US 20160245509A1

(19) United States
(12) Patent Application Publication
(10) Pub. No.: US 2016/0245509 A1
(43) Pub. Date: Aug. 25, 2016
KARKOW et al.

(54) FLARE STACK WITH PERFORATED FLAME HOLDER

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(21) Appl. No.: **15/045,164**

(22) Filed: **Feb. 16, 2016**

Related U.S. Application Data

(60) Provisional application No. 62/117,887, filed on Feb. 18, 2015.

Publication Classification

(51) **Int. Cl.**

F23G 7/08 (2006.01)
F23D 99/00 (2006.01)
F23D 14/48 (2006.01)
F23D 14/14 (2006.01)

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

CPC ***F23G 7/085*** (2013.01); ***F23D 14/145*** (2013.01); ***F23D 91/00*** (2015.07); ***F23D 14/48*** (2013.01)

(57) **ABSTRACT**

A flare stack burner includes a fuel stack housing in which a fuel nozzle and a perforated flame holder are positioned. The fuel nozzle is configured to emit a fuel stream toward the flame holder.

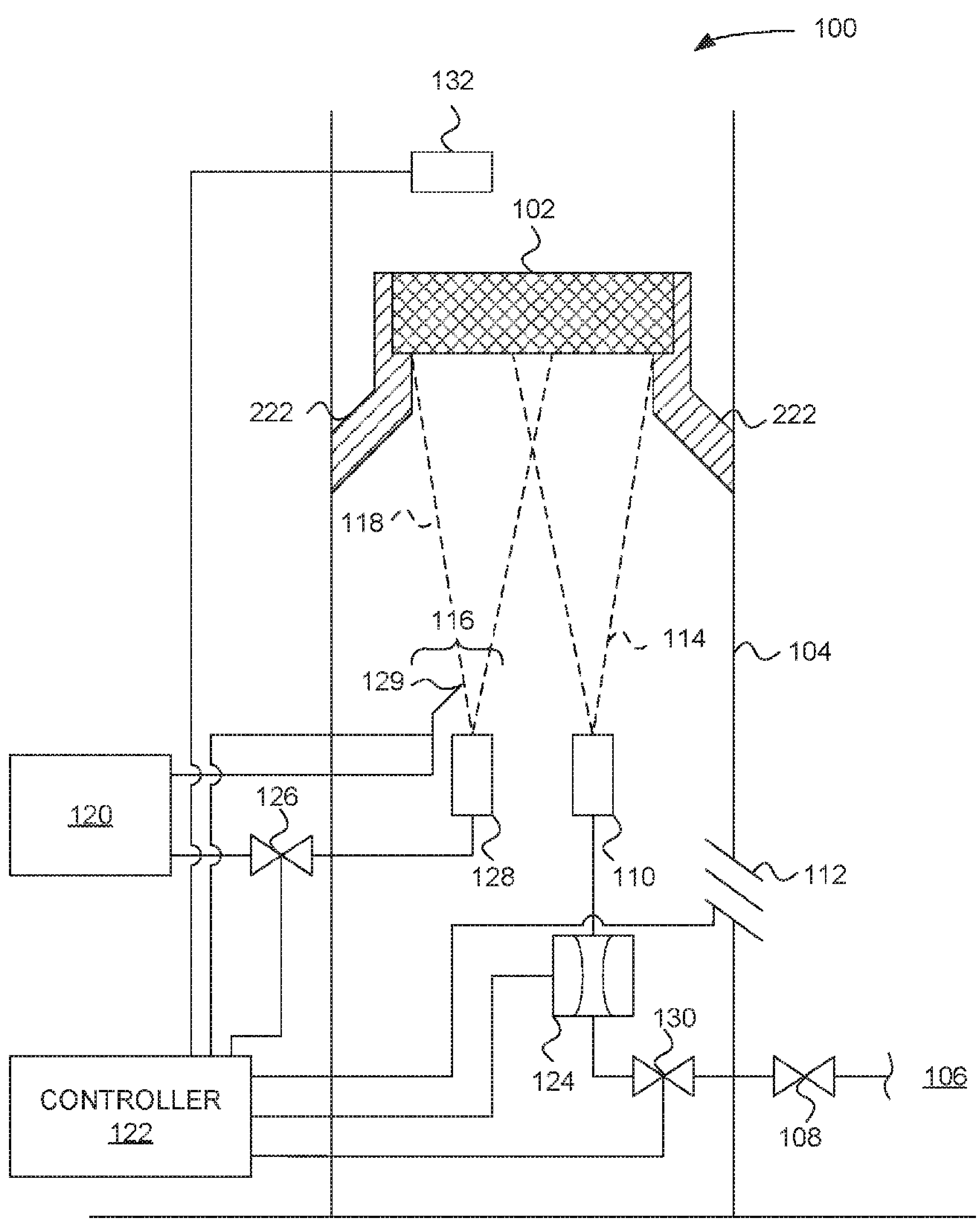


FIG. 1

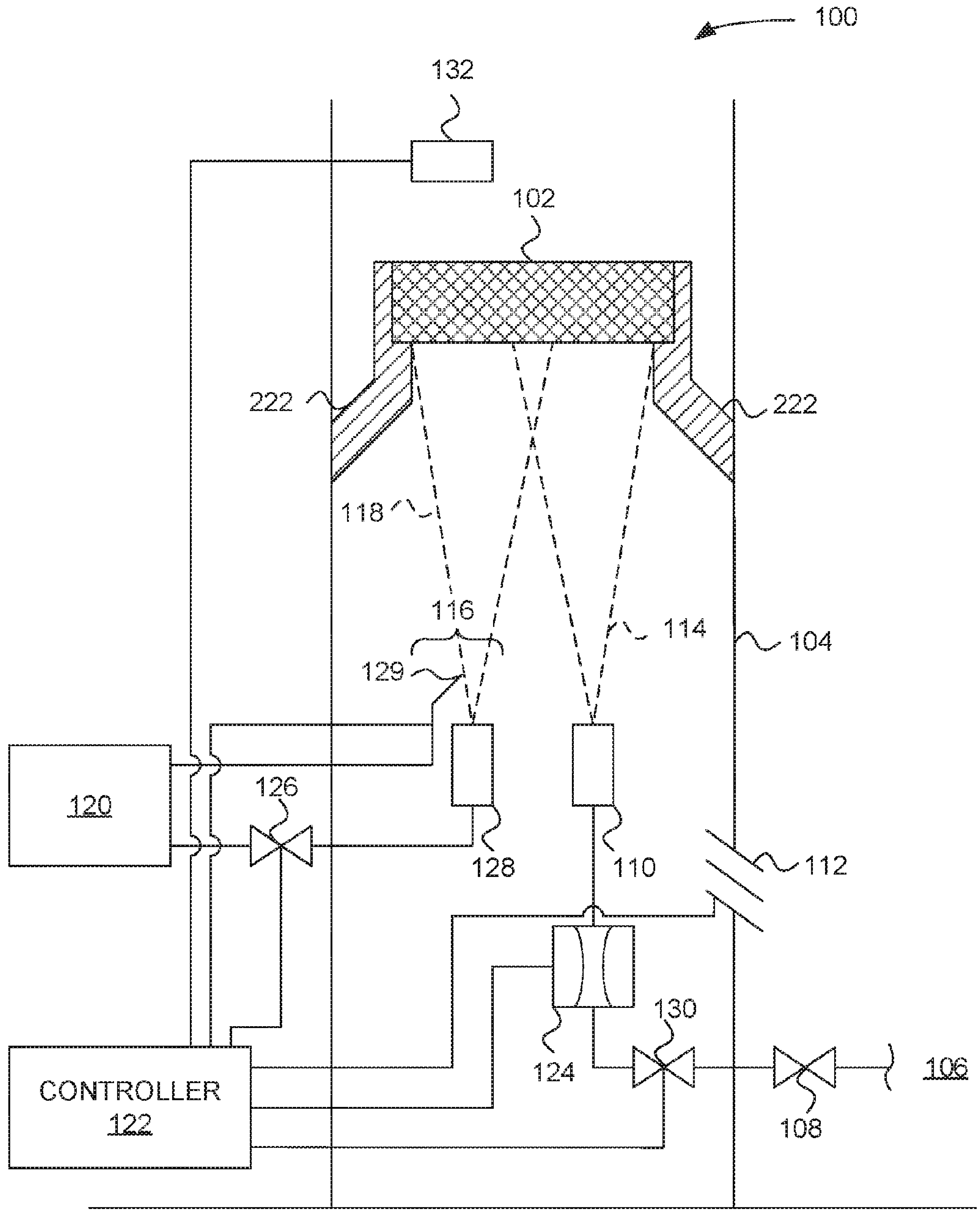

100
132
102
222
222
118
116
114
104
129
120
126
128
110
112
124
130
CONTROLLER
122
106
108

FIG. 2

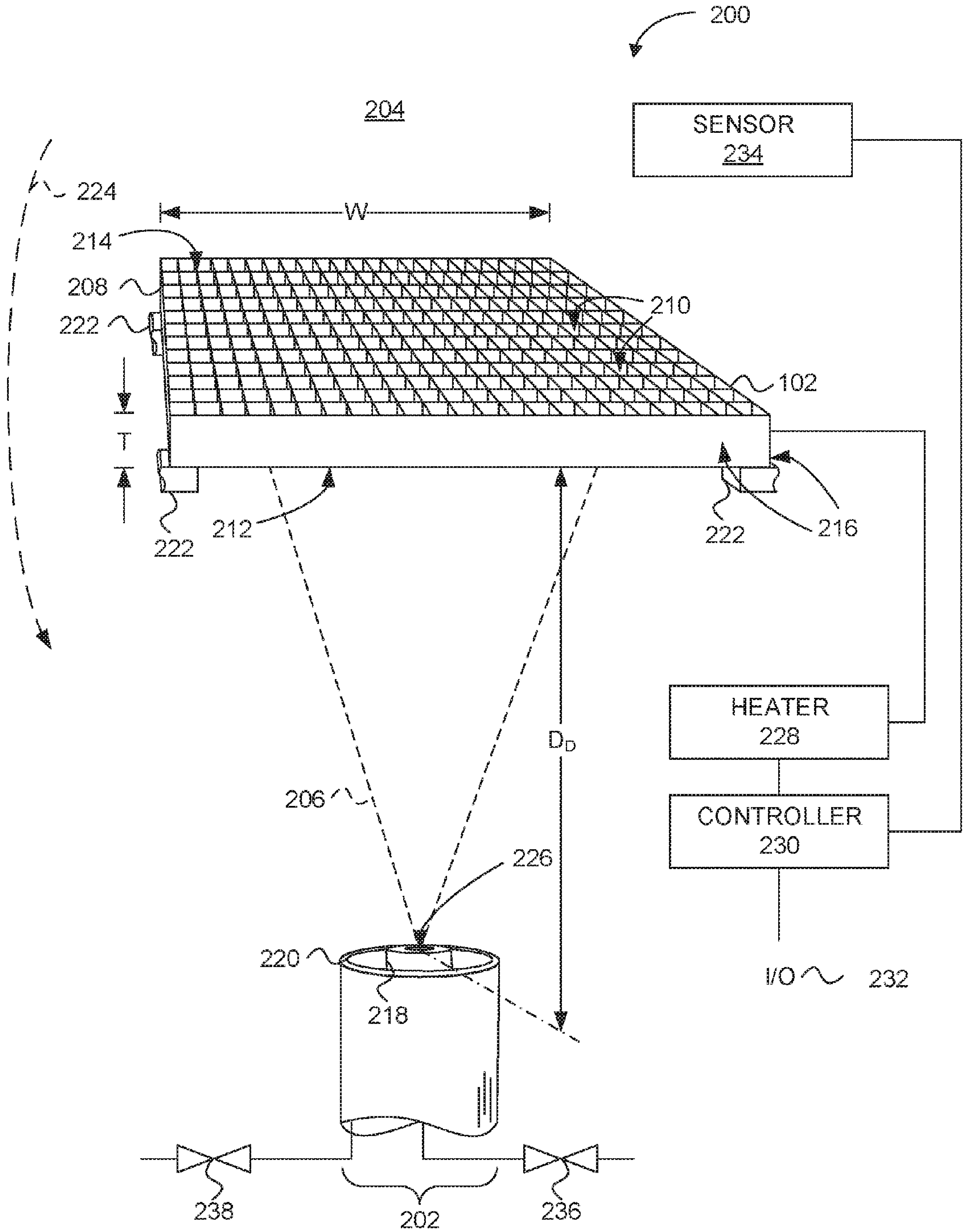
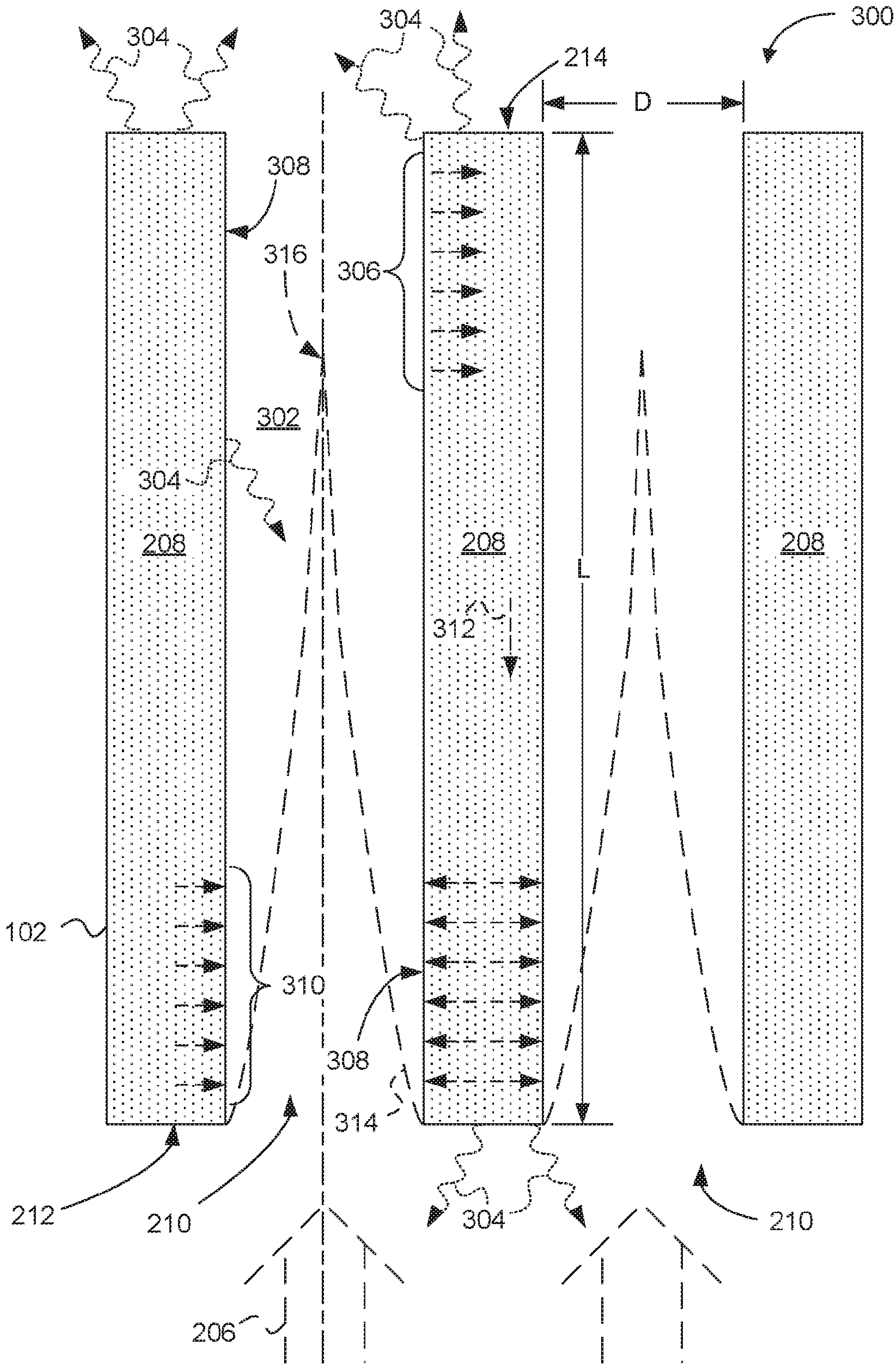

200
204
SENSOR
234
224
W
214
208
222
210
102
T
222
212
216
222
HEATER
228
D_D
206
CONTROLLER
230
226
220
218
I/O
232
238
202
236

FIG. 3



304
304
300
214
D
308
316
306
302
304
208
208
208
L
312
102
310
308
314
212
210
304
210
206

FIG. 4

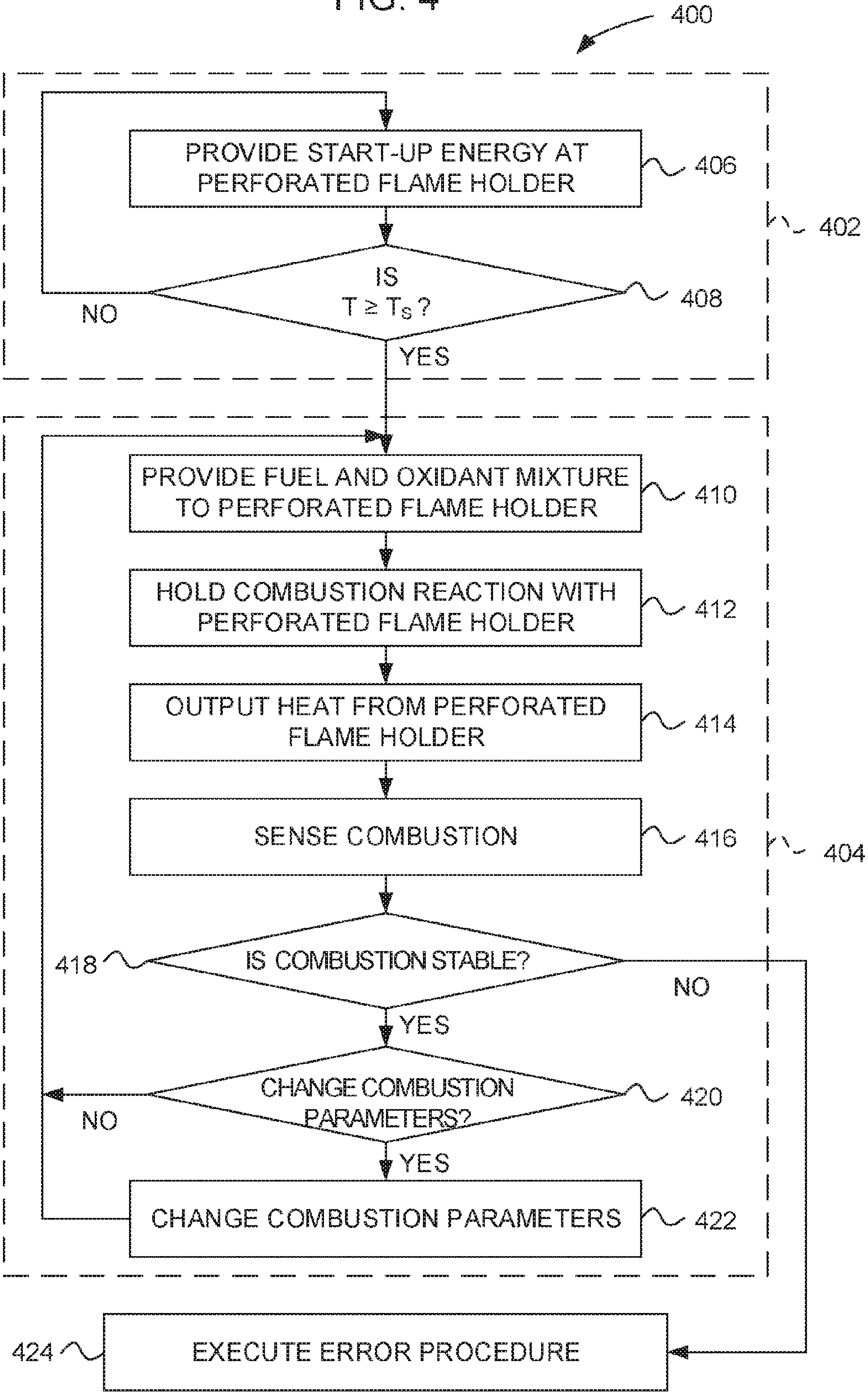

400
PROVIDE START-UP ENERGY AT PERFORATED FLAME HOLDER
406
402
IS T ≥ Ts ?
408
NO
YES
PROVIDE FUEL AND OXIDANT MIXTURE TO PERFORATED FLAME HOLDER
410
HOLD COMBUSTION REACTION WITH PERFORATED FLAME HOLDER
412
OUTPUT HEAT FROM PERFORATED FLAME HOLDER
414
SENSE COMBUSTION
416
404
418
IS COMBUSTION STABLE?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

FIG. 5

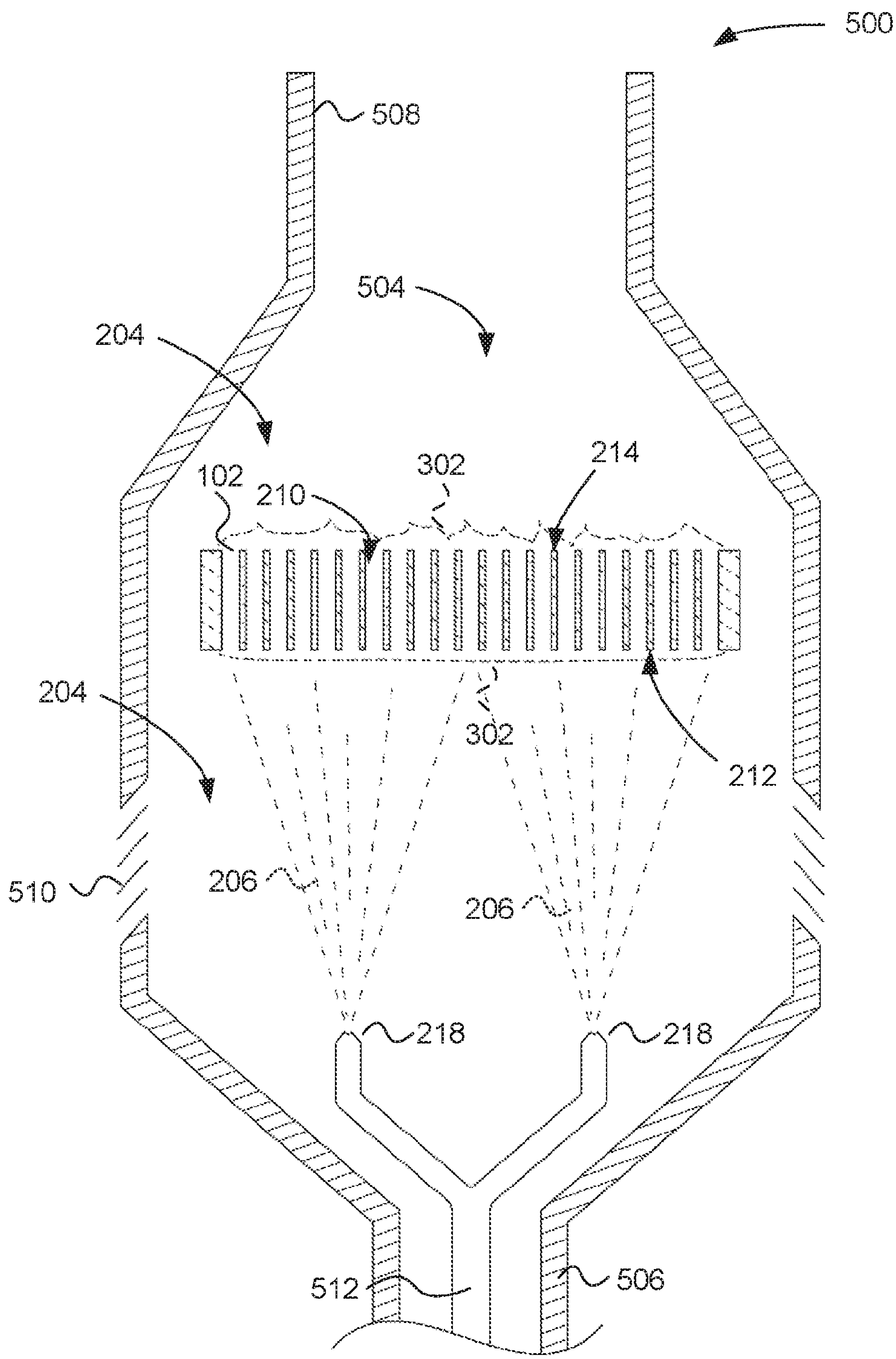

500
508
504
204
302
214
102
210
204
302
212
510
206
206
218
218
512
506

FIG. 6

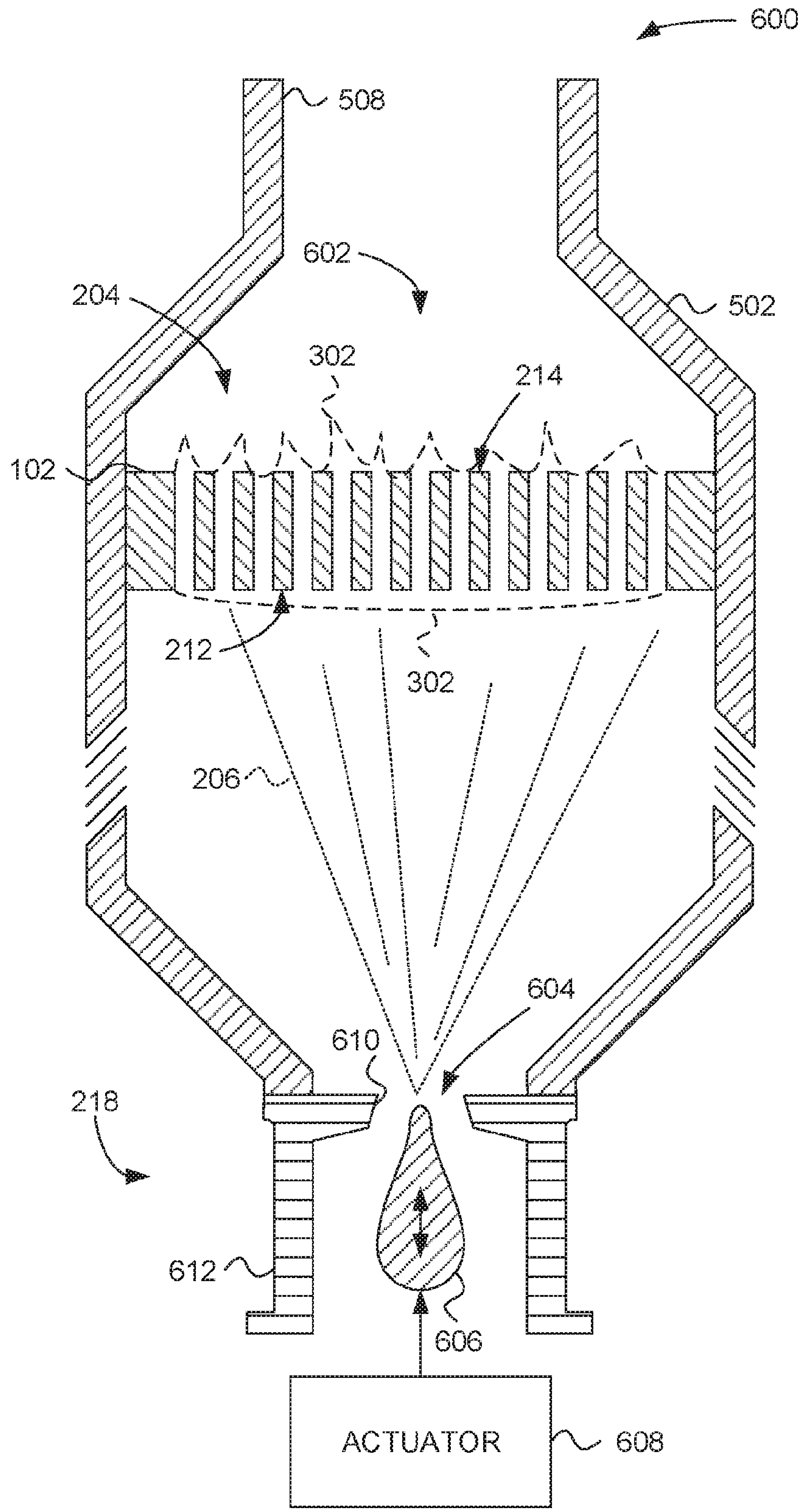
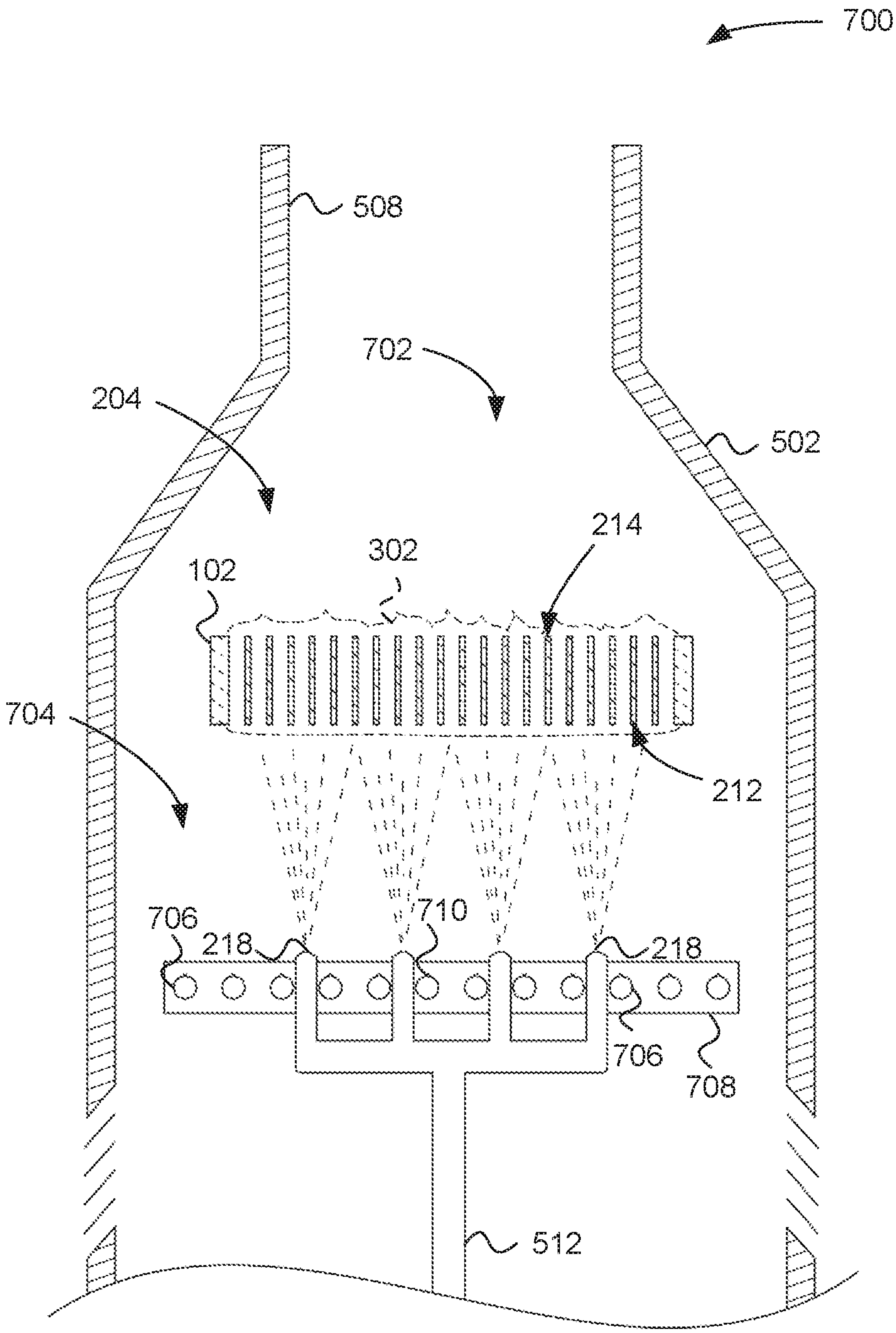

600
508
602
502
204
302
214
102
212
302
206
604
610
218
612
606
ACTUATOR
608

FIG. 7


700
508
702
204
502
214
302
102
704
212
706
710
218
218
706
708
512

FLARE STACK WITH PERFORATED FLAME HOLDER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority benefit from U.S. Provisional Patent Application No. 62/117,887, entitled "FLARE STACK WITH PERFORATED FLAME HOLDER," filed Feb. 18, 2015 (docket number 2651-257-02); which, to the extent not inconsistent with the disclosure herein, is incorporated by reference.

BACKGROUND

[0002] Flare stacks are used to burn off vented volatile organic compounds. For example, in an oil refinery, a flare stack may be used to provide emergency burning of volatile compounds, or provide for a safe way to relieve high sudden pressure events of flammable materials. In an oil field, a flare stack may be used to burn off natural gas that is produced as a byproduct of crude oil production. In a landfill, a flare stack may be used to burn off methane released by decomposition processes. Because volatile compounds are considered pollutants and are often flammable, it is generally considered preferable to burn the volatile compounds, rather than to vent the volatile compounds directly to the atmosphere. In flare stack applications, it can be important to control the height of a flame envelope created by the burner. In some applications, especially those known by the term of art "enclosed flares," it may be required or desired that the flame not exceed the height of the flare stack itself. By keeping the flame inside the flare stack, safety may be improved. Moreover, aesthetics may be improved sufficiently to avoid complaints about a visible flame.

[0003] Enclosed flare stacks or ground flares can be used for burning off unusable waste field gas in a variety of oil and gas production applications, for example. Waste gases may be released during over-pressuring of plant equipment. The waste gases may be transported to a corresponding ground flare. Some ground flares are enclosed. By "enclosed" it is meant that a flame envelope is substantially blocked from view by persons outside a controlled access area.

[0004] Flame length may determine a required height, girth, or other dimensions of the ground flare structure. A problem may arise when the flame becomes visible (e.g., is too high). Excessively high flame length may substantially halt operation, and/or may result in fines or be expressed as greater capital cost, increased operating expenses, and/or other remediation expenses.

SUMMARY

[0005] According to an embodiment, a device includes a housing including an inlet configured to be coupled to a waste gas supply as part of a flare stack, and an outlet configured to release products of combustion to the atmosphere. A perforated flame holder is positioned inside the housing, the perforated flame holder having a first face, a second face lying opposite the first face, and a plurality of perforations extending through the perforated flame holder between the first and second faces. A nozzle is configured to receive a flow of waste gas from the inlet and emit a waste gas stream toward the first face of the perforated flame holder. The perforated flame holder is configured to support combustion of the waste gas substantially within the plurality of perforations.

[0006] According to an embodiment, a method includes outputting a waste gas and supplemental fuel sufficient to raise a heating value of the waste gas plus supplemental fuel to about 100 BTU per cubic foot or less toward a perforated flame holder; and combusting the waste gas and supplemental fuel substantially within a plurality of perforations extending through the perforated flame holder.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. **1** is a diagram of a flare stack with a perforated flame holder, according to an embodiment.

[0008] FIG. **2** is a simplified perspective view of a burner system including a perforated flame holder, according to an embodiment.

[0009] FIG. **3** is a side sectional diagram of a portion of the perforated flame holder of FIGS. **1** and **2**, according to an embodiment.

[0010] FIG. **4** is a flow chart showing a method for operating a burner system including the perforated flame holder of FIGS. **1**, **2** and **3**, according to an embodiment.

[0011] FIG. **5** is a diagrammatic side-sectional view of a portion of a flare stack that includes a perforated flame holder substantially as described with reference to FIGS. **2** and **3**, according to an embodiment.

[0012] FIG. **6** is a diagrammatic side-sectional view of a portion of a flare stack, according to another embodiment.

[0013] FIG. **7** is a diagrammatic side-sectional view of a portion of a flare stack, according to an embodiment, that includes a retrofit burner installed in a pre-existing flare stack.

DETAILED DESCRIPTION

[0014] 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. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

[0015] FIG. **1** is a diagram of a flare stack **100** with a perforated flame holder **102**, according to an embodiment. The flare stack **100** includes a stack structure **104** configured to support a flare. A flare is a combustion reaction that burns off volatile compounds to control pressure in systems such as oil production, oil refining, and other chemical processing systems. A volatile compound source **106** at least intermittently outputs a flow of high vapor pressure flammable compounds. Optionally, a pressure control valve **108** may provide a constant pressure sink to the volatile compound source **106**, and determine a constant pressure flow of volatile compounds to a volatile compound nozzle **110**. For some systems, this can cause a variable flow rate of volatile compounds to the volatile compound nozzle **110**. When volatile compound flow is sufficient, the volatile compound nozzle outputs a stream of volatile compounds. A combustion air source **112**, such as a damper or a blower, provides combustion air. The stream of volatile compounds flows and entrains combustion air to form a volatile compound mixture **114**. A perforated flame holder **102** is supported by a perforated flame holder support structure **222** at a position selected to receive the volatile compound mixture **114**. As described elsewhere herein, a combustion reaction supported at least partially by the volatile compound mixture can be held by the perforated flame holder **102**.

[0016] According to an embodiment, a temperature-maintenance fuel nozzle **116** is configured to output a start-up flame or a temperature-maintenance fuel and air mixture **118** to establish or maintain an operating temperature of the perforated flame holder **102** using fuel from a fuel source **120**.

[0017] Because flow from the volatile compound source **106** can be intermittent or at least non-steady, the temperature-maintenance fuel nozzle **116** can be configured to cooperate with the fuel source **120** to provide a relatively high fuel and air mixture **118** flow rate when the volatile compound mixture **114** flow rate is low and provide a relatively low or zero fuel and air mixture **118** flow rate when the volatile compound mixture **114** flow rate is high.

[0018] According to an embodiment, a controller **122** is operatively coupled to a flow sensor **124** configured to measure flow of volatile compounds from the volatile compound source **106**. The controller can use digital logic to determine a corresponding flow rate appropriate for the fuel and air mixture **118**, and control a fuel flow valve **126** to provide a selected flow rate of fuel from the fuel source **120** to the temperature-maintenance fuel nozzle **116**.

[0019] The temperature-maintenance fuel nozzle **116** can include a fuel riser **128** and an ignition source **129** configured to ignite a start-up flame near the temperature-maintenance fuel nozzle. The ignition source **129** can include a hot surface igniter, a spark-discharge igniter, or a pilot flame, for example. Additionally or alternatively, the ignition source **129** may include a flame holder operable to hold a flame at a location proximate to the fuel riser **128**. The flame holder may be configured to be actuated to selectively hold a flame at the location proximate to the fuel source or to allow fuel from the fuel source to travel to the perforated flame holder **102** for combustion. In such an embodiment, the ignition source **129** may additionally include a separate igniter or alternatively the fuel riser **128** may be manually ignited at start-up.

[0020] According to an embodiment, when the ignition source **129** or actuatable flame holder is enabled, a start up flame is supported between the temperature-maintenance fuel nozzle **116** and the perforated flame holder **102**. When the ignition source **129** or flame holder is not enabled, the temperature-maintenance fuel nozzle **116** outputs a flow of the fuel and air mixture **118** to the perforated flame holder **102** for combustion in the perforated flame holder **102**. The controller **122** can be operatively coupled to the ignition source **129** to determine whether a start-up flame is supported or whether the fuel and air mixture **118** is delivered to the perforated flame holder **102** for combustion.

[0021] According to an embodiment, the temperature-maintenance fuel nozzle **116** can be configured to add a relatively high BTU-content fuel, such as propane or natural gas, to a relatively low BTU-content fuel from the volatile compound nozzle **110**. For continuous flow operations, the "temperature maintenance" performed by the temperature-maintenance fuel nozzle **116** may consist essentially of increasing the BTU content of the combustible materials (fuel plus volatile compound) delivered to the perforated flame holder **102**.

[0022] In one experiment, it was found that use of the perforated flame holder **102** could reduce the necessary BTU content of methane fuel plus volatile compound mixture from 300 BTUs per cubic foot to below 100 BTUs per cubic foot while maintaining steady combustion, compared to burning the volatile compound in a conventional flame. The capabilities of the perforated flame holder **102** can thus be used to advantage in many waste gas burn-off applications, whether or not in a contained flame flare stack, and can result in significant fuel cost savings.

[0023] During times when substantially no volatile compounds are output from the volatile compound source **106**, the controller **122** can cause the flare stack **100** to operate in a "cold standby" state, where minimal or no fuel from the fuel source **120** is consumed, and the fuel control valve **126** is maintained in an "off" position. Optionally, the system **100** can include a volatile compound flow valve **130** operatively coupled to the controller **122**. The controller can hold the volatile compound flow valve **130** in an off state whenever the flare stack **100** is in a cold standby state.

[0024] When an imminent volatile compound flow is detected (e.g., by a pressure sensor (not shown) or the volatile compound flow sensor **124**, the controller can convert the flare stack **100** to a "warm standby" state, wherein the fuel control valve **126** is opened sufficiently, and the ignition source **129** enabled to support a start-up flame. The system **100** can change from a warm standby state to a "hot standby" state when the temperature of the space between the volatile compound nozzle **110** and the perforated flame holder **102** is warmed by the start-up flame to a sufficiently hot temperature to ensure complete combustion of the volatile compound. In the hot standby state, the flare stack **100** can operate as a normal flare stack with volatile compound flaring occurring in a conventional flame below the perforated flame holder. In some cases, the volatile compound is itself a fuel of sufficient heating value to provide a continual flame without any additional or supporting fuel. In other cases, a supplemental fuel is required to raise the heat value of the (supplemental) fuel plus volatile compound. In still other cases, it is more proper to call the fuel an ignition fuel inasmuch as the volatile compound has sufficient heating value to maintain the combustion reaction, but for reasons of safety or convenience, it is preferable to have a fuel of known composition and pressure available as an ignition source. Unless noted, the term fuel may function in any of these senses.

[0025] When the perforated flame holder **102** is warmed to a start-up temperature, the controller can disable the ignition source **129** to lift from the start-up flame location and cause the fuel/air mixture **118** to impinge on the perforated flame holder **102**, wherein combustion is held. Simultaneously, with no ignition by the start-up flame, the volatile compound/air mixture **114** travels to the perforated flame holder **102** wherein the volatile compound is combusted.

[0026] When the volatile compound flow rate is sufficiently high to maintain combustion in the perforated flame holder **102**, the controller **122** can reduce the fuel flow rate or stop fuel flow using the fuel control valve **126**. Optionally, the controller **122** can include a proportional controller configured to maintain a fuel mixture **118** flow rate that is inversely proportional to the volatile compound mixture **114** flow rate.

[0027] Optionally, the controller can be operatively coupled to control the combustion air source **112**. Optionally, the controller can be operatively coupled to a sensor **132** configured to sense combustion, temperature, or other parameter related to performance of the flare stack **100**.

[0028] FIG. **2** is a simplified diagram of a burner system **200** including 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, porous reaction holder, duplex, and duplex tile shall be considered synonymous unless further definition is provided. 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 **200** 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 heroic extremes that may be required for conventional burners to even approach such clean combustion.

[0029] According to embodiments, the burner system **200** includes a fuel and oxidant source **202** disposed to output fuel and oxidant into a combustion volume **204** to form a fuel and oxidant mixture **206**. As used herein, the terms fuel and oxidant mixture and fuel stream may be used interchangeably and considered synonymous depending on the context, unless further definition is provided. As used herein, the terms combustion volume, combustion chamber, furnace volume, and the like shall be considered synonymous unless further definition is provided. The perforated flame holder **102** is disposed in the combustion volume **204** and positioned to receive the fuel and oxidant mixture **206**.

[0030] FIG. **3** is a side sectional diagram **300** of a portion of the perforated flame holder **102** of FIGS. **1** and **2**, according to an embodiment. Referring to FIGS. **2** and **3**, 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 **206** from the fuel and oxidant source **202**. 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 **206**.

[0031] 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 carbon monoxide (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, flue gas, and/or can include another oxidant, either pure or carried by a carrier gas. The terms oxidant and oxidizer shall be considered synonymous herein.

[0032] 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 **206**, 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 **206** at the input face **212**. The fuel and oxidant mixture **206** 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**.

[0033] According to an embodiment, the perforated flame holder **102** is configured to hold a majority of the combustion reaction **302** within the perforations **210**. For example, on a steady-state basis, more than half the molecules of fuel output into the combustion volume **204** 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 or thermal energy 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**. As used herein, the terms heat, heat energy, and thermal energy shall be considered synonymous unless further definition is provided. As used above, heat energy and thermal energy refer generally to the released chemical energy initially held by reactants during the combustion reaction **302**. As used elsewhere herein, heat, heat energy and thermal energy correspond to a detectable temperature rise undergone by real bodies characterized by heat capacities. 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 **302** 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**. Alternatively, if the cooling load is relatively low and/or the furnace temperature reaches a high level, the combustion may travel somewhat upstream of the input face **212** of the perforated flame holder **102**.

[0034] 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. 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 "huffing" or "flashback" wherein a visible flame momentarily ignites in a region lying between the input face **212** of the perforated flame holder **102** and the fuel nozzle **218**, within the dilution region D_D. Such transient huffing or 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 downstream from 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 from the perforated flame holder **102** that was observed.

[0035] 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 **204**. As used herein, terms such as radiation, thermal 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-type radiation of electromagnetic energy, primarily at infrared wavelengths, but also at visible wavelengths owing to elevated temperature of the perforated flame holder body **208**.

[0036] Referring especially to FIG. **3**, the perforated flame holder **102** outputs another portion of the received heat to the fuel and oxidant mixture **206** received at the input face **212** of the perforated flame holder **102**. The perforated flame holder body **208** may receive heat from the 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**.

[0037] The perforated flame holder body **208** can be characterized by a heat capacity. The perforated flame holder body **208** may hold thermal energy from the combustion reaction **302** in an amount corresponding to the heat capacity multiplied by temperature rise, and transfer the thermal energy 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 multiple heat transfer mechanisms including conduction, radiation, and possibly convection 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 **302** would not be stable when supported from a conventional flame holder.

[0038] The inventors believe that the perforated flame holder **102** causes the combustion reaction **302** to begin within thermal boundary layers **314** formed adjacent to walls **308** of the perforations **210**. Insofar as combustion is generally understood to include a large number of individual reactions, and since a large portion of combustion energy is released within the perforated flame holder **102**, it is apparent that at least a majority of the individual reactions occur within the perforated flame holder **102**. As the relatively cool fuel and oxidant mixture **206** 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 **206**. 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 define the ends of the perforations **210**. At some position along the length of a perforation **210**, the combustion reaction **302** outputs more heat to the perforated flame holder body **208** than it receives from the perforated flame holder body **208**. The heat is received at the heat receiving region **306**, is held by the perforated flame holder body **208**, and is transported to the heat output region **310** nearer to the input face **212**, where the heat is transferred into the cool reactants (and any included diluent) to bring the reactants to the ignition temperature.

[0039] In an embodiment, each of the perforations **210** is 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**. As used herein, the term reaction fluid refers to matter that travels through a perforation **210**. Near the input face **212**, the reaction fluid includes the fuel and oxidant mixture **206** (optionally including nitrogen, flue gas, and/or other "non-reactive" species). Within the combustion reaction region, the reaction fluid may include plasma associated with the combustion reaction **302**, molecules of reactants and their constituent parts, any non-reactive species, reaction intermediates (including transition states), and reaction products. Near the output face **214**, the reaction fluid may include reaction products and byproducts, non-reactive gas, and excess oxidant.

[0040] 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** to form 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 (i.e., produce low NOx, produce low CO, and maintain stable combustion).

[0041] 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**.

[0042] Referring especially to FIG. **2**, the fuel and oxidant source **202** can further include a fuel nozzle **218**, configured to output fuel, and an oxidant source **220** configured to output a fluid including the oxidant. For example, the fuel nozzle **218** can be configured to output pure fuel. The oxidant source **220** can be configured to output combustion air carrying oxygen, and optionally, flue gas.

[0043] The perforated flame holder **102** can be held by a perforated flame holder support structure **222** configured to hold the perforated flame holder **102** at a dilution distance D_D away from the fuel nozzle **218**. The fuel nozzle **218** can be configured to emit a fuel jet selected to entrain the oxidant to form the fuel and oxidant mixture **206** 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 **218** and the perforated flame holder **102**. Additionally or alternatively (particularly when a blower is used to deliver oxidant contained in combustion air), the oxidant or combustion air source can be configured to entrain the fuel and 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 **218** can be configured to emit a fuel jet 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 **218** and the input face **212** of the perforated flame holder **102**.

[0044] The fuel nozzle **218** can be configured to emit the fuel through one or more fuel orifices **226** having an inside diameter dimension that is referred to as "nozzle diameter." The perforated flame holder support structure **222** can support the perforated flame holder **102** to receive the fuel and oxidant mixture **206** at the distance D_D away from the fuel nozzle **218** greater than 20 times the nozzle diameter. In another embodiment, the perforated flame holder **102** is disposed to receive the fuel and oxidant mixture **206** at the distance D_D away from the fuel nozzle **218** 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** at a distance about **200** times or more of the nozzle diameter away from the fuel nozzle **218**. When the fuel and oxidant mixture **206** travels about **200** times the nozzle diameter or more, the mixture is sufficiently homogenized to cause the combustion reaction **302** to produce minimal NOx.

[0045] 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 oxidant (e.g., combustion air) channel configured to output the oxidant into the premix chamber. A flame arrestor 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.

[0046] The oxidant source **220**, whether configured for entrainment in the combustion volume **204** or for premixing, can include a blower configured to force the oxidant through the fuel and oxidant source **202**.

[0047] The support structure **222** can be configured to support the perforated flame holder **102** from a floor or wall (not shown) of the combustion volume **204**, 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.

[0048] 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**.

[0049] 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.

[0050] 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 the thickness dimension T between the input face **212** and the output face **214** of the perforated flame holder **102**.

[0051] In an embodiment, the perforated flame holder **102** can have a width dimension W less than a width of the combustion volume **204**. This can allow the flue gas circulation 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 the combustion volume wall (not shown). Referring again to both FIGS. **2** and **3**, the perforations **210** can be of various shapes. In an embodiment, the perforations **210** can include elongated squares, each having a transverse dimension D between opposing sides of the squares. In another embodiment, the perforations **210** can include elongated hexagons, each having a transverse dimension D between opposing sides of the hexagons. In yet another embodiment, the perforations **210** can include hollow cylinders, each having a transverse dimension D corresponding to a diameter of the cylinder. In another embodiment, the perforations **210** can include truncated cones or truncated pyramids (e.g., frustums), each having a transverse dimension D radially symmetric relative to a length axis that extends from the input face **212** to the output face **214**. In some embodiments, the perforations **210** can each have a lateral dimension D equal to or greater than a quenching distance of the flame based on standard reference conditions. Alternatively, the perforations **210** may have lateral dimension D less then than a standard reference quenching distance.

[0052] In one range of embodiments, each of the plurality of perforations **210** has a lateral dimension D between 0.05 inch and 1.0 inch. Preferably, each of the plurality of perforations **210** has a lateral dimension D between 0.1 inch and 0.5 inch. For example the plurality of perforations **210** can each have a lateral dimension D of about 0.2 to 0.4 inch.

[0053] 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 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.

[0054] 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 to include 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. Honeycomb is an industrial term of art that need not strictly refer to a hexagonal cross section and most usually includes cells of square cross section. Honeycombs of other cross sectional areas are also known.

[0055] 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.

[0056] 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 **308** can be one piece or can be formed from a plurality of sections.

[0057] In another embodiment, which is not necessarily preferred, the perforated flame holder **102** may be formed from reticulated ceramic material. The term "reticulated" refers to a netlike structure. Reticulated ceramic material is often made by dissolving a slurry into a sponge of specified porosity, allowing the slurry to harden, and burning away the sponge and curing the ceramic.

[0058] In another embodiment, which is not necessarily preferred, the perforated flame holder **102** may be formed from a ceramic material that has been punched, bored or cast to create channels.

[0059] In another embodiment, 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.

[0060] 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 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 include structured packing shapes. In another example, the discontinuous packing bodies include random packing shapes. For example, the discontinuous packing bodies can include ceramic Raschig ring, 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.

[0061] The inventors contemplate various explanations for why burner systems including the perforated flame holder **102** provide such clean combustion.

[0062] According to an embodiment, the perforated flame holder **102** may act as a heat source to maintain a combustion reaction even under conditions where a combustion reaction would not be stable when 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 stream **206** contacts the input face **212** of the perforated flame holder **102**, an average fuel-to-oxidant ratio of the fuel stream **206** is below a (conventional) lower combustion limit of the fuel component of the fuel stream **206**—lower combustion limit defines the lowest concentration of fuel at which a fuel and oxidant mixture **206** will burn when exposed to a momentary ignition source under normal atmospheric pressure and an ambient temperature of 25° C. (77° F.).

[0063] 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. According to one interpretation, such a performance can be achieved due to a sufficient mixing used to lower peak flame temperatures (among other strategies). Flame temperatures tend to peak under slightly rich conditions, which can be evident in any diffusion flame that is insufficiently mixed. By sufficiently mixing, a homogenous and slightly lean mixture can be achieved prior to combustion. This combination can result in reduced flame temperatures, and thus reduced NOx formation. In one embodiment, "slightly lean" may refer to 3% O_2, i.e. an equivalence ratio of ~0.87. Use of even leaner mixtures is possible, but may result in elevated levels of O_2. 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 temperatures and lower NOx.

[0064] 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**.

[0065] 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.

[0066] 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 the fuel and oxidant are provided to the perforated flame holder and combustion is held by the perforated flame holder.

[0067] According to a more detailed description, step **402** begins with step **406**, wherein start-up energy is provided at the perforated flame holder. Simultaneously or following providing start-up energy, a decision 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 steps **406** and **408** within the preheat step **402**. In 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 overall step **404**, wherein fuel and oxidant is supplied to and combustion is held by the perforated flame holder.

[0068] Step **404** may be broken down into several discrete steps, at least some of which may occur simultaneously.

[0069] Proceeding from step **408**, a fuel and oxidant mixture is provided to the perforated flame holder, as shown in step **410**. The fuel and oxidant may be provided by a fuel and oxidant source that includes a separate fuel nozzle and oxidant (e.g., combustion air) source, for example. In this approach, the fuel and oxidant are output in one or more directions selected to cause the fuel and oxidant mixture to be received by the input face of the perforated flame holder. 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.

[0070] Proceeding to step **412**, the combustion reaction is held by the perforated flame holder.

[0071] In 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.

[0072] In optional step **416**, the presence of combustion may be sensed. Various sensing approaches have been used and are contemplated by the inventors.

[0073] 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, flame rod, and/or other combustion sensing apparatuses. In an additional or alternative variant of step **416**, a pilot flame or other ignition source may be provided to cause ignition of the fuel and oxidant mixture in the event combustion is lost at the perforated flame holder.

[0074] Proceeding to decision step **418**, if combustion is sensed not to be stable, the method **400** may exit to step **424**, wherein an error procedure is executed.

[0075] For example, the error procedure may include turning off fuel flow, re-executing the preheating step **402**, outputting an alarm signal, igniting a stand-by combustion system, or other steps. If, in step **418**, combustion in the perforated flame holder is determined to be stable, the method **400** proceeds to decision 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 step **410**, and the combustion process continues. If a change in combustion parameters is indicated, the method **400** proceeds to step **422**, wherein the combustion parameter change is executed. After changing the combustion parameter (s), the method loops (within step **404**) back to step **410**, and combustion continues.

[0076] 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 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**.

[0077] Referring again to FIG. **2**, the burner system **200** includes a heater **228** operatively coupled to the perforated flame holder **102**. 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 **206**. After combustion is established, this heat is provided by the combustion reaction **302**; but before combustion is established, the heat is provided by the heater **228**.

[0078] Various heating apparatuses have been used and are contemplated by the inventors. In some embodiments, the heater **228** can include a flame holder configured to support a flame disposed to heat the perforated flame holder **102**. The fuel and oxidant source **202** can include a fuel nozzle **218** configured to emit a fuel stream **206** and an oxidant source **220** configured to output oxidant (e.g., combustion air) adjacent to the fuel stream **206**. The fuel nozzle **218** and oxidant source **220** can be configured to output the fuel stream **206** to be progressively diluted by the oxidant (e.g., combustion air). The perforated flame holder **102** can be disposed to receive a diluted fuel and oxidant mixture **206** that supports a 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 relatively unmixed fuel and oxidant mixture that is stable without stabilization provided by the heated perforated flame holder **102**.

[0079] 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 to hold the start-up flame when the perforated flame holder **102** needs to be pre-heated and to not hold the start-up flame when the perforated flame holder **102** is at an operating temperature (e.g., when $T \geq T_S$).

[0080] Various approaches for actuating a start-up flame are contemplated. In one embodiment, the start-up flame holder includes a mechanically-actuated bluff body configured to be actuated to intercept the fuel and oxidant mixture **206** to cause heat-recycling and/or stabilizing vortices and thereby hold a start-up flame; or to be actuated to not intercept the fuel and oxidant mixture **206** to cause the fuel and oxidant mixture **206** 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 a perforated flame holder **102** operating temperature, the flow rate may be increased to "blow out" the start-up flame. In another embodiment, the heater **228** may include an electrical power supply operatively coupled to the controller **230** and configured to apply an electrical charge or voltage to the fuel and oxidant mixture **206**. 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 **206**. 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.

[0081] 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 **206**. The electrical resistance heater 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**, to selectively couple the power supply to the electrical resistance heater.

[0082] An 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 by the perforated flame holder body **208**. Alternatively, the heater **228** can include an inductive heater, a high-energy beam heater (e.g. microwave or laser), a frictional heater, electro-resistive ceramic coatings, or other types of heating technologies.

[0083] 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 oxidant and fuel. Additionally or alternatively, a start-up apparatus can include a pilot flame apparatus disposed to ignite the fuel and oxidant mixture **206** that would otherwise enter the perforated flame holder **102**. The 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 **206** in or upstream from the perforated flame holder **102** before the perforated flame holder **102** is heated sufficiently to maintain combustion.

[0084] The burner system **200** can further include a sensor **234** operatively coupled to the control circuit **230**. The sensor **234** can include a heat sensor configured to detect infrared radiation or a temperature of the perforated flame holder **102**. The control circuit **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).

[0085] The sensor **234** can further include a combustion sensor operatively coupled to the control circuit **230**, the combustion sensor being configured to detect a temperature, video image, and/or spectral characteristic of a combustion reaction held by the perforated flame holder **102**. The fuel control valve **236** can be configured to control a flow of fuel from a fuel source to the fuel and oxidant source **202**. 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 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 to change the fuel and oxidant mixture **206** flow responsive to a heat demand change received as data via the data interface **232**.

[0086] FIG. **5** is a diagrammatic side-sectional view of a portion of a flare stack **500**, according to an embodiment, that includes a perforated flame holder **102** substantially as described with reference to FIGS. **2-3**. The flare stack **500** can include a housing **502** in which a flare burner **504** is positioned. The housing can enclose the combustion volume **204**, and includes an inlet **506**, an outlet **508**, and vent louvers **510**.

[0087] The flare burner **504** can include the perforated flame holder **102** and a plurality of fuel nozzles **218** configured to produce fuel streams **206** directed toward respective portions of the input face **212** of the flame holder. A fuel line **512** can extend into the housing **502** via the inlet **506**, and is coupled to the plurality of fuel nozzles **218** and configured to deliver fuel to the nozzles.

[0088] During operation, fuel, such as, for example, waste natural gas from an oil well, may be introduced via the fuel line **512** to the plurality of fuel nozzles **218**, which emit respective fuel streams **206** toward the perforated flame holder **102**. A combustion reaction **302** can be supported by the fuel streams **206** and held substantially within perforations **210** of the flame holder **102**. Products of the combustion, such as, for example, heated air, carbon dioxide (CO_2), water vapor (H_2O), etc., exit the housing **502** via the outlet **508**, whence they are dispersed in the atmosphere. Because the combustion reaction **302** is substantially contained within the perforations **210** of the flame holder **102**, no flames are visible outside the housing.

[0089] As shown in FIG. **5**, the flare stack **500** can be positioned at the top of a pole or stack, which serves to distribute the combustion products into the atmosphere at a height that allows them to dissipate

[0090] Two fuel nozzles **218** are shown in the embodiment of FIG. **5**. However, this is provided merely as an example. According to an embodiment, a flare stack **500** is provided, employing a single fuel nozzle. According to another embodiment, a flare stack is provided that includes a larger number of fuel nozzles. For example, FIG. **7** shows a retrofit flare stack that includes an array of fuel nozzles, as described below in detail. According to another embodiment, the flare stack **500** of FIG. **5** includes a similar array of fuel nozzles.

[0091] FIG. **6** is a diagrammatic side-sectional view of a portion of a flare stack **600**, according to an embodiment, that is similar in many respects to the embodiment of FIG. **5**. The flare stack **600** includes a flare burner **602** that includes a fuel nozzle **218** with a variable aperture **606**. The fuel nozzle **218** can include a control element **604** and a nozzle outlet **610**. The control element **604** can be coupled to an actuator element **608** that can be configured to move the control element vertically, thereby regulating the degree to which the control element occludes the nozzle outlet **610**.

[0092] The size of the fuel nozzle aperture **606** may correspond to the area of the opening, as viewed in transverse section, through which the fuel stream **206** exits the fuel nozzle **218**. In embodiments that include conventional fuel nozzles, the size of fuel nozzle aperture **606** is typically substantially equal to the area of the corresponding opening. However, in the embodiment shown in FIG. **6**, the size of fuel nozzle aperture **606** is equal to the area of the nozzle outlet **610** minus the area of the control element **604** bisected by a plane defined by the smallest diameter of the fuel nozzle outlet **610**. As the actuator **608** moves the control element **604** upward, a larger area of the control element **604** may be bisected, reducing the size of the fuel nozzle aperture **606**. Conversely, as the control element is moved downward, the size of the fuel nozzle aperture **606** may increase.

[0093] In applications where the fuel supply to a flare stack may vary over time, a fixed fuel nozzle aperture may be problematic. A reduction in the fuel supply can result in a corresponding reduction in fuel stream velocity. As discussed with reference to FIG. **2**, according to an embodiment, the velocity of the fuel stream **206** is preferably such that it cannot independently support a stable flame between the fuel nozzle and the flame holder. Under certain conditions, if the velocity of the fuel stream is too low, a flame can begin to burn in the fuel stream before it reaches the flame holder, which would interfere with proper operation of the flame holder, and would tend to increase undesirable emissions, such as NO_x. In such situations, it would be desirable to increase the velocity of the fuel stream **206**, in order to cause the flame to be held in the perforated flame holder **102**.

[0094] It is well understood that the velocity of a fluid passing through an opening is a function of the volume of fluid passing per unit of time, and the size of the opening through which it passes. Velocity rises in direct relation to fluid volume, and in inverse relation to the opening size. Thus, with reference to the embodiment of FIG. **6**, if during operation, the fuel supply drops, tending to reduce velocity of the fuel stream, a corresponding reduction in the size of the fuel nozzle aperture **606** will produce an increase in fuel stream velocity, and vice-versa.

[0095] During operation, a fuel stream **206** may exit the fuel nozzle **218** and support a combustion reaction **302** within the perforated flame holder **102**, substantially as previously described. If an increase in velocity of the fuel stream is required, such as when a drop in the fuel supply to the fuel nozzle **218** causes a reduction in velocity, the actuator **608** can be controlled to reduce the size of the fuel nozzle aperture **606**, thereby increasing velocity. Likewise, where desired or required, the actuator **608** can be controlled to increase the size of the fuel nozzle aperture **606** to reduce fuel stream velocity.

[0096] According to an embodiment, the actuator **608** is controlled by a pressure regulator feedback mechanism, in which changes in the fuel supply produce corresponding changes in fuel pressure. The regulator feedback mechanism is configured to respond to these changes by increasing the size of the aperture **218** as fuel pressure increases, and by reducing the size of the aperture as fuel pressure decreases.

[0097] According to another embodiment, a controller is provided, configured to control the size of the fuel nozzle aperture **606** in response to changes in one or more of fuel pressure, fuel stream velocity, flame temperature, flame position, emission composition, etc.

[0098] According to a further embodiment, the actuator **608** is configured to be controlled by an operator during operation of the flare stack **600**.

[0099] As previously noted, the perforated flame holder **102** is typically preheated prior to normal operation. According to another embodiment, the actuator **608** is controlled to reduce fuel stream velocity during a start-up procedure to permit a flame to be supported by the fuel stream **206** between the fuel nozzle **218** and the flame holder **102**, in order to heat the flame holder. Once a portion of the flame holder reaches a selected temperature, the actuator may be controlled to reduce the fuel nozzle aperture **606** and increase fuel stream velocity, causing the flame to rise to the flame holder **102**.

[0100] In FIG. **6**, the fuel nozzle **218** is shown as having a separate housing **612** that is configured to be coupled to a stack or pipe, and to which the housing **502** is in turn coupled. According to other embodiments, the fuel nozzle **218** is enclosed within the housing **502** or within the stack, just upstream of the housing.

[0101] In FIG. **6**, the perforated flame holder **102** is shown occupying substantially all of the cross sectional area of the flare stack. According to other embodiments, as shown, for example, in FIG. **5**, the perforated flame holder **102** occupies less than the entire cross sectional area of the flare stack. In some cases, it may be beneficial to configure a flare stack system such that no circulation of gases around the perforated flame holder is permitted, while in other cases, such circulation may be advantageous. Accordingly, the determination of the size and shape of the perforated flame holder, in relation to the housing, is a design consideration.

[0102] According to an embodiment, the perforated flame holder occupies between ⅔ and 100% of the cross sectional area of the flare stack. According to another embodiment, the perforated flame holder occupies approximately ⅔ of the cross sectional area of the flare stack. According to a further embodiment, the perforated flame holder occupies between ⅓ and ⅔ of the cross sectional area of the flare stack. According to an embodiment, the perforated flame holder occupies the minimum cross sectional area of the flare stack necessary to maintain sufficient combustion of the volatile compound.

[0103] FIG. **7** is a diagrammatic side-sectional view of a portion of a flare stack **700**, according to an embodiment, that includes a retrofit burner **702** installed in a pre-existing flare stack. In the example shown, the pre-existing flare stack includes a fin-tube burner **704**, which in turn includes a plurality of fuel tubes **706** extending substantially parallel to each other—along axes that lie perpendicular to the plane of the drawing—through transverse-oriented fin plates **708**, one of which is shown. Each of the plurality of fuel tubes **706** can have a respective plurality of fuel nozzles **710** interleaved with the fin plates **708**. In operation, as fuel is ejected from the fuel nozzles **710**, it can entrain air passing between the fin plates **708**, and a gas flare is supported inside the housing **502** and close to the fin-tube burner **704**.

[0104] According to an embodiment, the retrofit burner **702** includes a plurality of fuel nozzles **218** coupled to a common fuel line **512**. The fuel nozzles **218** are interleaved between fuel tubes **706** of a start-up fin-tube burner **704**. Each of the plurality of fuel nozzles **218** can be configured to provide a fuel stream **206** to a respective portion of the perforated flame holder **102**. Four fuel nozzles **218** are shown in the view of FIG. **7**, but the plurality of fuel nozzles can include an array of fuel nozzles extending beyond the plane represented in the drawing.

[0105] According to an embodiment, during a start-up procedure of the flare stack **700**, the fin-tube burner **704** is operated in a mode in which fuel is ejected from the fuel nozzles **710** and a flame is supported below the perforated flame holder **102**, which serves to pre-heat the flame holder **102**. The fuel supply to the fuel tubes **706** is then cut off, and a fuel supply is supplied to the fuel line **512**. Fuel streams **206** are emitted from each of the plurality of fuel nozzles **218**, and a combustion reaction **302** is ignited and held in the perforated flame holder **102**.

[0106] As discussed above with reference to FIG. **6**, in some applications, the fuel supply can vary. Thus, according to an embodiment, valves are provided, and configured to individually control flows of fuel to each of the plurality of fuel nozzles **218**. As the fuel supply increases or decreases, a corresponding number of the plurality of fuel nozzles **218** may be brought online or shut down, as necessary. According to an embodiment, the fuel supply to each of the nozzles is controlled so that, when additional fuel nozzles are to be brought online, only fuel nozzles that are immediately adjacent to currently operating nozzles are activated. Heat from combustion supported by the adjacent fuel nozzles will enable a newly activated fuel nozzle to come up to normal operation very quickly, avoiding extended warm-up time during which unburned fuel might pass through the flame holder.

[0107] Embodiments are described and shown in a stack configuration, i.e., a configuration in which the respective systems are supported some distance above the ground. However, other embodiments are envisioned, in which similar structures are positioned on the ground.

[0108] 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.

What is claimed is:

1. A device, comprising:

a housing including an inlet configured to be coupled to a waste fuel supply as part of a flare stack, and an outlet configured to release products of combustion to the atmosphere;

a perforated flame holder positioned inside the housing and having a first face, a second face lying opposite the first face, and a plurality of perforations extending through the perforated flame holder between the first and second faces; and

a nozzle configured to receive a flow of fuel from the inlet, and to emit a fuel stream toward the first face of the perforated flame holder.

2. The device of claim **1**, wherein the housing is configured to be freestanding, supported only by a coupling at the inlet.

3. The device of claim **1**, wherein the housing is configured to be coupled to the flare stack and to be supported thereby.

4. The device of claim **1**, wherein the nozzle is coupled to receive the flow of fuel via a fuel line extending through the inlet into the housing.

5. The device of claim **1**, wherein the nozzle is one of a plurality of nozzles, each configured to receive a flow of fuel from the inlet, and to emit a fuel stream toward a respective portion of the first face of the perforated flame holder.

6. The device of claim **5**, wherein each of the plurality of nozzles is coupled to receive the respective flow of fuel via a common fuel line extending through the inlet into the housing.

7. The device of claim **6**, further comprising a plurality of fuel valves operatively coupled between the common fuel line and a respective one of the plurality of nozzles and configured to independently control operation of the respective nozzle.

8. The device of claim **1**, further comprising:

a start-up burner positioned within the housing; and

a retrofit burner positioned within the housing, the retrofit burner including the perforated flame holder and the nozzle.

9. The device of claim **8**, wherein the start-up burner includes a plurality of burner nozzles arranged in an array within the housing.

10. The device of claim **9**, wherein the nozzle is one of a plurality of nozzles of the retrofit burner, interleaved among the array of burner nozzles of the start-up burner.

11. The device of claim **10**, wherein the start-up burner is a fin-tube burner, and wherein the plurality of nozzles of the retrofit burner is interleaved among fin plates of the fin-tube burner.

12. The device of claim **8**, wherein the start-up burner is configured to support a flame between the start-up burner and the perforated flame holder of the retrofit burner.

13. The device of claim **1**, wherein the nozzle includes an aperture having a size that is variable.

14. The device of claim **13**, wherein the nozzle is configured to regulate a velocity of the fuel stream.

15. The device of claim **13**, further comprising an actuator operatively coupled to the nozzle and configured to control the size of the aperture.

16. The device of claim **13**, wherein the nozzle includes a nozzle outlet and a control element, the control element being positioned to occlude some portion of the nozzle outlet, and wherein movement of the control element varies a degree to which the nozzle outlet is occluded by the control element.

17. A method, comprising:

outputting a waste gas and supplemental fuel sufficient to raise a heating value of the waste gas plus supplemental fuel to about **100** BTU per cubic foot or less toward a perforated flame holder; and

combusting the waste gas and supplemental fuel substantially within a plurality of perforations extending through the perforated flame holder.

18. The method of claim **17**, wherein the combusting waste gas comprises emitting a fuel stream that includes the waste gas from a nozzle positioned within a flare stack and toward the perforated flame holder.

19. The method of claim **18**, further comprising, prior to performing the combusting waste gas substantially within a plurality of perforations extending through the perforated flame holder, preheating the perforated flame holder by operating a start-up burner positioned within the flare stack.

20. The method of claim **19**, comprising, after performing the preheating the flame holder:

shutting off a flow of fuel to the start-up burner; and
introducing a flow of fuel to the nozzle.

21. The method of claim **18**, wherein the emitting a fuel stream from the nozzle positioned within the flare stack is comprised by emitting a fuel stream from each of a plurality of nozzles positioned within the flare stack, each toward a respective portion of the perforated flame holder.

22. The method of claim **21**, wherein the emitting a fuel stream from each of the plurality of nozzles positioned within the flare stack comprises selecting a number of the plurality of nozzles based upon a volume of waste gas to be combusted.

23. The method of claim **22**, wherein the selecting a number of the plurality of nozzles based upon the volume of waste gas to be combusted comprises varying the number of the plurality of nozzles in response to changes in the volume of waste gas.

24. The method of claim **18**, comprising varying an aperture size of the nozzle in response to changes in a volume of waste gas to be combusted.

25. The method of claim **24**, wherein the varying an aperture size of the nozzle comprises varying a degree of occlusion of an outlet of the nozzle.

26. The method of claim **17**, wherein the perforated flame holder is positioned within a flare stack; and
further comprising venting products of the combustion to the atmosphere.

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