuel and oxidant are provided to the perforated flame holder and combustion is held by the perforated flame holder.

[0106] According to a more detailed description, step **402** begins with sub-step **406**, wherein start-up energy is provided at the perforated flame holder. Simultaneously or following providing start-up energy, a decision sub-step **408** determines whether the temperature T of the perforated flame holder is at or above the start-up temperature, T_S. As long as the temperature of the perforated flame holder is below its start-up temperature, the method loops between sub-steps **406** and **408** within the preheat step **402**. In sub-step **408**, if the temperature T of at least a predetermined portion of the perforated flame holder is greater than or equal to the start-up temperature, the method **400** proceeds to step **404**, wherein fuel and oxidant are supplied to and combustion is held by the perforated flame holder.

[0107] Step **404** may be broken down into several discrete sub-steps, at least some of which may occur simultaneously.

[0108] Proceeding from sub-step **408**, a fuel and oxidant mixture is provided to the perforated flame holder, as shown in sub-step **410**. The fuel and oxidant may be provided by a fuel and oxidant source that may include a fuel nozzle and combustion air source that are distinct from a fuel nozzle and combustion air source(s) used for the start-up, for example. In this approach, the fuel and combustion air are output in one or more directions selected to cause a mixture of the fuel and combustion air to be received by an input face (e.g., **212**) of the perforated flame holder **102**. The fuel may entrain the combustion air (or alternatively, the combustion air may dilute the fuel) to provide a fuel and oxidant mixture at the input face of the perforated flame holder at a fuel dilution selected for a stable combustion reaction that can be held within the perforations of the perforated flame holder.

[0109] Proceeding to sub-step **412**, the combustion reaction is held by the perforated flame holder.

[0110] In sub-step **414**, heat may be output from the perforated flame holder. The heat output from the perforated flame holder may be used to power an industrial process, heat a working fluid, generate electricity, or provide motive power, for example.

[0111] In an optional sub-step **416**, the presence of combustion may be sensed. Various sensing approaches have been used and are contemplated by the inventors. Generally, combustion held by the perforated flame holder is very stable and no unusual sensing requirement is placed on the system. Combustion sensing may be performed using an infrared sensor, a video sensor, an ultraviolet sensor, a charged species sensor, thermocouple, thermopile, and/or other known combustion sensing apparatuses. In an additional or alternative variant of sub-step **416**, a pilot flame or other ignition source (e.g., ignition and start-up flame source **120**) may be provided to cause ignition of the fuel and oxidant mixture in the event combustion is lost at the perforated flame holder.

[0112] Proceeding to decision sub-step **418**, if combustion is sensed not to be stable, the method **400** may exit to step **424**, wherein an error procedure is executed. For example, the error procedure may include turning off fuel flow, re-executing the preheating step **402**, adjusting fuel and/or air flow rates or direction, outputting an alarm signal, igniting a stand-by combustion system, or other steps. If, in sub-step **418**, combustion in the perforated flame holder is determined to be stable, the method **400** proceeds to decision sub-step **420**, wherein it is determined if combustion parameters should be changed. If no combustion parameters are to be changed, the method loops (within step **404**) back to sub-step **410**, and the combustion process continues. If a change in combustion parameters is indicated, the method **400** proceeds to sub-step **422**, wherein the combustion parameter change is executed. After changing the combustion parameter(s), the method loops (within step **404**) back to sub-step **410**, and combustion continues.

[0113] Combustion parameters may be scheduled to be changed, for example, if a change in heat demand is encountered. For example, if less heat is required (e.g., due to decreased electricity demand, decreased motive power requirement, or lower industrial process throughput), the fuel and oxidant flow rate may be decreased in sub-step **422**.

Conversely, if heat demand is increased, then fuel and oxidant flow may be increased. Additionally or alternatively, if the combustion system is in a start-up mode, then fuel and oxidant flow may be gradually increased to the perforated flame holder over one or more iterations of the loop within step **404**.

[0114] As described in conjunction with FIGS. **3** and **4**, the perforated flame holder **102** operates by outputting heat to the incoming fuel and oxidant mixture **112**. After normal combustion is established, this heat is provided by the combustion reaction **302**; but before combustion is established, the heat may be provided by the heater **228**.

[0115] Various preheating apparatuses have been used and are contemplated by the inventors. In some embodiments, the heater **228** can include a proximal flame holder configured to support a flame disposed to heat the perforated flame holder **102**, e.g., by radiant or convective heating depending on fuel type and/or other parameters. The fuel and oxidant source **202** can connect to the fuel nozzle assembly **104** configured to emit a fuel stream and connect to an oxidant conduit **220** configured to convey combustion air adjacent to the fuel stream. The fuel nozzle assembly **104** can be configured to output the fuel stream to be progressively diluted by the combustion air. The perforated flame holder **102** can be disposed to receive a diluted fuel and air mixture **112** that supports a combustion reaction (such as combustion reaction **302**) that is stabilized by the perforated flame holder **102** when the perforated flame holder **102** is at an operating temperature. A start-up flame holder, in contrast, can be configured to support a start-up flame, at a location corresponding to a rich fuel and air mixture **112**, that is stable without stabilization provided by the heated perforated flame holder **102**.

[0116] The burner system **200** can further include a controller **230** operatively coupled to the heater **228** and to a data interface **232**. For example, the controller **230** can be configured to control a start-up flame holder actuator configured to cause the start-up flame holder (such as the proximal flame holder described above) to hold the start-up flame **206** when the perforated flame holder **102** needs to be preheated and to not hold the start-up flame when the perforated flame holder **102** is at an operating temperature (e.g., when $T \geq T_S$).

[0117] Various alternative approaches for actuating a start-up flame are contemplated. In one embodiment, a start-up flame holder includes a mechanically-actuated bluff body configured to be actuated to intercept the fuel and oxidant mixture **112** to cause heat-recycling vortices and thereby hold a start-up flame; or to be actuated to not intercept the fuel and oxidant mixture **112** to cause the fuel and oxidant mixture **112** to proceed to the perforated flame holder **102**. In another embodiment, a fuel control valve, blower, and/or damper may be used to select a fuel and oxidant mixture flow rate that is sufficiently low for a start-up flame to be jet-stabilized; and upon reaching an operating temperature of the perforated flame holder **102**, the flow rate may be increased to "blow out" the start-up flame, thus permitting the combustible materials to enter the perforated flame holder **102**. In another embodiment, the heater **228** may include an electrical power supply operatively coupled, via, e.g., a control output of the heater **228**, to the controller **230** and configured to apply an electrical charge or voltage to the fuel and oxidant mixture **112**. An electrically conductive start-up flame holder may be selectively coupled to a voltage ground or other voltage selected to attract the electrical charge in the fuel and oxidant mixture **112**. The attraction of the electrical charge was found by the inventors to cause a start-up flame to be held by the electrically conductive start-up flame holder.

[0118] In another embodiment, the heater **228** may include an electrical resistance heater configured to output heat to the perforated flame holder **102** and/or to the fuel and oxidant mixture **112**. The electrical resistance heater **228** can be configured to heat up the perforated flame holder **102** to an operating temperature. The heater **228** can further include a power supply and a switch operable, under control of the controller **230** via a control input of the heater **228**, to selectively couple the power supply to the electrical resistance heater.

[0119] The electrical resistance heater **228** can be formed in various ways. For example, the electrical resistance heater **228** can be formed from KANTHAL wire (available from Sandvik Materials Technology division of Sandvik AB of Hallstahammar, Sweden) threaded through at least a portion of the perforations **210** defined formed by the perforated flame holder body **208**. Alternatively, the heater **228** can include an inductive heater, a high energy (e.g. microwave or laser) beam heater, a frictional heater, or other types of heating technologies.

[0120] Other forms of start-up apparatuses are contemplated. For example, the heater **228** can include an electrical discharge igniter or hot surface igniter configured to output a pulsed ignition to the air and fuel. Additionally or alternatively, a start-up apparatus can include a pilot flame apparatus (e.g., at ignition and start-up flame source **120** shown in FIGS. **1**, **2**A) disposed to ignite a fuel and oxidant mixture **112** resulting from fuel expelled from fuel nozzle **218** that would otherwise enter the perforated flame holder **102**. An electrical discharge igniter, hot surface igniter, and/or pilot flame apparatus can be operatively coupled to the controller **230**, which can cause the electrical discharge igniter or pilot flame apparatus to maintain combustion of the fuel and oxidant mixture **112** in or upstream from the perforated flame holder **102** before the perforated flame holder **102** is heated sufficiently to maintain combustion.

[0121] The burner system **200** can further include the sensor **234** operatively coupled to the controller **230**.

[0122] The sensor **234** can include a heat sensor configured to detect infrared radiation or a temperature of the perforated flame holder **102** and convey data indicating a characteristic of the infrared radiation or temperature via a temperature indication output of the sensor **234**. The controller **230** can be configured to control the heating apparatus **228** responsive to input from the sensor **234**. Optionally, a fuel control valve **236** can be operatively coupled to the controller **230** and configured to control a flow of fuel to the fuel and oxidant source **202**. Additionally or alternatively, an oxidant blower or damper **238** can be operatively coupled to the controller **230** and configured to control flow of the oxidant (or combustion air).

[0123] The sensor **234** can further include a combustion sensor operatively coupled to the controller **230**, the combustion sensor being configured to detect or measure a temperature, video image, and/or spectral characteristic of a combustion reaction held by the perforated flame holder **102**. Although presence of combustion may be detected proximate a downstream side of the perforated flame holder **102**, it will be recognized that any combination of combustion effects may be measured upstream, within, and/or downstream of the perforated flame holder **102** in order to evaluate and control the flame and its effects. The combustion sensor may be implemented to detect or measure temperature by means of infrared sensor, thermocouple, and/or thermopile.

[0124] In some embodiments, the sensor **234** may detect or measure a particulate species concentration and/or an ionization level. Concentration of particulate species in the combustion products may by measured by analyzing concentrations of, e.g., OH* radicals, OH— ions, CH* radicals, and/or other particulate species at predetermined location(s). In some instances, the concentrations may be measured spectroscopically, e.g., using one or more spectrometers arranged to analyze a spectral characteristic of such particular species. Ionization level may be determined in some embodiments by detecting or measuring conductivity of the combustion products using, e.g., one or more flame rods.

[0125] The fuel control valve **236** can be configured to control one or more flows of fuel from a fuel source to the fuel and oxidant source **202**. For example, the controller **230** may be configured to control at least one of fuel supply to the fuel nozzle **105**, **218** and the ignition and start-up flame source **120**. The controller **230** can be configured to control the fuel control valve **236** responsive to input from the combustion sensor **234**. The controller **230** can be configured to control the fuel control valve **236** and/or oxidant blower or damper **238** to control a preheat flame type of heater **228** to heat the perforated flame holder **102** to an operating temperature. The controller **230** can similarly control the fuel control valve **236** and/or the oxidant blower or damper **238** to change the fuel and oxidant mixture **112** flow responsive to a heat demand change received as data via the data interface **232**.

[0126] FIGS. **5**A and **5**B are a simplified top view and a sectional side perspective view, respectively, of a tapered fuel nozzle **105** of a fuel nozzle assembly **104**, according to an embodiment. The fuel nozzle assembly **104** of the illustrated embodiment may include a toroidal airfoil section **502** with a channel **506** formed therein for carrying fuel to the fuel orifices **108** spaced around the airfoil section **502**. A major transverse plane of the airfoil section **502** may be arranged substantially perpendicular to a longitudinal direction L. The channel **506** of the airfoil section **502** may be connected to a feed channel **509** within one or more feed spokes **510** to a fuel riser **511**. The fuel riser **511** may convey fuel supplied from a fuel supply line **508**. The airfoil section **502** may have an acute trailing edge **106**, oriented substantially in the longitudinal direction L, and may also have a leading edge **514** that is rounded or angled. In some embodiments, the leading edge **514** may be sharply angled or tapered similar to the acute trailing edge **106**.

[0127] Embodiments of the tapered fuel nozzle **105** may further include a pilot or start-up fuel connection **504** for delivery of pilot or startup fuel from a pilot fuel line **512** to an ignition and start-up flame source **120** (such as a pilot burner). The pilot fuel line **512** is illustrated as being coaxial with fuel riser **511**. Alternatively, the pilot fuel line **512** may be disposed parallel to the fuel riser **511** or supplied from a different direction altogether. The pilot or start-up fuel connection **504** may be operably connected to the ignition source **120**. The ignition source or pilot burner **120** may include a nozzle (e.g., conventional nozzle **122** in FIG. **2**A) connected to the pilot fuel line **512** via the pilot or start-up fuel connection **504**. The nozzle of the ignition source or pilot burner **120** may be a conventional nozzle having a structure that, according to an interpretation, causes vortices to form in passing combustion air (oxidant). According to an interpretation, vortices formed due to a nozzle shape having relatively higher drag may aid in mixing pilot fuel with combustion air to support an ignited combustion reaction proximate the ignition source or pilot burner **120**. However, the vortices believed to be formed from such higher drag nozzle(s) are understood to also impede release or transfer of a start-up flame held near the nozzle.

[0128] The fuel nozzle assembly **104** is configured to allow airflow F to travel in the longitudinal direction L, airflow F combining with the fuel from the fuel orifices **108** to form the fuel oxidant mixture **112**. The fuel orifices **108** are equally spaced at or along the acute trailing edge **106** to aid homogenous mixture of fuel expelled therefrom with an oxidant (e.g., the air in airflow F) for the fuel and oxidant mixture **112**. The leading edge **514** may be rounded or otherwise formed with a reduced angle of attack with respect to the airflow F.

[0129] While the illustrated fuel nozzle assembly **104** is arranged with the airfoil section **502** forming a toric shape when viewed in the longitudinal direction L, (see FIG. **5**A), the airfoil section **502** may be formed in any other advantageous shape. The shape of the airfoil section **502** may be a two-dimensional, symmetrical shape, with the ignition source **120** arranged to have one or more igniters central thereto.

[0130] As described herein, a fuel nozzle assembly **104** according to an embodiment may be used to accomplish the preheating step **402** of the associated method shown in FIG. **4**. Accordingly, a preheat flame **206** may be produced by igniting a fuel and oxidant mixture (such as the fuel and oxidant mixture **112** of FIGS. **1-3**) at the ignition source **120**. Referring to FIG. **2**A, the pilot, start-up or preheat flame **206** is used to heat the perforated flame holder **102** until the perforated flame holder **102** is capable of sustaining a combustion reaction, which condition may be sensed as described herein.

[0131] In some embodiments the ignition source **120** may comprise a plurality of igniters disposed at various locations about the fuel nozzle assembly **104** to allow a preheat flame **206** to consume a portion of the fuel and oxidant mixture **112** expelled from orifices **108**, while an unconsumed portion of the fuel and oxidant mixture **112** reaches the perforated flame holder **102**. That is, fuel expelled from orifices **108** may be ignited during a start-up period to heat the perforated flame holder **102**. A combustion reaction at the perforated flame holder **102** then ignites the unconsumed portion of the fuel and oxidant mixture **112**. Partitioning the fuel and oxidant mixture **112** to include both a preheat flame or partial preheat flame and an unconsumed portion may also be accomplished by moving the ignition source **120** or igniters thereof from a first position to a second position. The first position allows the entire fuel and oxidant mixture **112** to be consumed by the preheat flame **206** and the second position allows the unconsumed portion of the fuel and oxidant mixture **112** to reach the perforated flame holder **102**. When the fuel nozzle **105** is used alternately for preheat and normal operating conditions, the perforated flame holder **102** or the nozzle **105** itself may be moved from one position to another to effect various changes in characteristics or results. For example, such position movement may effect a change in flame size, shape, and/or intensity; may change oxidant flow characteristics (e.g., by utilizing the airfoil section **502** to guide air in a desired manner), and/or may otherwise permit efficient use of fuel and/or oxidant for the preheat flame **206** for preheating the perforated flame holder **102**.

[0132] The fuel nozzle assembly **104** may be configured to allow the fuel and oxidant mixture **112** to reach the perforated flame holder **102** without being consumed by a preheat flame upon the disabling or partial disabling of the ignition source **120**. Both the acute trailing edge **106** and rounded leading edge **514** of the airfoil section **502** can be configured to reduce the angle of trajectory for the fuel as it leaves the fuel orifices **108** and/or configured to reduce the turbulence of the airflow as it passes the airfoil section **502**. The shape of the airfoil section **502**, including the acute trailing edge **106** and rounded leading edge **514**, thereby reduces the ability of the flame to propagate through the fuel and oxidant mixture **112** when the ignition and start-up flame source **120** is disabled or partially disabled.

[0133] The airfoil section **502** may be formed from a piece of tubing that may be elongated by rolling or some other method in order to form an elongated (e.g., oblong) internal channel **506**, where the trailing edge **106** may be machined or otherwise formed into a tapered shape as illustrated in FIG. **5**B. The airfoil section **502** may alternatively include a piece of tubing forming the channel **506** and a secondary structure attached to the tubing, such as a sheet metal structure formed into a V shape and welded or otherwise attached to the tubing, to form the acute trailing edge **106**. An example of this form is illustrated in the cross member **510** of FIG. **5**B. Other formation methods, such as extrusion, 3D printing, other methods, or a combination thereof, are also within the scope of this disclosure.

[0134] FIGS. **6**A-**6**E illustrate alternative fuel nozzle embodiments, wherein one or more individual fuel nozzles **218** may form at least part of a burner system (such as the burner system **200** shown in FIG. **2**B), according to embodiments. The fuel nozzles **218** may be arranged into an array of discrete nozzles, the combination of which may be similar in function to the toroidal fuel nozzle **105** described above, but without the unitary structure. The fuel nozzles **218** may be formed having a tapered profile and/or a pointed tip **602**, which provides advantages similar to the acute trailing edge **106** described above in connection with the toroidal fuel nozzle assembly **104** of FIGS. **5**A and **5**B. The fuel nozzles **218** may also be formed with a circumferential leading edge **514** that is rounded or angled (e.g., frustoconical). The fuel nozzles **218** may include at least one fuel orifice **226** that is located at or near the tip **602**. Like fuel orifices **108** described above, the fuel orifices **226** of fuel nozzle(s) **218** may have a dimension that is referred to as “nozzle diameter.” Each fuel orifice **226** may be in fluid connection with a fuel chamber **608** of the fuel nozzle **218** for distribution of fuel received from, e.g., one or more fuel supply lines such as the fuel riser **511** illustrated in FIGS. **6**A and **6**E.

[0135] The fuel nozzles **218** may also have an oblate or flattened section **604** formed thereon that can be utilized in handling the fuel nozzles **218** (e.g., for accepting a conventional wrench for installation and removal). Each of the fuel nozzles **218** may include a connection portion such as threads **606** for connection to one or more fuel supply lines, such as the fuel riser **511**. The connection portion may alternatively (or additionally) include a structure for pressure fit, snap fit, or other attachment mechanism. An array of the fuel nozzles **218** may be arranged in, e.g., a two-dimensional array (not shown) that may correspond to the shape of a perforated flame holder **102**.

[0136] The fuel nozzle **218** of FIG. **6**A has a single acicular tip **602** with an orifice **226** at or near the tip **602**, an external threading **606** disposed to permit threaded engagement with a complementary internal-threaded portion of the fuel supply line or fuel riser **511**. However, the fuel nozzle **218** may include more than one orifice **226**, as illustrated in FIGS. **6**B, **6**D, or may accommodate a relatively large central orifice **226** as shown in FIG. **6**C.

[0137] In some embodiments, it may be desirable for the fuel nozzle **218** to have an external diameter that is substantially the same as the diameter of the fuel riser **511** in order to best approximate laminar flow of oxidant past the fuel nozzle **218**. Thus the fuel nozzle **218** may have an attachment structure, such as threads **606** as shown in FIGS. **6**A-**6**D, disposed to engage the inside diameter of the fuel riser **511**. In other embodiments a fuel nozzle **218** may have an external structure having a larger diameter than the fuel riser **511**, as shown in FIG. **6**E that may effect a desired oxidant direction, mixing characteristic, or the like.

[0138] Those having skill in the art will acknowledge that various features of the fuel nozzles **218** described above may be implemented in various combinations. For example, a fuel nozzle **218** may have an outside diameter larger than the fuel riser **511** and may include a plurality of orifices **226**. As the fuel nozzles **218** may be arrayed in any pattern to facilitate delivery of fuel and oxidant to the perforated flame holder **102**, the fuel riser **511** may be formed having a lateral portion either remote from the fuel nozzles **218** or proximate the fuel nozzles **218**. For example, each fuel nozzle **218** in an array of nozzles may have a respective fuel riser **511** that extends a distance behind the fuel nozzles in a direction away from the perforated flame holder **102** and culminating in a manifold (not shown) that may deliver the fuel to the respective fuel risers **511**. This structure, in conjunction with individual fuel control valves (e.g., fuel control valve **236**) may facilitate individual control of fuel delivery to each fuel nozzle **218**. Alternatively, fuel may be delivered to the fuel nozzles **218** via a primary fuel riser **511** which may be divided proximate the fuel nozzles **218** via lateral fuel tubes (not shown).

[0139] FIG. **7** is a flowchart illustrating a process **700** for utilizing a burner system that includes a perforated flame holder and a tapered main fuel nozzle described herein. In step **702**, a perforated flame holder, such as the perforated flame holder **102** described above, is preheated. In some embodiments, a temperature of the perforated flame holder may be sensed and compared to a preheat threshold temperature (step **704**). In step **706**, an oxidant may be delivered to the perforated flame holder via an oxidant flow. For example an oxidant flow, such as air, may be supplied from an oxidant source via an oxidant conduit (e.g., conduit **110**, **220**) or other oxidant path. In some implementations, the oxidant flow may be directed to flow past one or more main fuel nozzles, such as the fuel nozzles **105**, **218** described above. In step **708**, a stream of fuel is emitted from such fuel nozzle(s) via one or more fuel delivery orifices, such as orifices **108**, **226** of the fuel nozzle(s). In implementations utilizing a temperature sensor, the delivery of the fuel may be controlled based on the sensed temperature. For example, the fuel stream may be initiated when a temperature output is received, from the temperature sensor, by a controller. The controller may compare the sensed temperature with a predetermined threshold temperature and may output a control signal indicating that the fuel may be emitted. In an embodiment, the control signal may control opening of an electromechanical valve to provide the fuel to the fuel nozzle. In some implementations, the control signal may be a simple binary (on/off) control, whereas in other implementations, the control signal may provide a range of analog or digital signals that may be used to control a rate of fuel delivery, oxidant delivery, and/or other parameters of the burner system.

[0140] The fuel nozzle(s), as described above, may have a structure, shape, and/or orientation that limits an amount of fuel and oxidant mixture near the fuel nozzle(s). For example, a tapered structure that decreases in width from a nozzle base to a nozzle tip (such as an acicular tip or acute trailing edge or tip) reduces an area that in conventional flat-ended fuel nozzles may provide a low pressure region adjacent the fuel delivery orifice. According to an interpretation, oxidant flowing past that low pressure region is drawn by the lower pressure and thus interrupts laminar flow. Resulting vortices cause mixture of oxidant and fuel near the orifice. In some instances the fuel-oxidant mixture proximate the fuel nozzle can support combustion. Thus, the tapered nozzle structure is provided to limit generation of such vortices—and thus shifts mixture of the fuel and oxidant to a region closer to the perforated flame holder.

[0141] The adjacent fuel stream and oxidant flow eventually mix proximate the perforated flame holder to provide a fuel and oxidant mixture (step **710**) for receipt by the perforated flame holder. The perforated flame holder, preheated and/or maintained at an operating temperature, ignites the fuel and oxidant mixture for combustion (step **712**).

[0142] FIG. **8** is a flowchart illustrating a method **800**, according to an embodiment for preheating a perforated flame holder of a burner system employing the fuel nozzle assembly described herein. In step **802**, fuel is delivered to a fuel and oxidant mixture through fuel nozzles with an acute trailing edge or tip, such as the fuel nozzles **105** and **218** described above, which, due to their aerodynamic shape, minimize formation of oxidant vortices proximate the fuel nozzle(s). At step **804**, the fuel and oxidant mixture is ignited to produce a preheat flame. The preheat flame is held at a disengagable, proximal flame holder disposed between the fuel nozzles and a perforated flame holder (such as perforated flame holder **102**) and is used to heat the perforated flame holder, step **806**. At step **808**, heat or temperature of the perforated flame holder is sensed or detected and compared with a predetermined preheat threshold to determine if the perforated flame holder is capable of sustaining a combustion reaction to consume the fuel and oxidant mixture. When the temperature of the perforated flame holder meets or exceeds the preheat threshold, the disengagable flame holder is disengaged (step **810**), and the fuel and oxidant mixture is then ignited and consumed by a combustion reaction at the perforated flame holder (step **812**) and perpetuated by heat radiating from the perforated flame holder. The ignition at the perforated flame holder may occur naturally from the heat of the perforated flame holder. According to this method **800**, an ignition source is configured to ignite the preheat flame between the fuel nozzle and the perforated flame holder. In some instances the ignition source may comprise one or a plurality of igniters.

[0143] The disengagable flame holder may, as described above, be a physically movable flame holder, an electrical charge introduced into the fuel and oxidant mixture between the nozzles and perforated flame holder, or may be vortices formed by aerodynamic characteristics of the burner and controllable by managing the flow characteristics (e.g., rate, direction, spread) of fuel and/or oxidant. It will be appreciated that the precise order of steps represented in FIG. **8** may include steps that occur simultaneously or that may be exchanged. For example, ignition of the fuel-oxidant mixture, or of an un-combusted portion of the fuel-oxidant mixture, at the perforated flame holder (step **812**) may occur prior to or at the same time as disengagement of the disengagable flame holder (step **810**).

[0144] FIG. **9** is a flowchart illustrating a method **900** according to another embodiment for preheating a perforated flame holder of a burner system employing the fuel nozzle assembly described herein. In method **900**, a preheating scheme permits a coordinated transfer of combustion by a preheating flame at a pilot fuel nozzle to combustion at a perforated flame holder. Initially, fuel may be supplied through one or more pilot fuel nozzles (step **902**), apart from any fuel supplied through a fuel nozzle assembly such as fuel nozzle assembly **104** described above.

[0145] Turning again to FIG. **9**, the fuel and oxidant mixture resulting from fuel delivered by the pilot fuel nozzle(s) is ignited to produce a preheat flame, step **904**, that heats the perforated flame holder, step **906**. The temperature at the perforated flame holder is sensed and compared to a predetermined preheat threshold temperature, step **908**. When the temperature at a sensed portion of the perforated flame holder is equal to or higher than the threshold temperature, the supply of fuel to the pilot nozzle(s) is adjusted (e.g., to a lower volume or off) (step **910**) while fuel is delivered to a fuel and oxidant mixture through one or more non-pilot fuel nozzles each having an acute trailing edge or tip (step **912**). The fuel and oxidant mixture from the non-pilot fuel nozzles may be auto-ignited at the sufficiently heated, perforated flame holder (step **914**), and, in some embodiments, from a reduced fuel flow from the pilot nozzle(s).

[0146] Once the combustion reaction is taking place at the perforated flame holder and is stable, the burner system may be operated according to the method described in connection with FIG. **4**.

[0147] FIGS. **10**A-**10**B illustrate side and top views, respectively, of a fuel nozzle **1018** having a plurality of fuel orifices **1026** (similar to fuel orifices **226** described above) arranged about a tapered portion of the fuel nozzle **1018**. The fuel nozzle **1018** may taper to a trailing tip **1002**. As noted above with respect to the fuel nozzles **218**, each fuel orifice **1026** is in fluid connection with a fuel chamber **1008**, may include an attachment structure such as threaded portion **1006**, and may include an oblate section **1004** that aids handling such as installation and removal.

[0148] Each fuel orifice **1026** may be connected to the fuel chamber **1008** via an orifice path **1010**. The orifice path **1010** may be selected to affect a desired swirl of fuel as it is emitted from the fuel nozzle **1018**. The orifice path **1018** and fuel orifice **1026** may be arranged to generate fuel distribution with a swirl number of 0.6 or less. In some embodiments each orifice path **1010** fuel orifice **1026** are arranged to result in a swirl number (in aggregate with oxidant swirl) that is much lower than 0.6. Swirl number is a dimensionless ratio of angular to axial momentum, e.g., as described by Chigier and Beer (N. A. Chigier, and J. M. Beer. *J. Basic Eng.* 788-796, 1964). While an actual swirl number is difficult to measure, a "geometric swirl number" may, in some instances, be based on the geometric angles of swirl generators.

[0149] Thus, a compound angle of an orifice path **1010** and fuel orifice **1026** can be provided that creates swirl in the fuel. Compound angle may be defined using at least two angles α and β. In FIGS. **10**A-**10**B a first orifice path angle α is provided relative to a longitudinal direction of the fuel nozzle **1018** and a center of the respective fuel orifice **1026**, while a second orifice path angle β is provided relative to a transverse direction of the fuel nozzle **1018** and a center of the respective fuel orifice **1026**.

[0150] Similarly, depending on swirl of associated oxidant introduced to the burner, the fuel nozzle **1018** can be configured to emit the fuel in a manner that enhances or that limits mixing of the fuel and oxidant. For example, fuel swirl introduced by the compound angle of the fuel orifice **1026** and its orifice path **1010** may be complementary to an oxidant swirl (thus limiting mixture initially) or may be opposed to an oxidant swirl (enhancing initial mixture). Because there are losses in the system, the geometric swirl number is always higher than the real swirl number.

[0151] FIGS. **11**A-**11**B illustrate a fuel nozzle **1118** having oxidant swirl features. For example, FIG. **11**A includes swirl fins or vanes **1120** configured to direct oxidant into a swirl pattern. The swirl fins or vanes **1120** may be attached to or formed integrally with the fuel nozzle **1118** and may stand out a distance from the surface of the fuel nozzle **1118**. For example, the swirl fins or vanes **1120** may stand out between ⅛ and ½ of the diameter of the fuel nozzle **1118**, may stand out $3/16$ to $5/16$ of the diameter of the fuel nozzle **1118**, or in some embodiments may stand out more than half the diameter of the fuel nozzle **1118**.

[0152] FIG. **11**B illustrates a variation of the fuel nozzle **1118** that includes grooves **1122** in the surface of the fuel nozzle **1118**. The grooves **1122** may effect oxidant swirl in a manner similar to the swirl fins or vanes **1120** in FIG. **11**A.

[0153] The oxidant swirl features described above may be combined with the fuel swirl features described with respect to FIGS. **10**A-**10**B. Moreover, one of ordinary skill in the art will recognize that fuel swirl features and fuel nozzle based oxidant swirlers may be implemented on any of the fuel nozzles or fuel nozzle assemblies described in this disclosure. For example, the fuel nozzle assembly **105** may include an oxidant swirling structure on the feed spokes **510**, on the airfoil section **502**, and/or on a start-up flame source **120**.

[0154] FIG. **12** illustrates a burner having the fuel nozzle **1018** described above with relation to FIGS. **10**A-**10**B and an oxidant conduit **1220** (having features in common with the oxidant conduits **120**, **220** described above). The oxidant conduit **1220** includes an oxidant swirler mechanism **1222**, such as swirl vanes, configured to provide oxidant swirl **1224** as the oxidant passes the fuel nozzle **1018**. Embodiments may include oxidant swirler mechanism(s) **1222** for primary oxidant and/or for secondary (recirculated) oxidant. Fuel swirling features (e.g., compound angles of orifice paths **1010** and fuel orifices **1026**) of the fuel nozzle **1018** may be selected to generate a fuel swirl **1230** that achieves a desired effect. For example, the fuel swirl features may be selected to substantially match fuel swirl to that of the swirled oxidant **1224** thus minimizing mixing of the oxidant and fuel proximate to the fuel nozzle and/or shifting mixture of the oxidant and fuel closer to a flame holder (e.g., perforated flame holder **102**).

[0155] FIG. **13** illustrates a method **1300** of delivering fuel and oxidant to a perforated flame holder (e.g., perforated flame holder **102**). Step **1302** includes delivering oxidant to a perforated flame holder via an oxidant conduit (e.g., conduit **110**, **220**, **1220** described above). In some embodiments, the oxidant conduit may include an oxidant swirling structure (e.g., oxidant swirling mechanism **1222** described above). Step **1304** includes delivering swirled fuel to the perforated flame holder via a fuel nozzle (e.g., fuel nozzle **1018**, **1118**) having an angled fuel orifice (e.g., fuel orifice **1026**, **1126**, and/or including orifice path **1010**). The angle of the fuel orifice generates a swirl pattern (e.g., fuel swirl **1230**) for fuel delivered therethrough. In step **1306**, an oxidant swirl feature of the fuel nozzle provides an oxidant swirl (e.g., oxidant swirl **1224**). Fuel nozzle embodiments including an oxidant swirl feature are described above with respect to FIG. **12**. It is appreciated that some embodiments of the method may alternatively, or additionally include oxidant swirl features, such as swirl vanes or fins, that are disposed in or integral to the oxidant conduit or as a separate feature. In an example, the oxidant swirl feature may be independent of both the oxidant conduit and the fuel nozzle, such as an oxidant swirl vane (not illustrated) suspended between the oxidant conduit and the perforated flame holder. Similarly, the inventors note that a fuel jet or stream may be redirected to form a fuel swirl by a structure external to the fuel nozzle. Such fuel redirection structure may include a physical diverting structure such as a flat or curved channel external to the fuel orifice.

[0156] As used herein, the term complete mixing can include mixing of fuel and oxidant such that there is less than 1% variation in concentration of the fuel in the oxidant or combustion air. As used herein, the term complete mixing can include mixing of fuel and combustion air such that there is a less than 0.1% variation in concentration of the fuel in the oxidant.

[0157] FIG. **14** is a block diagram of a combustion system **1400**, according to one embodiment. The combustion system **1400** includes a perforated flame holder **102** and a fuel and oxidant source **202** positioned in a furnace volume **1401**.

[0158] According to an embodiment, the fuel and oxidant source **202** is configured to output an oxidant **1407** and a fuel stream **1405** including a fuel into the furnace volume **1401**. The fuel and oxidant source **202** is configured to promote mixing of the oxidant **1407** with the fuel stream **1405** by imparting a swirling motion to at least one of the fuel stream **1405** and the oxidant **1407**.

[0159] According to an embodiment, the perforated flame holder **102** is positioned to receive the fuel stream **1405** and is configured to support a combustion reaction **302** of the fuel and the oxidant **1407** within the perforated flame holder **102**. The perforated flame holder **102** is separated from the fuel and oxidant source **202** by a dilution distance D_D selected to enable complete mixing of the oxidant **1407** with the fuel stream **1405**. According to an embodiment, the dilution distance D_D corresponds to a distance at which complete mixing of the fuel and the oxidant **1407** would not occur in the absence of the swirling motion.

[0160] According to an embodiment, complete mixing of the fuel and the oxidant **1407** can include mixing of the fuel and the oxidant **1407** such that there is less than 1% variation in concentration of the fuel in the oxidant **1407**. In an example in which the oxidant **1407** includes combustion air, complete mixing can include mixing of the fuel and the combustion air such that there is less than 1% variation in concentration of the fuel in the combustion air.

[0161] According to an embodiment, complete mixing of the fuel and the oxidant **1407** can include mixing of the fuel and the oxidant **1407** such that there is less than 0.1% variation in concentration of the fuel in the oxidant **1407**. In an example in which the oxidant **1407** includes combustion air, complete mixing can include mixing of the fuel and the combustion air such that there is less than 0.1% variation in concentration of the fuel in the combustion air.

[0162] According to an embodiment, the fuel and oxidant source **202** can include a fuel nozzle configured to output the fuel stream **1405**. The fuel nozzle can include a plurality of apertures each configured to output a respective fuel stream **1405** including the fuel. The fuel nozzle can include a plurality of fuel channels each configured to convey a respective fuel stream **1405** to a respective aperture. Each fuel channel can convey the respective fuel stream **1405** at a respective compound angle with respect to a central axis of the fuel nozzle. The apertures and the fuel channels can collectively impart a swirling motion on the fuel streams **1405**.

[0163] According to an embodiment, the perforated flame holder **102** is separated from the fuel nozzle by the dilution distance D_D. According to an embodiment, the dilution distance D_D is less than 100 times the diameter of one of the apertures. According to an embodiment, the dilution distance D_D is less than 50 times the diameter of one of the apertures. According to an embodiment, the dilution distance D_D is less than 20 times the diameter of one of the apertures. In one embodiment, all of the apertures have a same diameter.

[0164] According to an embodiment, the fuel and oxidant source **202** can include a swirler configured to impart the swirling motion to the oxidant **1407**. Additionally, or alternatively, the fuel and oxidant source **202** can include a blower configured to blow oxidant **1407** into the furnace volume **1401**. Additionally, or alternatively, the fuel and oxidant source **202** can draft the oxidant **1407** into the furnace volume **1401**. Additionally, or alternatively, the fuel and oxidant source **202** can include a barrel register configured to draft the oxidant **1407** into the furnace volume **1401**.

[0165] FIG. **15** is a diagram of a combustion system **1500**, according to an embodiment. The combustion system **1500** includes a perforated flame holder **102** in a furnace volume **1501**. The combustion system **1500** further includes fuel nozzles **1508**, a fuel source **1522**, and an oxidant source **1510**.

[0166] According to an embodiment, the fuel source **1522** supplies a fuel to the fuel nozzles **1508**. Each fuel nozzle **1508** includes a plurality of apertures **1518**. When the fuel source **1522** supplies the fuel to the fuel nozzles **1508**, each aperture **1518** outputs a respective fuel stream **1405** including the fuel.

[0167] According to an embodiment, the oxidant source **1510** outputs an oxidant **1407** into the furnace volume **1501**.

[0168] According to an embodiment, the components of the combustion system **1500** are configured to impart a swirling motion to at least one of the fuel stream **1405** and the oxidant **1407**. The swirling motion is configured to promote mixing of the oxidant **1407** with the fuel stream **1405** by causing more vigorous mixing of the fuel stream **1405** and the oxidant **1407**.

[0169] In one embodiment, the perforated flame holder **102** is positioned to receive the fuel stream **1405** and is configured to support a combustion reaction **1540** of the fuel and oxidant **1405** within the perforated flame holder **102**. The perforated flame holder **102** is separated from the fuel and oxidant source **202** by a dilution distance D_D selected to enable complete mixing of the oxidant **1407** with the fuel stream **1405**. The dilution distance D_D corresponds to a distance at which complete or sufficient mixing of the fuel and oxidant **1405** would not occur in the absence of the swirling motion.

[0170] According to an embodiment, complete or sufficient mixing refers to a level of mixing of the fuel and oxidant **1405** that results in an output of oxides of nitrogen and carbon monoxide from the combustion reaction **1540** below respective threshold levels.

[0171] According to an embodiment, the dilution distance is less than 100 times the diameter of one of the apertures **1518**. According to an embodiment, the dilution distance is less than 50 times the diameter of one of the apertures **1518**.

[0172] According to an embodiment, the dilution distance is less than 20 times the diameter of one of the apertures **1518**. In one embodiment, all of the apertures **1518** have a same diameter.

[0173] According to an embodiment, the fuel nozzle **1508** outputs the fuel stream **1405** from the apertures **1518** with a swirling motion. The swirling motion enhances mixing of the fuel stream **1405** and oxidant **1407**.

[0174] According to an embodiment, the oxidant source **1510** outputs the oxidant **1407** with a swirling motion that enhances mixing of the fuel stream **1405** and the oxidant **1407**.

[0175] According to an embodiment, the fuel nozzles **1508** output a plurality of fuel streams **1405** including the fuel toward the perforated flame holder **102**. The fuel streams **1405** mix with the oxidant **1407** and enter into the perforated flame holder **102**.

[0176] According to an embodiment, each aperture **1518** outputs a respective fuel stream **1405**. The apertures **1518** output the fuel streams **1405** with a trajectory and characteristics selected to sufficiently mix with the oxidant **1407** before the fuel streams **1405** reach the perforated flame holder **102**. If the fuel streams **1405** sufficiently mix with the oxidant **1407** before the fuel streams **1405** reach the perforated flame holder **102**, then the perforated flame holder **102** can sustain the combustion reaction **1540** of the fuel and the oxidant **1407** within the perforated flame holder **102**.

[0177] According to an embodiment, the fuel nozzles **1508** output the plurality of fuel streams **1405** with trajectories that enhance the mixing of the oxidant **1407** in comparison to a situation in which the fuel streams **1405** are each output with a same trajectory straight toward the perforated flame holder **102**. According to an embodiment, the fuel nozzles **1508** output the fuel streams **1405** with a vortex motion. The vortex motion enhances the mixing of the oxidant **1407** in the fuel streams **1405**. According to an embodiment, the fuel nozzle **1508** includes a plurality of fuel channels that each convey the fuel to the respective aperture **1518**. Each fuel channel is formed within a fuel nozzle **1508**

at a respective angle with respect to a central axis of the fuel nozzle **1508**. The central axis includes a shortest distance between the fuel nozzle **1508** and the perforated flame holder **102**. The respective angles of the fuel channels cause the apertures **1518** to output the fuel streams **1405** with trajectories that enhance mixing of the oxidant **1407** with the fuel streams **1405**. According to an embodiment, the fuel channels and the apertures **1518** cause the output of the fuel streams **1405** at respective compound angles with respect to the central axis of the fuel nozzle **1508**.

[0178] According to an embodiment, the combustion system **1500** imparts a motion to the oxidant **1407** that enhances mixing in the oxidant **1407** with the fuel stream(s) **1405**. For example, the oxidant source **1510** can include a blower that blows the oxidant **1407** into the furnace volume **1501** with a motion that enhances mixing of the oxidant **1407** with the fuel stream(s) **1405**. According to an embodiment, the combustion system **1500** includes one or more swirlers that impart a swirling or vortex motion to the oxidant **1407**. The swirling or vortex motion of the oxidant **1407** enhances mixing of the oxidant **1407** with the fuel stream(s) **1405**.

[0179] FIG. **16** is an enlarged illustration of a fuel nozzle **1608**, according to an embodiment. The fuel nozzle **1608** includes an aerodynamic shape that comes to a sharp point at the top. The fuel nozzle **1608** defines a central axis **1650** that points straight to the perforated flame holder **102**. The fuel nozzle **1608** includes a plurality of apertures **1518**. The fuel nozzle **1608** includes a plurality of fuel channels **1652** positioned within the fuel nozzle **1608** and represented by dashed lines. Each of the fuel channels **1652** conveys the fuel to the respective aperture **1518**. According to an embodiment, the fuel channels **1652** are formed with a compound angle relative to the central axis **1650**. As the fuel flows through the fuel channel **1652** and exits the apertures **1518**, the configuration of the fuel channel **1652** imparts a vortex motion to the fuel streams **1405** exiting the apertures **1518**. Because the fuel streams **1405** have a swirling or vortex motion, the fuel streams **1405** are capable of mixing with the oxidant **1407** in a relatively short distance. Each of the apertures **1518** outputs a fuel stream **1405** at a respective angle with respect to the central axis **1650**. The various angles enhance the overall mixing of the oxidant **1407** with the fuel streams **1405**. In particular, the vortex motion causes the fuel streams **1405** to mix with the oxidant **1407** in a shorter distance than otherwise would be achieved in similar conditions, but with each fuel stream **1405** being injected parallel to the central axis **1650**.

[0180] FIG. **17** is an enlarged illustration of a fuel nozzle **1708**, according to an embodiment. The fuel nozzle **1708** includes an aerodynamic shape that comes to a sharp point at the top. The fuel nozzle **1708** defines a central axis **1650** that points straight to the perforated flame holder **102**. The fuel nozzle **1708** includes a plurality of apertures **1518**. Each of the apertures **1518** outputs a fuel stream **1405** at a respective angle with respect to the central axis **1650**. The various angles enhance the overall mixing of the oxidant **1407** with the fuel streams **1405**.

[0181] FIG. **18** is an enlarged illustration of a fuel nozzle **1808**, according to an embodiment. The fuel nozzle **1808** includes an aerodynamic shape that comes to a sharp point at the top. The fuel nozzle **1808** defines a central axis **1650** that points straight to the perforated flame holder **102**. The fuel nozzle **1808** includes a plurality of apertures **1518** that face substantially perpendicular to the central axis **1650**. The fuel nozzle **1808** includes a plurality of fuel channels **1852** positioned within the fuel nozzle **1808** and represented by dashed lines. Each of the fuel channels **1852** conveys the fuel to a respective aperture **1518**. According to an embodiment, the fuel channels **1852** are formed with respective angles that are substantially perpendicular to central axis **1650**. The fuel nozzle **1808** also includes an internal main fuel channel **1856** that supplies the fuel to the fuel channels **1852** and is represented by dashed lines. Thus, the fuel nozzle **1808** outputs the fuel streams **1405** at an angle substantially perpendicular to the central axis **1650**. According to an embodiment, the oxidant **1407** is introduced into the furnace volume with a relatively high upward velocity. As the oxidant **1407** flows toward the perforated flame holder **102**, the oxidant **1407** mixes with the fuel streams **1405** causing mixing of the oxidant **1407** with the fuel streams **1405**. Additionally, the upper velocity of the oxidant **1407** causes both fuel streams **1405** mixed with the oxidant **1407** to flow upward toward the perforated flame holder **102**. Because the fuel streams **1405** and the oxidant **1407** have trajectories that are initially transverse to each other, and in some embodiments perpendicular to each other, the mixing of the oxidant **1407** with the fuel streams **1405** is enhanced. Sufficient mixing of the oxidant **1407** with the fuel streams **1405** can occur in a relatively short distance. Thus, when the fuel streams **1405**, mixed with the oxidant **1407**, reach the perforated flame holder **102**, the perforated flame holder **102** can sustain the combustion reaction **1540** of the fuel and the oxidant **1407** substantially within the perforated flame holder **102**.

[0182] According to an embodiment, the fuel channels **1852** and the apertures **1518** impart a lateral rotational motion to the fuel streams **1405** as they exit the apertures **1518**. This can be achieved, for example, by having the fuel channels **1852** formed in compound angles, or by effect of the fuel streams **1405** impinging on the rounded outer wall of the preheating flame holder **2160** (see, e.g., FIG. **21**). The rotational motion of the fuel streams **1405** can further enhance the mixing of the oxidant **1407** with the fuel streams **1405**.

[0183] FIG. **19** is an illustration of a fuel nozzle **1908** and a swirler **1960** of a combustion system, according to an embodiment. According to an embodiment, the oxidant source **1510** outputs the oxidant **1407** with an upward motion toward the perforated flame holder **102**. The swirlers **1960** impart a swirling or vortex motion to the oxidant **1407** as the oxidant **1407** travels upward toward the perforated flame holder **102**. The swirling or vortex motion of the oxidant **1407** enhances mixing of the oxidant **1407** with the fuel streams **1405** output from the fuel nozzle **1908**. The enhanced mixing of the oxidant **1407** with the fuel streams **1405** enables mixing within a shorter distance. This means that the fuel nozzle **1908** can be positioned relatively close to the perforated flame holder **102** and yet have sufficient mixing of the fuel streams **1405** and the oxidant **1407** before the fuel streams **1405** reach the perforated flame holder **102**.

[0184] According to an embodiment, the swirlers **1960** can rotate around the fuel nozzle **1908**. Alternatively, the swirlers **1960** can include fan blades that rotate on either side of the fuel nozzle **1908**. According to an embodiment, the oxidant source **1510** can include a blower **238** that both blows the oxidant **1407** toward the perforated flame holder **102** and imparts a vortex or swirling motion to the oxidant **1407**.

[0185] FIG. **20** is a flow diagram of a process **2000** for operating a combustion system, according to an embodiment. At **1002**, an oxidant is output into a furnace volume. At **1004**, a fuel stream is output into the furnace volume. At **1006**, the oxidant is mixed with the fuel stream by imparting a swirling motion to at least one of the oxidant and the fuel stream. At **1008**, a perforated flame holder is supported in the furnace volume separated from the fuel and oxidant source by a dilution distance selected to enable complete mixing of the oxidant with the fuel stream, the dilution distance corresponding to a distance at which complete mixing of the fuel and the oxidant would not occur in the absence of the swirling motion. At **1010**, the fuel stream and the oxidant are received at the perforated flame holder. At **1012**, a combustion reaction of the fuel and the oxidant is supported within the perforated flame holder.

[0186] FIG. **21** is block diagram of a combustion system **2100**, according to one embodiment. The combustion system **2100** includes a perforated flame holder **102** and a preheating flame holder **2160** positioned in a furnace volume **1401**. The combustion system **2100** also includes a preheating fuel nozzle **2162**, a primary fuel nozzle **1508**, and an oxidant source **1510**. According to an embodiment, the components of the combustion system **2100** are operable to preheat the perforated flame holder **102** to a threshold temperature and to support a combustion reaction **1540** within the perforated flame holder **102** after the perforated flame holder **102** has reached the threshold temperature.

[0187] According to an embodiment, the combustion system **2100** operates in a preheating state by supporting a preheating flame that transfers heat to the perforated flame holder **102** and preheats the perforated flame holder **102** to the threshold temperature. In the preheating state, the preheating fuel nozzle **2162** outputs a preheating fuel stream including the preheating fuel onto the preheating flame holder **2160**. The oxidant source **1510** introduces an oxidant **1407** into the furnace volume **1401**. The preheating flame holder **2160** holds a preheating flame supported by the preheating fuel and the oxidant **1407**. The preheating flame holder **2160** is positioned relative to the perforated flame holder **102** so that the perforated flame holder **102** can be heated by the preheating flame held by the preheating flame holder **2160**.

[0188] According to an embodiment, the combustion system **2100** enters the normal operating state after the perforated flame holder **102** has been heated to the threshold temperature. In the normal operating state, the preheating fuel nozzle **2162** ceases to output the preheating fuel stream onto the preheating flame holder **2160**, thereby removing the preheating flame. After the preheating fuel nozzle **2162** has ceased to output the preheating fuel stream onto the preheating flame holder **2160**, the primary fuel nozzle **1508** begins outputting a primary fuel stream **1405** including a primary fuel onto the perforated flame holder **102**. The primary fuel nozzle **1508** and the oxidant source **1510** collectively output the primary fuel stream **1405** and the oxidant **1407** in such a way that the primary fuel stream **1405** mixes with the oxidant **1407** as the primary fuel stream **1405** travels toward the perforated flame holder **102** in spite of a relatively short distance between the perforated flame holder **102** and the primary fuel nozzle **1508**. Because the perforated flame holder **102** has been heated to the threshold temperature, and because the primary fuel stream **1405** has mixed with the oxidant **1407** before reaching the perforated flame holder **102**, the perforated flame holder **102** sustains a combustion reaction **1540** of the primary fuel and the oxidant **1407** primarily within the perforated flame holder **102**.

[0189] According to an embodiment, the primary fuel nozzle **1508** includes a plurality of apertures **1518** that each output a respective primary fuel stream **1405** toward the perforated flame holder **102**. The plurality of primary fuel streams **1405** are able to mix with the oxidant **1407** in a shorter distance than if the primary fuel nozzle **1508** outputs a single primary fuel stream **1405** equal to the collective flow rate of the plurality of primary fuel streams **1405**. Accordingly, rather than outputting a single large primary fuel stream **1405**, the primary fuel nozzle **1508** outputs a plurality of primary fuel streams **1405**. The plurality of primary fuel streams **1405** mix with the oxidant **1407** prior to impinging on the perforated flame holder **102**. The perforated flame holder **102** supports a combustion reaction **1540** of the primary fuel and the oxidant **1407** primarily within the perforated flame holder **102**.

[0190] According to an embodiment, the primary fuel nozzle **1508** outputs the plurality of primary fuel streams **1405** with trajectories that enhance the mixing of the oxidant **1407** in comparison to the situation in which the primary fuel streams **1405** each output a single trajectory straight toward the perforated flame holder **102**. According to an embodiment, the primary fuel nozzle **1508** outputs the primary fuel streams **1405** with a vortex motion. The vortex motion enhances the mixing of the oxidant **1407** in the primary fuel streams **1405**. According to an embodiment, the primary fuel nozzle **1508** includes a plurality of fuel channels **1652** that each convey the primary fuel to the respective aperture **1518**. Each fuel channel **1652** is formed within the primary fuel nozzle **1508** at a respective angle with respect to a central axis **1650** of the primary fuel nozzle **1508**. The central axis **1650** includes a shortest distance between the primary fuel nozzle **1508** and the perforated flame holder **102**. The respective angles of the primary fuel channels **1652** cause the apertures **1518** to output the primary fuel streams **1405** with trajectories that enhance mixing of the oxidant **1407** with the primary fuel streams **1405**. According to an embodiment, the fuel channels **1652** and the apertures **1518** cause the output of the primary fuel streams **1405** at respective compound angles with respect to the central axis **1650** of the primary fuel nozzle **1508**.

[0191] According to an embodiment, the combustion system **2100** imparts a motion to the oxidant **1407** that enhances mixing in the oxidant **1407** with the primary fuel stream(s) **1405**. For example, the oxidant source **1510** can include a blower **238** that blows the oxidant **1407** into the furnace volume **1401** with a motion that enhances mixing of the oxidant **1407** with the primary fuel stream(s) **1405**. According to an embodiment, the combustion system **2100** includes one or more swirlers **1960** that impart a swirling or vortex motion to the oxidant **1407**. The swirling or vortex motion of the oxidant **1407** enhances mixing of the oxidant **1407** with the primary fuel stream(s) **1405**.

[0192] According to an embodiment, the combustion system **2100** includes a controller **2164** and the temperature sensor **2168**. The controller **2164** is coupled to the temperature sensor **2168**, the preheating fuel nozzle **2162**, and the primary fuel nozzle **1508**. The temperature sensor **2168** senses the temperature of the perforated flame holder **102** during the preheating state and outputs a temperature signal indicating the temperature of the perforated flame holder **102** to the controller **2164**. When the temperature of the perforated flame holder **102** reaches the threshold temperature at which the perforated flame holder **102** can sustain combustion of the primary fuel and oxidant (or fuel stream) **1405**, the controller **2164** causes the combustion system **2100** to exit the preheating state by removing the preheating flame.

[0193] According to an embodiment, the controller **2164** removes the preheating flame by causing the preheating fuel nozzle **2162** to cease outputting the preheating fuel stream. When the preheating fuel nozzle **2162** ceases to output the preheating fuel stream, the preheating flame is extinguished. Thus, shutting off the preheating fuel nozzle **2162** removes the preheating flame.

[0194] According to an embodiment, after the preheating flame is removed, the controller **2164** causes the combustion system **2100** to enter the standard operating phase. The controller **2164** causes the combustion system **2100** to enter into the standard operating phase by causing the primary fuel nozzle **1508** to output the primary fuel stream(s) **1405** toward the perforated flame holder **102**. The characteristics of the primary fuel stream(s) **1405** and the oxidant **1407** cause the primary fuel stream(s) **1405** to mix with the oxidant **1407** en route to the perforated flame holder **102**. Because the perforated flame holder **102** has been preheated to the threshold temperature, the perforated flame holder **102** sustains a combustion reaction **1540** of the primary fuel and oxidant **1407** within the perforated flame holder **102**.

[0195] According to an embodiment, the controller **2164** executes software instructions causing the controller **2164** to automatically cause the preheating fuel nozzle **2162** and the primary fuel nozzle **1508** to output or cease outputting the preheating fuel streams based on the temperature sensor **2168**. Alternatively, the controller **2164** can cause the preheating fuel nozzle **2162** and the primary fuel nozzle **1508** to cease outputting the preheating fuel streams based on input from a technician. The input can include entering instructions via an input device such as a keyboard, a touchscreen, audio commands, or the like. The temperature sensor **2168** can output temperature data to the controller **2164** or in a manner that the technician can ascertain the temperature of the perforated flame holder **102**. The technician can then cause the controller **2164** to adjust the operation of the preheating and primary fuel nozzles **2162**, **1508**.

[0196] According to one embodiment, the combustion system **2100** is functional to allow a technician to directly control the preheating and primary fuel nozzles **2162**, **1508** without the controller **2164** by operating switches, buttons, manual valves, or in another suitable way. Thus, according to an embodiment, the controller **2164** may not be present. Additionally, or alternatively, the temperature sensor **2168** may not be present. In this case, the technician can view the perforated flame holder **102** to determine, based on the color, or other visual characteristics of the perforated flame holder **102**, that the perforated flame holder **102** has reached the threshold temperature. The technician can then cause the primary fuel nozzle **1508** to cease outputting fuel.

[0197] According to one embodiment, the combustion system **2100** includes a plurality of preheating fuel nozzles **2162**, each configured to output a respective preheating fuel stream onto the preheating flame holder **2160**. The preheating flame holder **2160** holds a combustion reaction **1540** of the preheating fuel and the oxidant **1407** during the preheating state of the combustion system **2100**.

[0198] According to one embodiment, the combustion system **2100** includes a plurality of primary fuel nozzles **1508**, each configured to output a plurality of primary fuel streams **1405**. The preheating flame holder **2160** holds a combustion reaction **1540** of the preheating fuel and the oxidant **1407** during the preheating state of the combustion system **2100**.

[0199] FIG. **22**A is a diagram of a combustion system **2200**, according to an embodiment. The combustion system **2200** includes the perforated flame holder **102** and the preheating flame holder **2160** disposed in the furnace volume **1501**. The combustion system **2200** further includes the preheating fuel nozzles **2162**, the primary fuel nozzles **1508**, a preheating fuel source **2271**, a primary fuel source **2272**, the oxidant source **1510**, the controller **2164**, and the temperature sensor **2168**. The preheating fuel source **2271** is configured to supply a preheating fuel to the preheating fuel nozzles **2162** on a preheating fuel line **2273**. A valve **2274** can control the flow of the preheating fuel from the preheating fuel source **2271** to the preheating fuel nozzles **2162**. The primary fuel source **2272** is configured to supply a primary fuel to the primary fuel nozzles **1508** on a fuel line **2275**. A valve **2276** can control the flow of the primary fuel from the primary fuel source **2272** to the primary fuel nozzles **1508**. According to an embodiment, the components of the combustion system **2200** are operable to preheat the perforated flame holder **102** to a threshold temperature and to support a combustion reaction **1540** within the perforated flame holder **102** after the perforated flame holder **102** has reached the threshold temperature.

[0200] FIG. **22**B is a diagram of the combustion system **2200** of FIG. **22**A in a preheating state. In the preheating state, the combustion system **2200** preheats the perforated flame holder **102** to a threshold temperature at which the perforated flame holder **102** can sustain a stable combustion reaction **1540** of the primary fuel and the oxidant **1407** within the perforated flame holder **102**.

[0201] According to an embodiment, in the preheating state, the preheating fuel nozzles **2162** output respective preheating fuel streams **2279** including the preheating fuel. In particular, in the preheating state, the valve **2274** in the preheating fuel line **2273** is opened so that the preheating fuel can flow from the preheating fuel source **2271** to the preheating fuel nozzles **2162**. The preheating fuel nozzles **2162** output the preheating fuel streams **2279** onto the preheating flame holder **2160**. The oxidant source **1510** introduces an oxidant **1407** into the furnace volume **1501**. The preheating fuel streams **2279** mix with the oxidant **1407** and impinge upon the preheating flame holder **2160**. The preheating flame holder **2160** holds a preheating flame **2280** of the preheating fuel and the oxidant **1407** at a top surface **2278** of the preheating flame holder **2160**.

[0202] According to an embodiment, the preheating flame **2280** transfers heat to the perforated flame holder **102**. In particular, the perforated flame holder **102** and the preheating flame holder **2160** are positioned relative to each other such that the preheating flame **2280** heats the perforated flame holder **102**. The combustion system **2200** maintains the preheating flame **2280** held on the preheating flame holder **2160** until the perforated flame holder **102** has reached the threshold temperature. The threshold temperature is the temperature at which the perforated flame holder

102 can sustain a combustion reaction **1540** of the primary fuel and the oxidant **1407** within the perforated flame holder **102**. Once the perforated flame holder **102** has reached the threshold temperature, the combustion system **2200** exits the preheating state and enters the standard operating state.

[0203] According to an embodiment, the combustion system **2200** transitions from the preheating state to the standard operating state by causing the preheating fuel nozzles **2162** to stop outputting the preheating fuel streams **2279** and by causing the primary fuel nozzles **1508** to output the primary fuel streams **1405**. This can be accomplished by closing the valve **2274** and opening the valve **2276**.

[0204] According to an embodiment, the temperature sensor **2168** detects the temperature of the perforated flame holder **102** and passes a temperature signal indicating the temperature of the perforated flame holder **102** to the controller **2164**. The controller **2164** receives the temperature signal. When the controller **2164** detects that the perforated flame holder **102** has reached the threshold temperature, the controller **2164** causes the preheating fuel nozzles **2162** to cease outputting the preheating fuel streams **2279** by closing the valve **2274**. When the preheating fuel nozzles **2162** cease outputting the preheating fuel streams **2279**, the preheating flame **2280** is extinguished. The controller **2164** causes the combustion system **2200** to transition to the normal operating state by opening the valve **2276** that enables a flow of the primary fuel to the primary fuel nozzles **1508**.

[0205] According to an embodiment, the combustion system **2200** transitions from the preheating state to the standard operating state under the control of a technician. In particular, the technician can view the temperature of the perforated flame holder **102** on a display or by directly viewing the visual characteristics of the perforated flame holder **102**. When the technician determines that the perforated flame holder **102** has reached the threshold temperature, the technician can cause the combustion system **2200** to transfer from the preheating state to the standard operating state. The technician can cause the combustion system **2200** to transition to the standard operating state by inputting commands to the controller **2164**, or by manually turning one or more switches, dials, knobs or other input devices, in order to cause the preheating fuel nozzles **2162** to cease outputting the preheating fuel streams **2279** and to cause the primary fuel nozzles **1508** to begin outputting primary fuel streams **1405**.

[0206] FIG. 22C is a diagram of the combustion system **2200** of FIG. 22A in the standard operating state. In the standard operating state, the perforated flame holder **102** has reached the threshold temperature and the valve **2276** has been opened so that the primary fuel source **2272** supplies the primary fuel to the primary fuel nozzles **1508**. The primary fuel source **2272** supplies the primary fuel to the primary fuel nozzles **1508** via the fuel line **2275**.

[0207] According to an embodiment, the primary fuel nozzles **1508** output a plurality of primary fuel streams **1405** including the primary fuel toward the perforated flame holder **102**. The primary fuel streams **1405** mix with the oxidant **1407** and enter into the perforated flame holder **102**. Because the perforated flame holder **102** is at the threshold temperature, the perforated flame holder **102** sustains a combustion reaction **1540** of the primary fuel and the oxidant **1407** primarily within the perforated flame holder **102**. Thus, in the standard operating state, the perforated flame holder **102** supports a combustion reaction **1540** of the primary fuel and the oxidant **1407** within the perforated flame holder **102**.

[0208] According to an embodiment, the primary fuel nozzles **1508** each include a plurality of apertures **1518**. Each aperture **1518** outputs a respective primary fuel stream **1405**. The apertures **1518** output the primary fuel streams **1405** with a trajectory and characteristics selected to sufficiently mix with the oxidant **1407** before the primary fuel streams **1405** reach the perforated flame holder **102**. If the primary fuel streams **1405** sufficiently mix with the oxidant **1407** before the primary fuel streams **1405** reach the perforated flame holder **102**, then the perforated flame holder **102** can sustain the combustion reaction **1540** of the primary fuel and oxidant **1405** within the perforated flame holder **102**.

[0209] According to an embodiment, the primary fuel nozzles **1508** output the plurality of primary fuel streams **1405** with trajectories that enhance the mixing of the oxidant **1407** in comparison to a situation in which the primary fuel streams **1405** are each output with a same trajectory straight toward the perforated flame holder **102**. According to an embodiment, the primary fuel nozzles **1508** output the primary fuel streams **1405** with a vortex motion. The vortex motion enhances the mixing of the oxidant **1407** in the primary fuel streams **1405**. According to an embodiment, the primary fuel nozzle **1508** includes a plurality of fuel channels **1652** that each convey the primary fuel to the respective aperture **1518**. Each fuel channel **1652** is formed within a primary fuel nozzle **1508** at a respective angle with respect to a central axis **1650** of the primary fuel nozzle **1508**. The central axis **1650** includes a shortest distance between the primary fuel nozzle **1508** and the perforated flame holder **102**. The respective angles of the fuel channels **1652** cause the apertures **1518** to output the primary fuel streams **1405** with trajectories that enhance mixing of the oxidant **1407** with the primary fuel streams **1405**. According to an embodiment, the fuel channels **1652** and apertures **1518** cause the output of the primary fuel streams **1405** at respective compound angles with respect to the central axis **1650** of the primary fuel nozzle **1508**.

[0210] According to an embodiment, the combustion system **2200** imparts a motion to the oxidant **1407** that enhances mixing in the oxidant **1407** with the primary fuel stream(s) **1405**. For example, the oxidant source **1510** can include a blower **238** that blows the oxidant **1407** into the furnace volume **1401** with a motion that enhances mixing of the oxidant **1407** with the primary fuel stream(s) **1405**. According to an embodiment, the combustion system **2200** includes one or more swirlers **1960** that impart a swirling or vortex motion to the oxidant **1407**. The swirling or vortex motion of the oxidant **1407** enhances mixing of the oxidant **1407** with the primary fuel stream(s) **1405**.

[0211] FIG. 22D is a top view of the preheating flame holder **2160**, the preheating fuel nozzles **2162**, and the primary fuel nozzles **1508**, according to an embodiment. The preheating flame holder **2160** includes a toroidal shape that defines a central opening **1547** in the preheating flame holder **2160**. According to an embodiment, the plurality of preheating fuel nozzles **2162** are positioned in the central opening of the preheating flame holder **2160**. According to an embodiment, the primary fuel nozzles **1508** extend through the central opening of the preheating flame holder **2160**. Because the primary fuel nozzles **1508** extend through the central opening **1547**, the primary fuel nozzles **1508** are closer to the perforated flame holder **102** than is the preheating flame holder **2160**. In the embodiment of FIG. **22**D, each primary fuel nozzle **1508** includes four apertures **1518**. However, in practice, each primary fuel nozzle **1508** can have fewer or more apertures **1518** than are shown in FIG. **22**D.

[0212] FIG. **23** is a flow diagram of a process **2300** for operating a combustion system, according to an embodiment. At **2302**, an oxidant is introduced into the furnace volume. At **2304**, a preheating fuel stream including a preheating fuel is output from a preheating fuel nozzle onto a preheating flame holder positioned within the furnace volume. At **2306**, a perforated flame holder is preheated to a threshold temperature by supporting a preheating flame of the preheating fuel and oxidant on the preheating flame holder. At **2308**, a plurality of primary fuel streams with respective trajectories configured to mix with the oxidant are output. At **2310**, the primary fuel streams and entrained oxidant are received in the perforated flame holder. At **2312**, a combustion reaction of the primary fuel and oxidant is supported within the perforated flame holder after the perforated flame holder has reached the threshold temperature.

[0213] While various aspects and embodiments have been disclosed herein, other aspects and embodiments are contemplated. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

1.-**61**. (canceled)

62. A method, comprising:

outputting an oxidant into a furnace volume;

outputting a fuel stream including a fuel into the furnace volume;

mixing the oxidant and the fuel stream;

supporting a perforated flame holder in the furnace volume separated from the fuel and oxidant source by a dilution distance selected to enable complete mixing of the oxidant with the fuel stream;

imparting a swirling motion to at least one of the oxidant and the fuel stream;

receiving the fuel stream mixed with the oxidant at the perforated flame holder; and

supporting a combustion reaction of the fuel and oxidant within the perforated flame holder;

wherein the dilution distance corresponds to a distance at which the complete mixing of the fuel and the oxidant would not occur in the absence of imparting the swirling motion.

63. (canceled)

64. The method of claim **62**, comprising outputting the fuel stream from a fuel nozzle, and wherein imparting the swirling motion includes outputting the fuel stream from the fuel nozzle with a fuel swirling motion.

65. The method of claim **64**, wherein outputting the fuel stream includes outputting a plurality of fuel streams each from a respective aperture of the fuel nozzle.

66.-**69**. (canceled)

70. The method of claim **65**, including passing the fuel stream through the respective aperture at a compound angle with respect to a central axis of the fuel nozzle.

71. The method of claim **62**, wherein imparting the swirling motion includes imparting the swirling motion to the oxidant before the oxidant contacts the fuel stream.

72.-**74**. (canceled)

75. The method of claim **71**, wherein imparting the swirling motion includes passing the oxidant through a swirler and propelling the oxidant toward the perforated flame holder with the swirling motion.

76. The method of claim **75**, wherein outputting the fuel stream includes outputting the fuel stream in a direction transverse to a primary direction of the oxidant downstream from the swirler.

77. (canceled)

78. The method of claim **62**, wherein the complete mixing of the fuel and the oxidant is such that there is less than a 1% variation in concentration of the fuel in the oxidant.

79. The method of claim **62**, wherein the complete mixing of the fuel and the oxidant is such that there is less than a 0.1% variation in concentration of the fuel in the oxidant.

80. A combustion system, comprising:

a fuel and oxidant source configured to output an oxidant and a fuel stream including a fuel into a furnace volume, the fuel and oxidant source including a swirler configured to impart a swirling motion to at least one of the fuel stream and the oxidant, and

a perforated flame holder positioned to receive the fuel stream and being configured to support a combustion reaction of the fuel and the oxidant within the perforated flame holder, the perforated flame holder being separated from the fuel and oxidant source by a dilution distance selected to enable complete mixing of the oxidant with the fuel stream;

wherein the dilution distance corresponds to a distance at which the compete mixing of the fuel and the oxidant would not occur in the absence of imparting the swirling motion.

81. (canceled)

82. The combustion system of claim **80**, wherein the fuel and oxidant source includes a fuel nozzle configured to output the fuel stream, wherein the fuel nozzle includes a plurality of apertures each configured to output a respective fuel stream including the fuel, and wherein each fuel channel conveys the respective fuel stream at a respective compound angle to a central axis of the fuel nozzle.

83.-**84**. (canceled)

85. The combustion system of claim **82**, wherein the dilution distance is less than 100 times a diameter of one of the apertures.

86. The combustion system of claim **82**, wherein the dilution distance is less than 50 times a diameter of one of the apertures.

87. The combustion system of claim **82**, wherein the dilution distance is less than 20 times a diameter of one of the apertures.

88. The combustion system of claim **80**, wherein the swirler is configured to impart the swirling motion to the oxidant prior to mixing with the fuel stream.

89.-**90**. (canceled)

91. The combustion system of claim **80**, wherein the fuel and oxidant source includes a barrel register configured to draft the oxidant into the furnace volume.

92. The combustion system of claim **80**, wherein the dilution distance corresponds to a distance at which complete mixing of the fuel and the oxidant is such that there is either:

a 1% variation in concentration of the fuel in the oxidant; or a 0.1% variation in concentration of the fuel in the oxidant.

93. The combustion system of claim **80**, wherein the perforated flame holder is a reticulated ceramic perforated flame holder.

94. The combustion system of claim **93**, wherein the perforated flame holder includes a plurality of reticulated fibers.

95. The combustion system of claim **94**, wherein the perforated flame holder includes zirconia.

96. The combustion system of claim **94**, wherein the perforated flame holder includes alumina silicate.

97. The combustion system of claim **94**, wherein the perforated flame holder includes silicon carbide.

98. The combustion system of claim **94**, wherein the reticulated fibers are formed from extruded mullite.

99. The combustion system of claim **94**, wherein the reticulated fibers are formed from cordierite.

100. (canceled)

101. The combustion system of claim **94**, wherein the perforated flame holder includes about 100 pores per square inch of surface area.

102. The combustion system of claim **94**, wherein perforations are formed as passages between the reticulated fibers.

103. The combustion system of claim **94**, wherein perforations are branching perforations.

104. The combustion system of claim **94**, wherein the perforated flame holder includes:

an input face corresponding to an extent of the reticulated fibers proximal to one or more primary fuel distributors; and

an output face corresponding to an extent of the reticulated fibers distal to the one or more primary fuel distributors; and

wherein perforations extend between the input face and the output face.

105. (canceled)

106. The combustion system of claim **104**, wherein the perforated flame holder is configured to support at least a portion of the combustion reaction within the perforated flame holder between the input face and the output face.

107. A combustion system, comprising:

a perforated flame holder positioned in a furnace volume;

a preheating flame holder positioned in the furnace volume;

a preheating fuel nozzle configured to output a preheating fuel stream including a preheating fuel onto the preheating flame holder, the preheating flame holder being configured to hold a preheating combustion reaction supported by the preheating fuel stream;

an oxidant source configured to output an oxidant into the furnace volume; and

a main fuel nozzle including a plurality of apertures each configured to output a respective fuel stream including a main fuel with a trajectory selected to mix with the oxidant before reaching the perforated flame holder, the perforated flame holder being configured to support a second combustion reaction of the fuel and the oxidant substantially within the perforated flame holder.

108. The combustion system of claim **107**, wherein the main fuel nozzle includes a plurality of fuel channels each configured to convey a respective fuel stream to a respective aperture.

109. The combustion system of claim **108**, wherein each fuel channel conveys the respective fuel stream at a respective compound angle with respect to a central axis of the main fuel nozzle.

110. The combustion system of claim **107**, further comprising a swirler configured to impart a rotational motion to the oxidant prior to mixing with the main fuel.

111. The combustion system of claim **107**, wherein the oxidant source includes a blower configured to blow the oxidant into the furnace volume.

112. The combustion system of claim **107**, wherein the oxidant source drafts the oxidant into the furnace volume.

113. The combustion system of claim **107**, further comprising:

a temperature sensor configured to sense a temperature of the perforated flame holder; and

a controller configured to receive from the temperature sensor a temperature signal indicative of the temperature of the perforated flame holder;

wherein the controller and the preheating fuel nozzle are configured to output the preheating fuel stream until the preheating combustion reaction has heated the perforated flame holder to a threshold temperature and then to cease outputting the preheating fuel stream after the perforated flame holder has reached the threshold temperature.

114. (canceled)

115. The combustion system of claim **113**, wherein the threshold temperature is a temperature at which the perforated flame holder can sustain combustion of the fuel and the oxidant.

116.-**118**. (canceled)

119. The combustion system of claim **113**, wherein the controller is configured to cause the main fuel nozzle to output the main fuel streams when the perforated flame holder has reached the threshold temperature.

120. The combustion system of claim **107**, wherein the preheating flame holder includes a toroidal shape defining a central gap.

121. The combustion system of claim **120**, wherein the preheating fuel nozzle is positioned in the central gap.

122. The combustion system of claim **121**, further including a plurality of the preheating fuel nozzle configured to output respective preheating fuel streams onto the preheating flame holder.

123. The combustion system of claim **120**, wherein the main fuel nozzle extends through the central gap.

124. The combustion system of claim **107**, wherein the main fuel nozzle is closer to the perforated flame holder than is the preheating flame holder.

125. The combustion system of claim **124**, wherein the main fuel nozzle is closer to the perforated flame holder than is the preheating fuel nozzle.

126. The combustion system of claim **125**, wherein the preheating flame holder includes a flame holding surface facing the perforated flame holder and configured to hold the preheating flame.

127. The combustion system of claim **107**, wherein the perforated flame holder is a reticulated ceramic perforated flame holder.

128. A method, comprising:

introducing an oxidant into a furnace volume;

outputting, from a preheating fuel nozzle, a preheating fuel stream including a preheating fuel onto a preheating flame holder positioned in the furnace volume;

preheating a perforated flame holder to a threshold temperature by supporting a preheating flame of the preheating fuel and the oxidant on the preheating flame holder;

outputting a plurality of primary fuel streams with respective trajectories configured to mix with the oxidant, the primary fuel streams including a primary fuel;

receiving the fuel streams mixed with the oxidant in the perforated flame holder; and

supporting, after the perforated flame holder has reached the threshold temperature, a combustion reaction of the fuel and the oxidant within the perforated flame holder.

129. (canceled)

130. The method of claim **128**, further comprising outputting the primary fuel streams each at a respective compound angle with respect to a central axis of the fuel nozzle.

131. (canceled)

132. The method of claim **128**, further comprising outputting the primary fuel streams with a vortex motion.

133.-**137**. (canceled)

138. The method of claim **128**, wherein the threshold temperature is a temperature at which the perforated flame holder can sustain combustion of the fuel and the oxidant.

139. (canceled)

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