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(54) **ELECTRICALLY HEATED BURNER**

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CPC ***F23D 14/84*** (2013.01); ***F23D 14/02*** (2013.01); *F23D 2207/00* (2013.01)

(57) **ABSTRACT**

A burner includes an electrically powered heater configured to output heat energy to a burner portion configured to contact a fuel stream or a combustion reaction supported by the fuel stream.

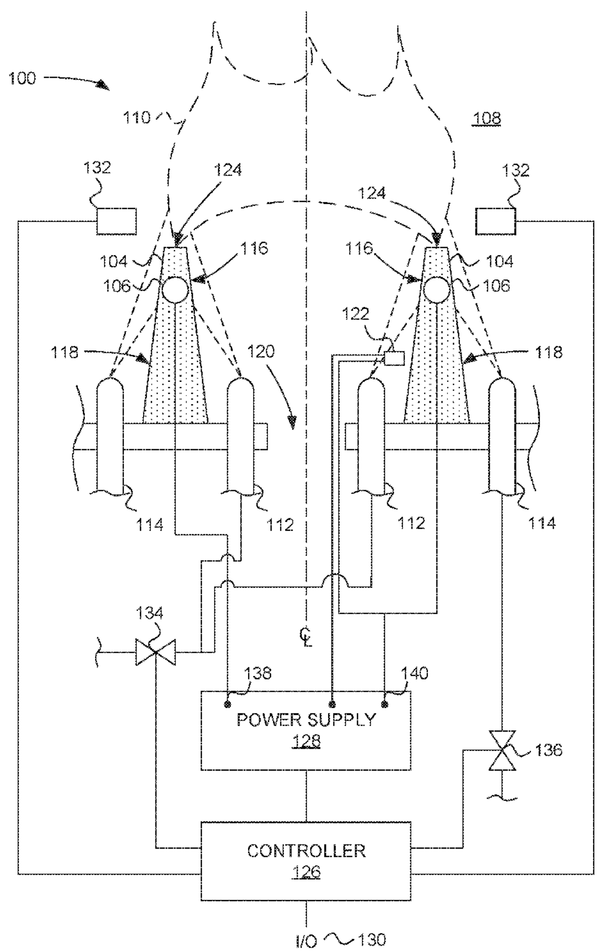


FIG. 1

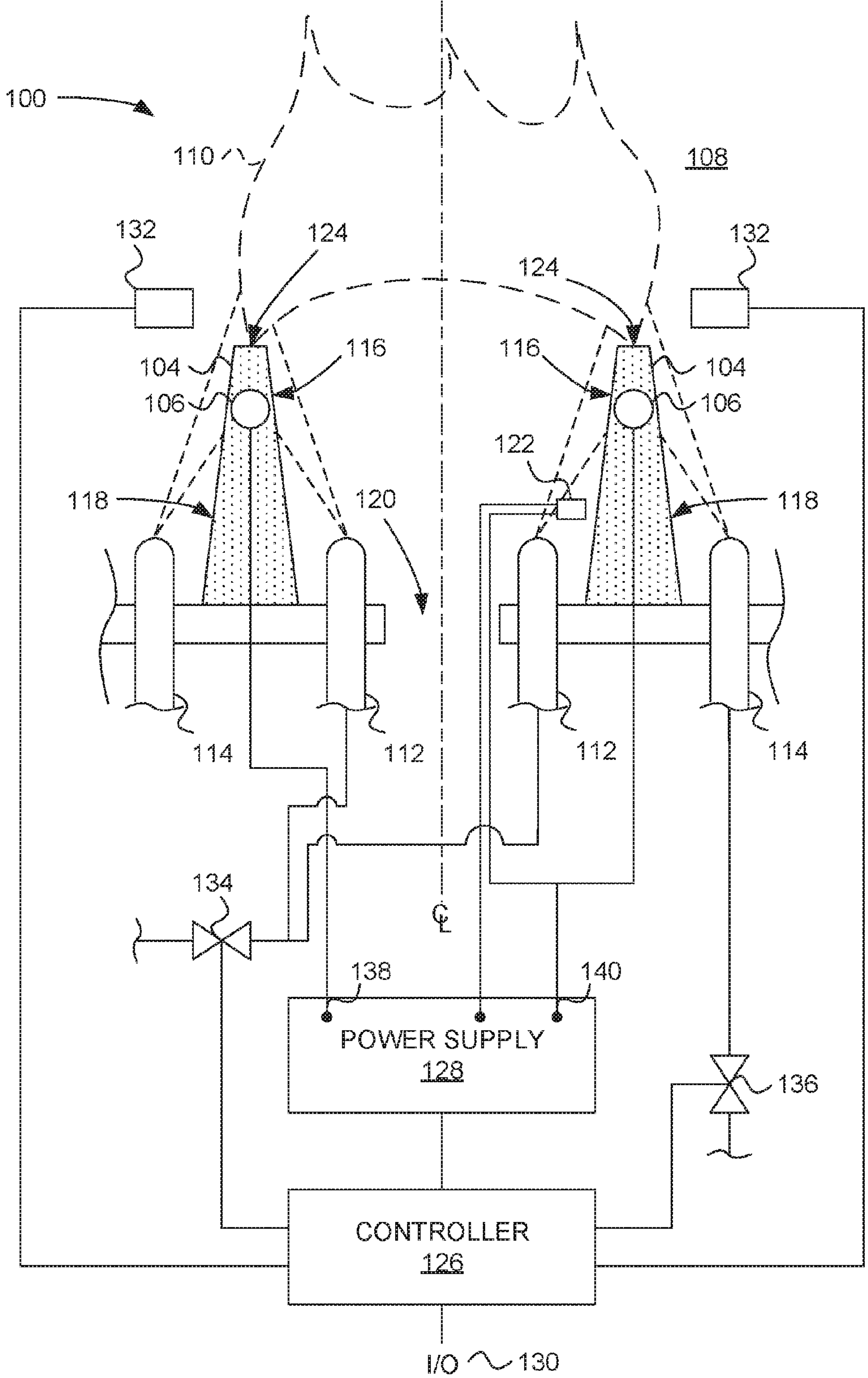

100
110
108
132
124
132
124
104
116
116
104
106
106
122
118
120
118
114
112
112
114
134
CL
138
140
POWER SUPPLY
128
136
CONTROLLER
126
I/O
130

FIG. 2

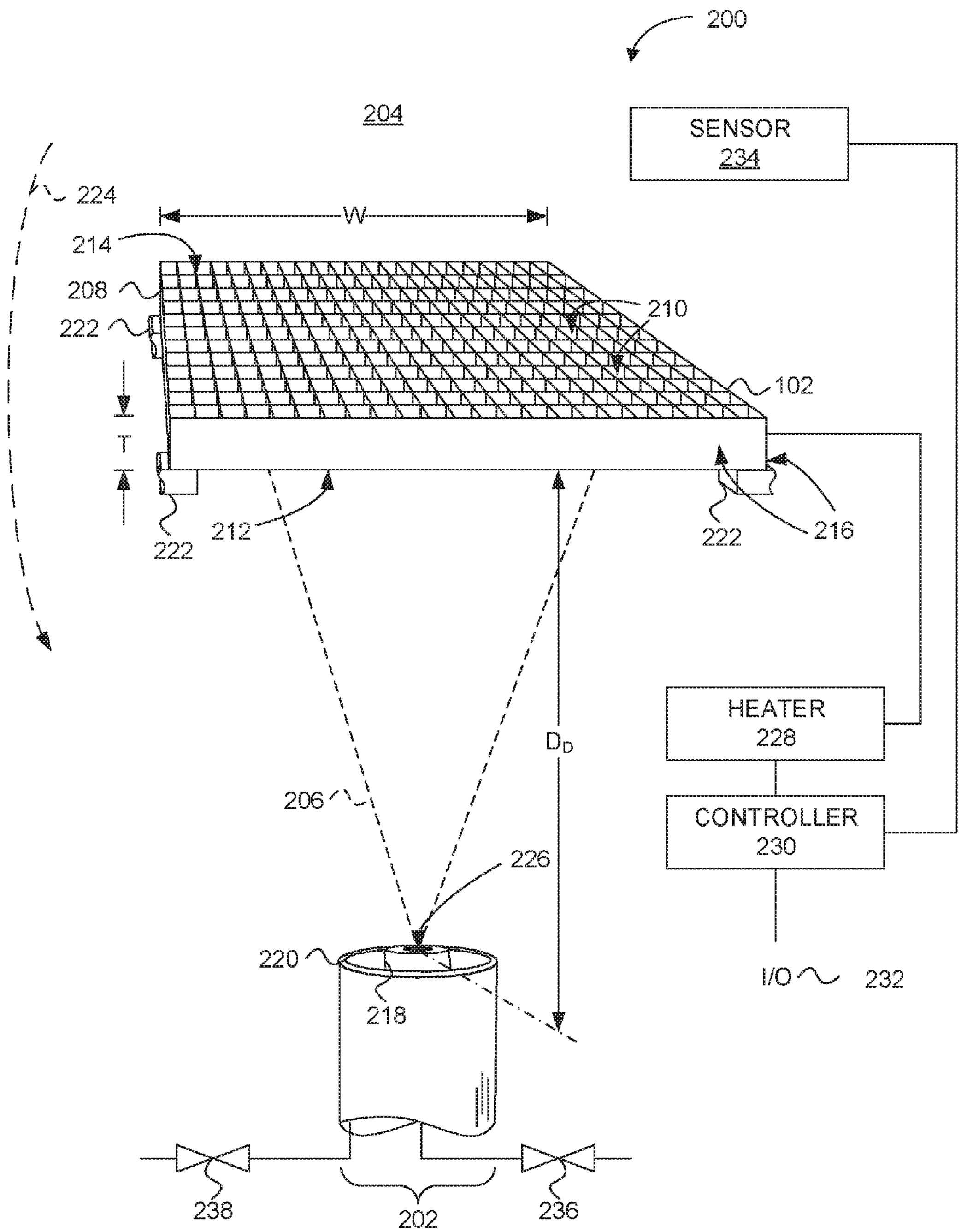
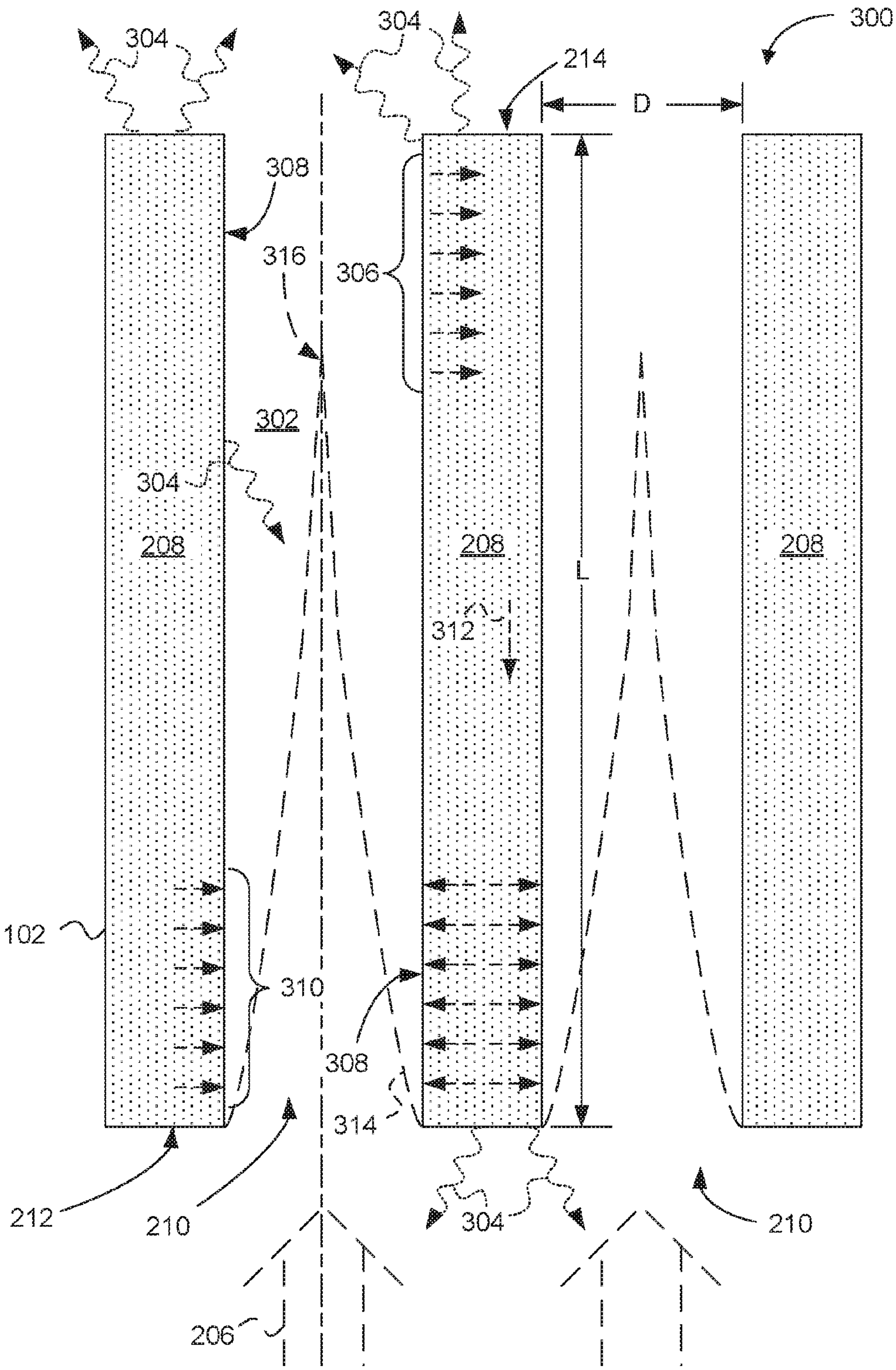

200
204
SENSOR
234
224
W
214
208
222
210
102
T
212
222
222
216
HEATER
228
CONTROLLER
230
D_D
206
226
220
218
I/O
232
238
202
236

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

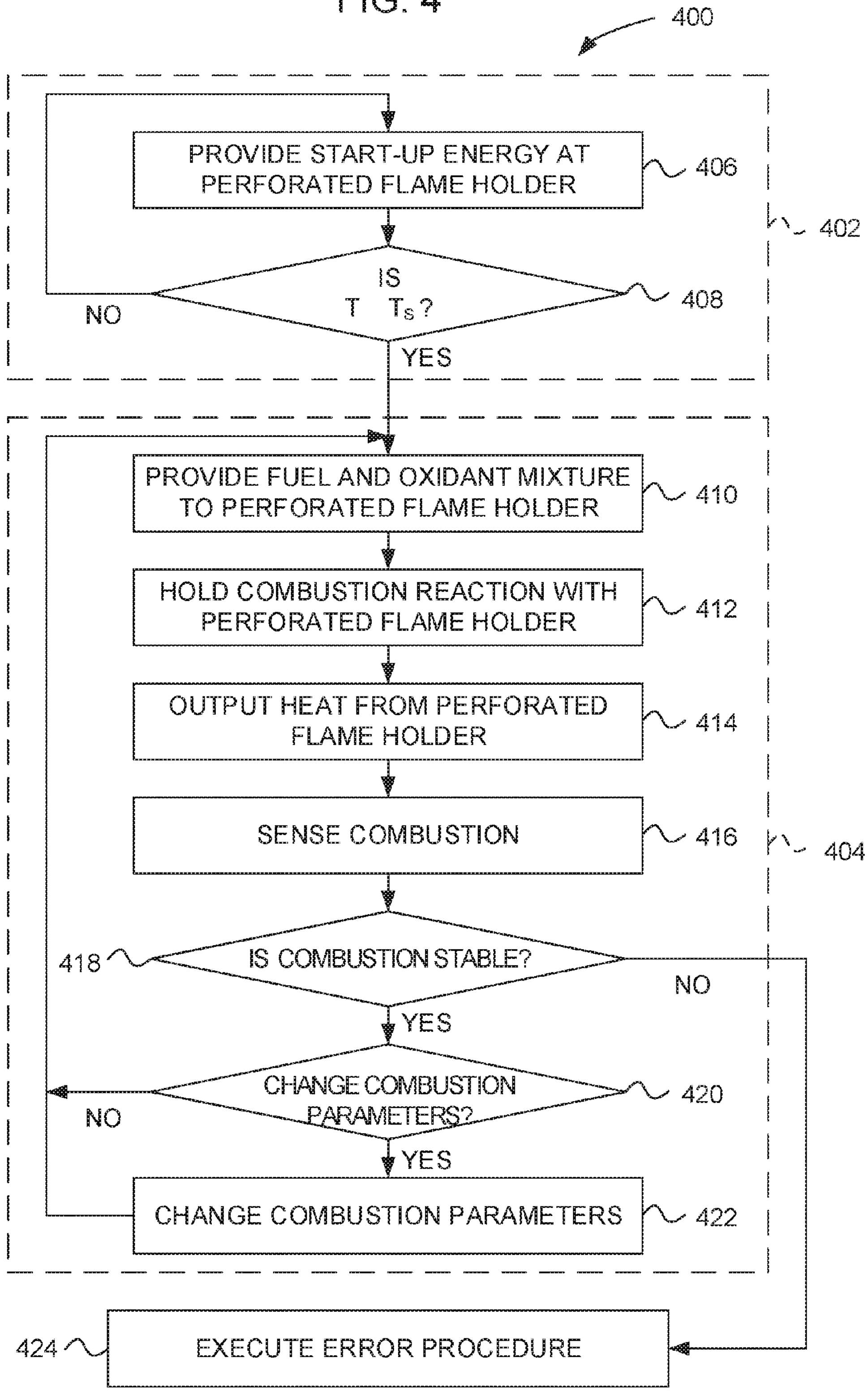

400
PROVIDE START-UP ENERGY AT PERFORATED FLAME HOLDER
406
402
IS T Ts?
408
NO
YES
PROVIDE FUEL AND OXIDANT MIXTURE TO PERFORATED FLAME HOLDER
410
HOLD COMBUSTION REACTION WITH PERFORATED FLAME HOLDER
412
OUTPUT HEAT FROM PERFORATED FLAME HOLDER
414
SENSE COMBUSTION
416
404
418
IS COMBUSTION STABLE?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

FIG. 5

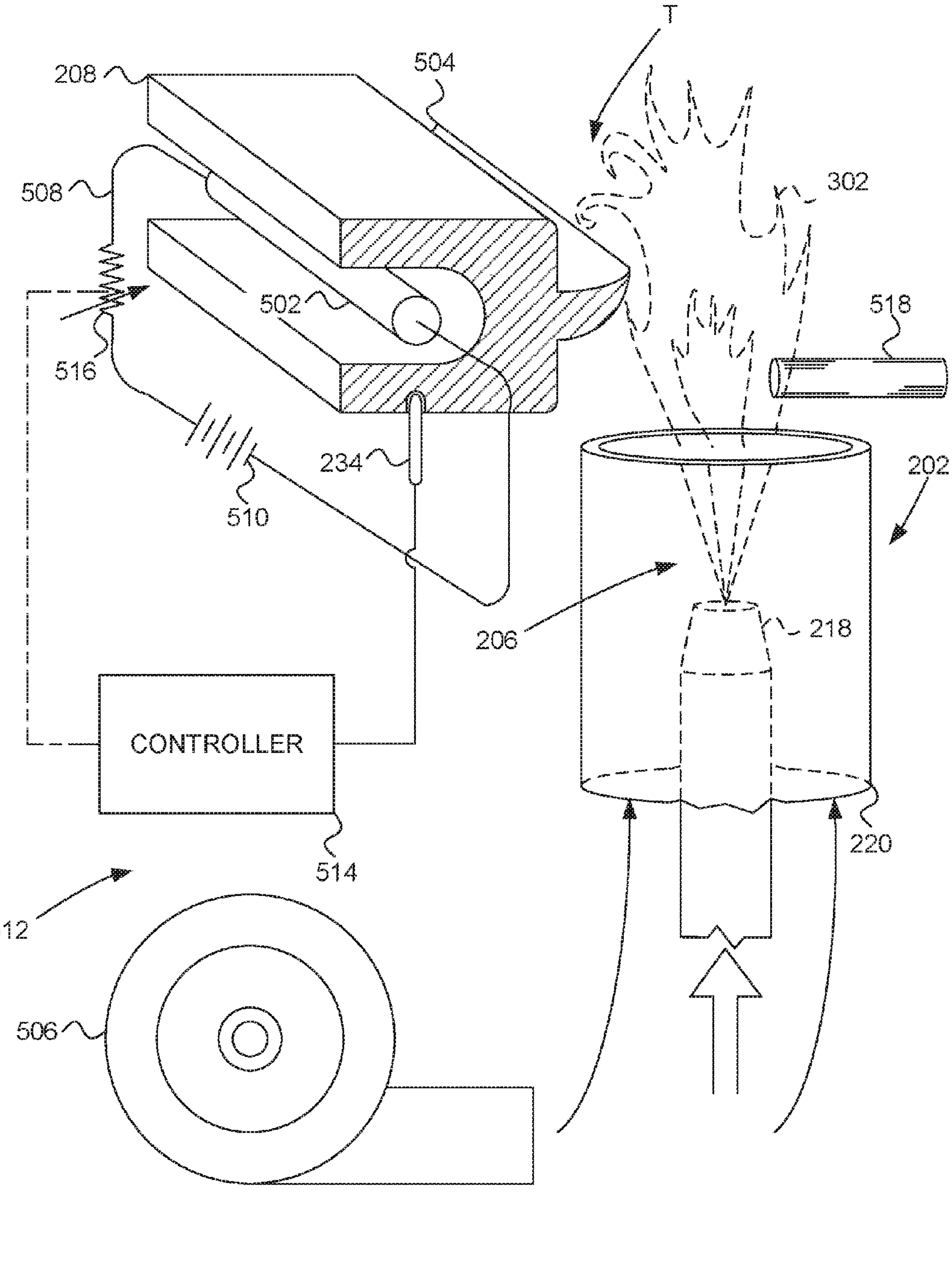

T
208
504
508
302
502
516
518
234
202
510
206
218
CONTROLLER
220
514
512
506

FIG. 6

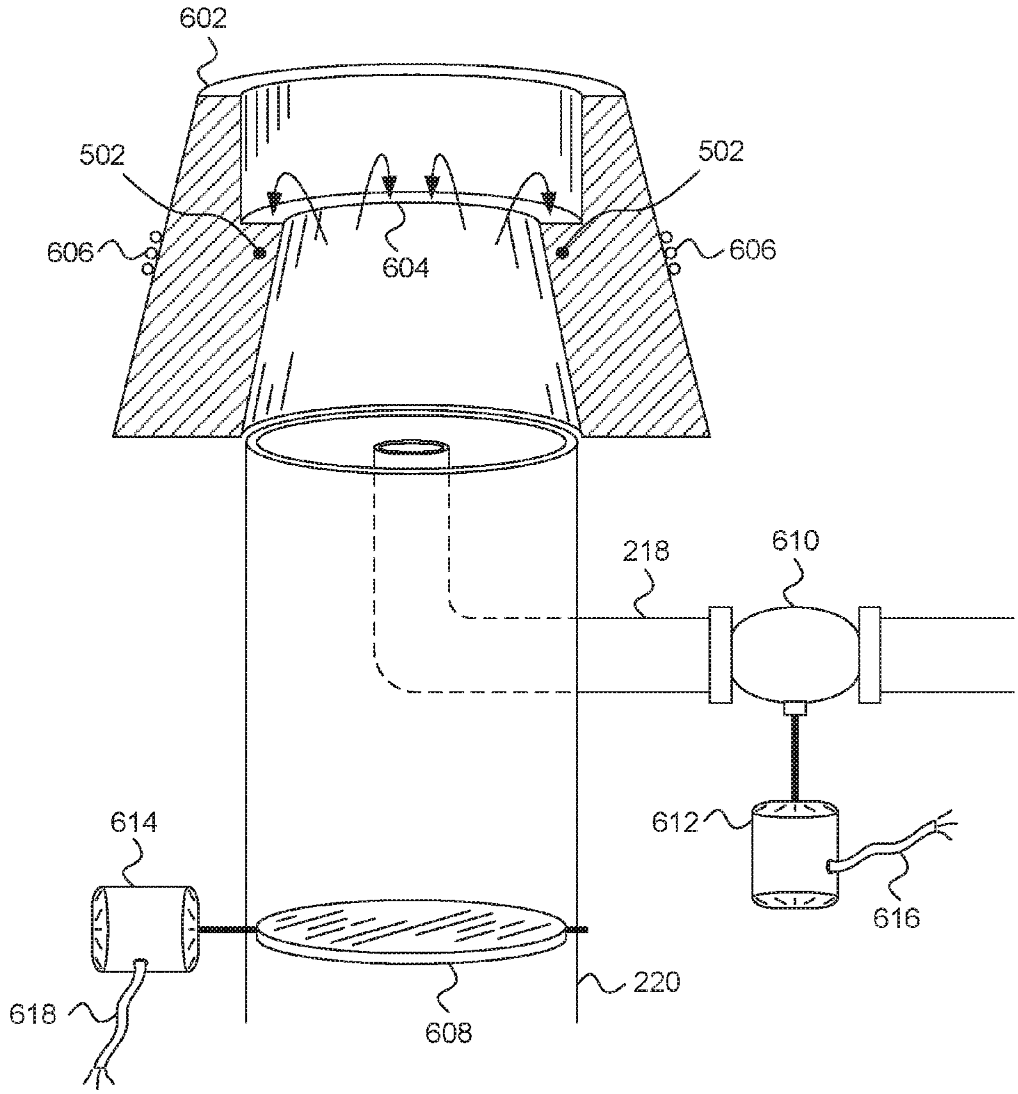


FIG. 7

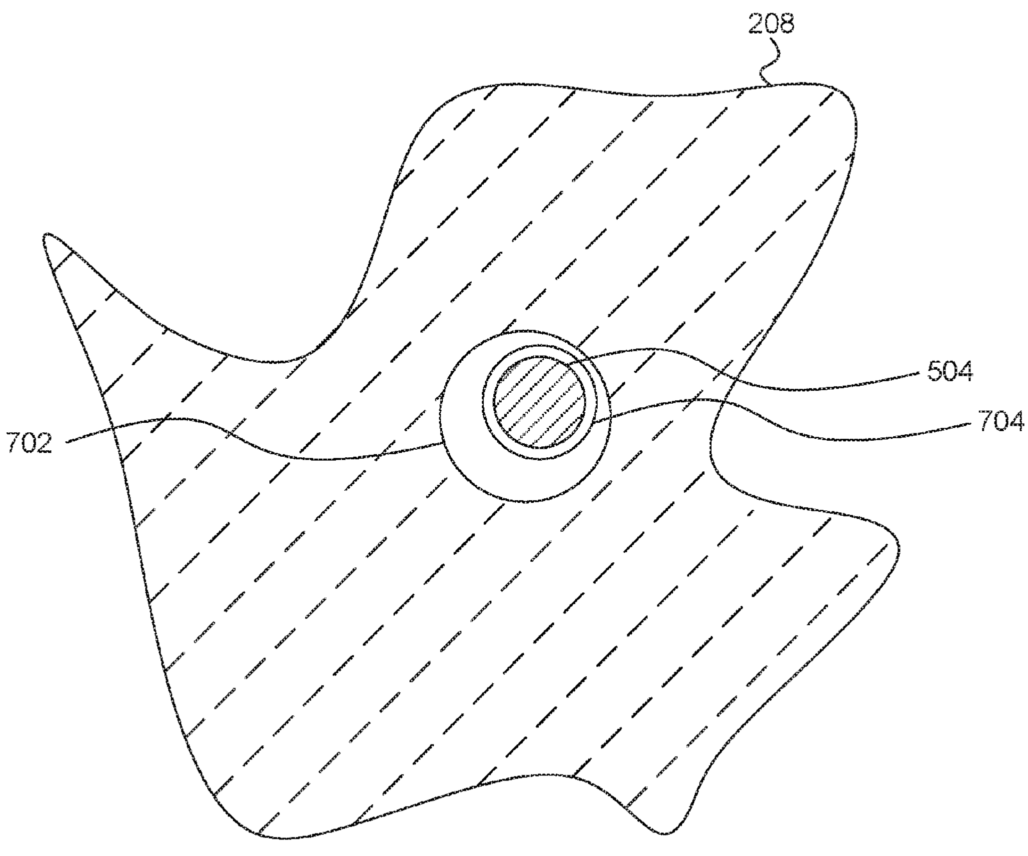


FIG. 8

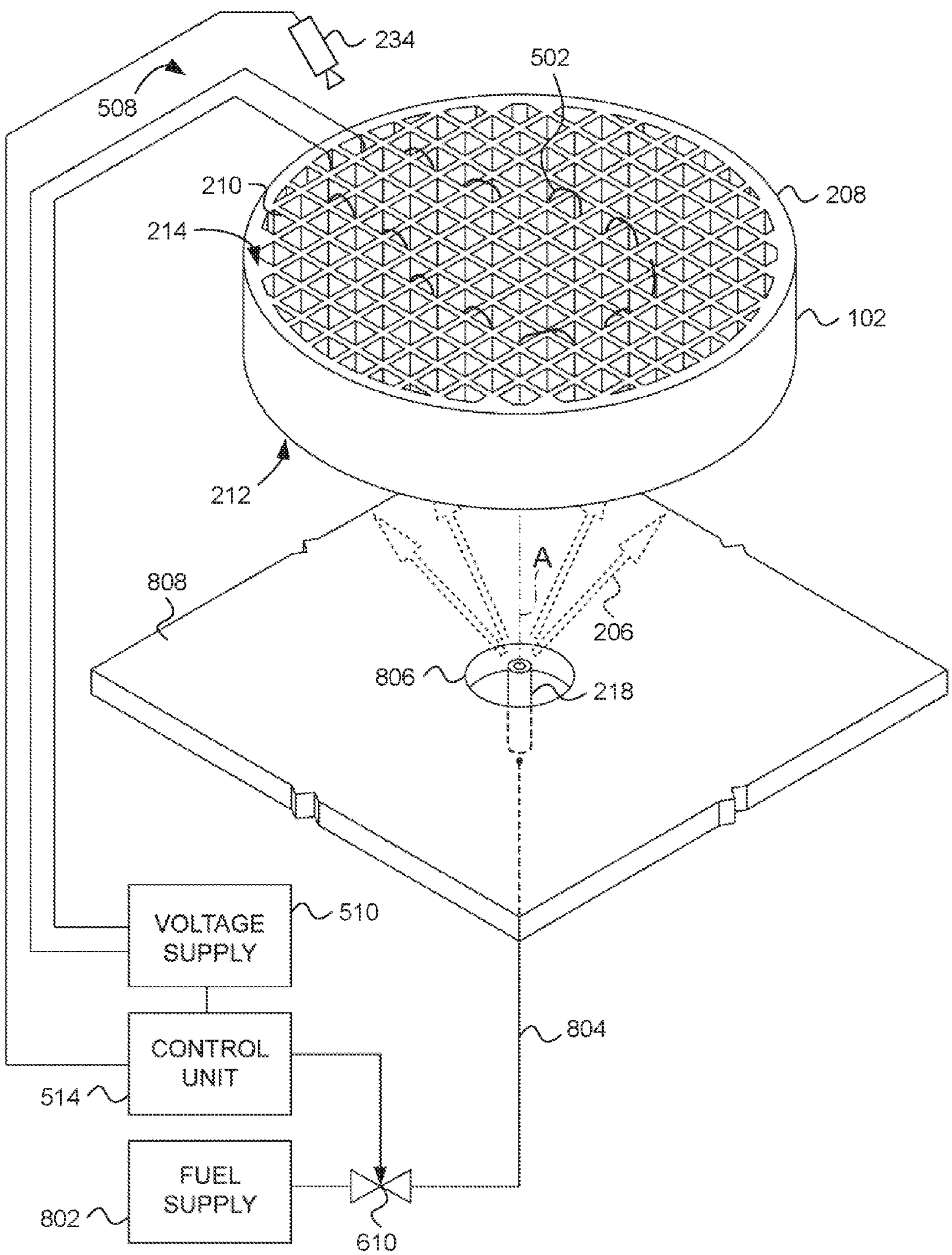

234
502
508
210
208
214
102
212
A
808
206
806
218
VOLTAGE SUPPLY
510
CONTROL UNIT
804
514
FUEL SUPPLY
802
610

FIG. 9

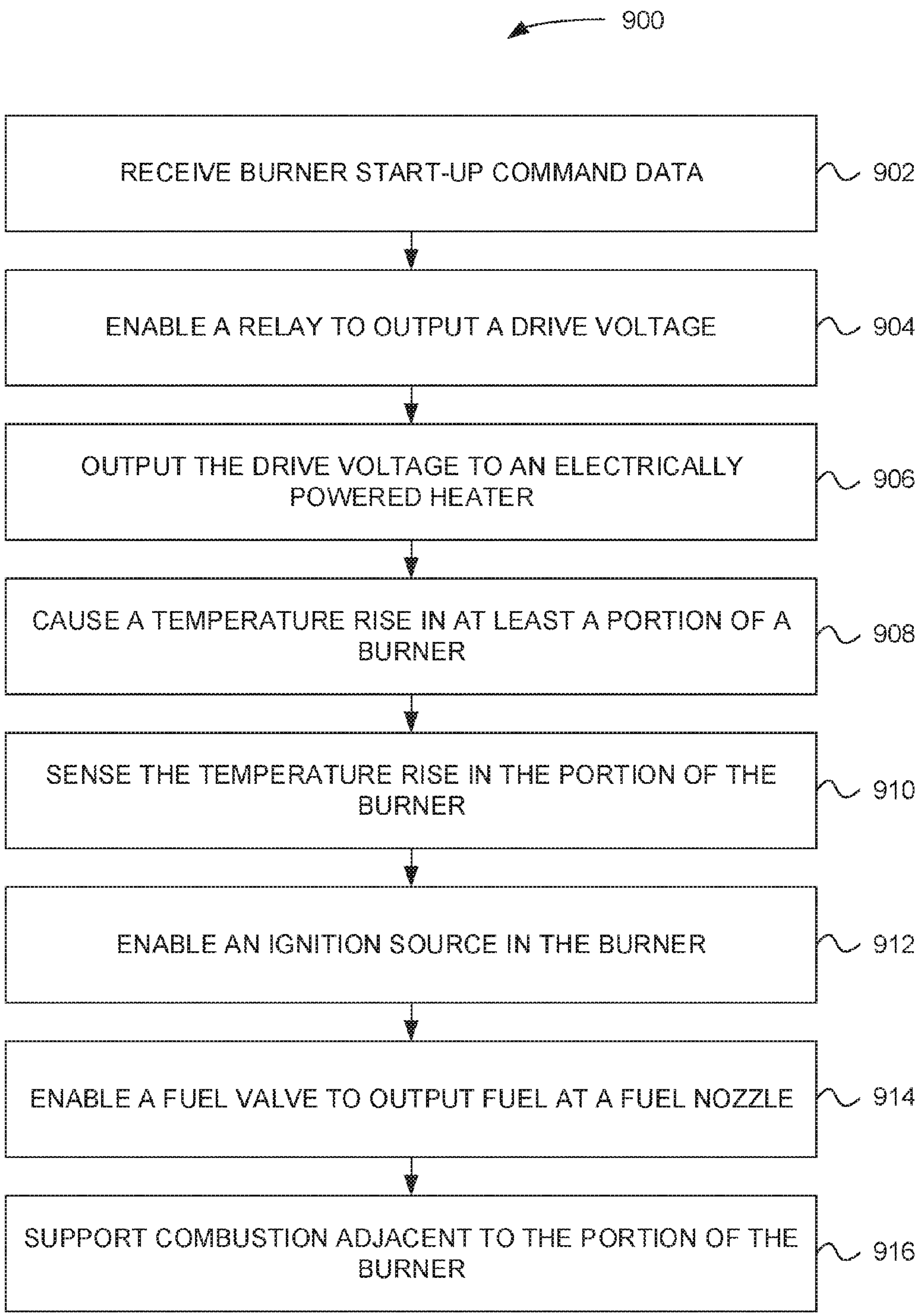
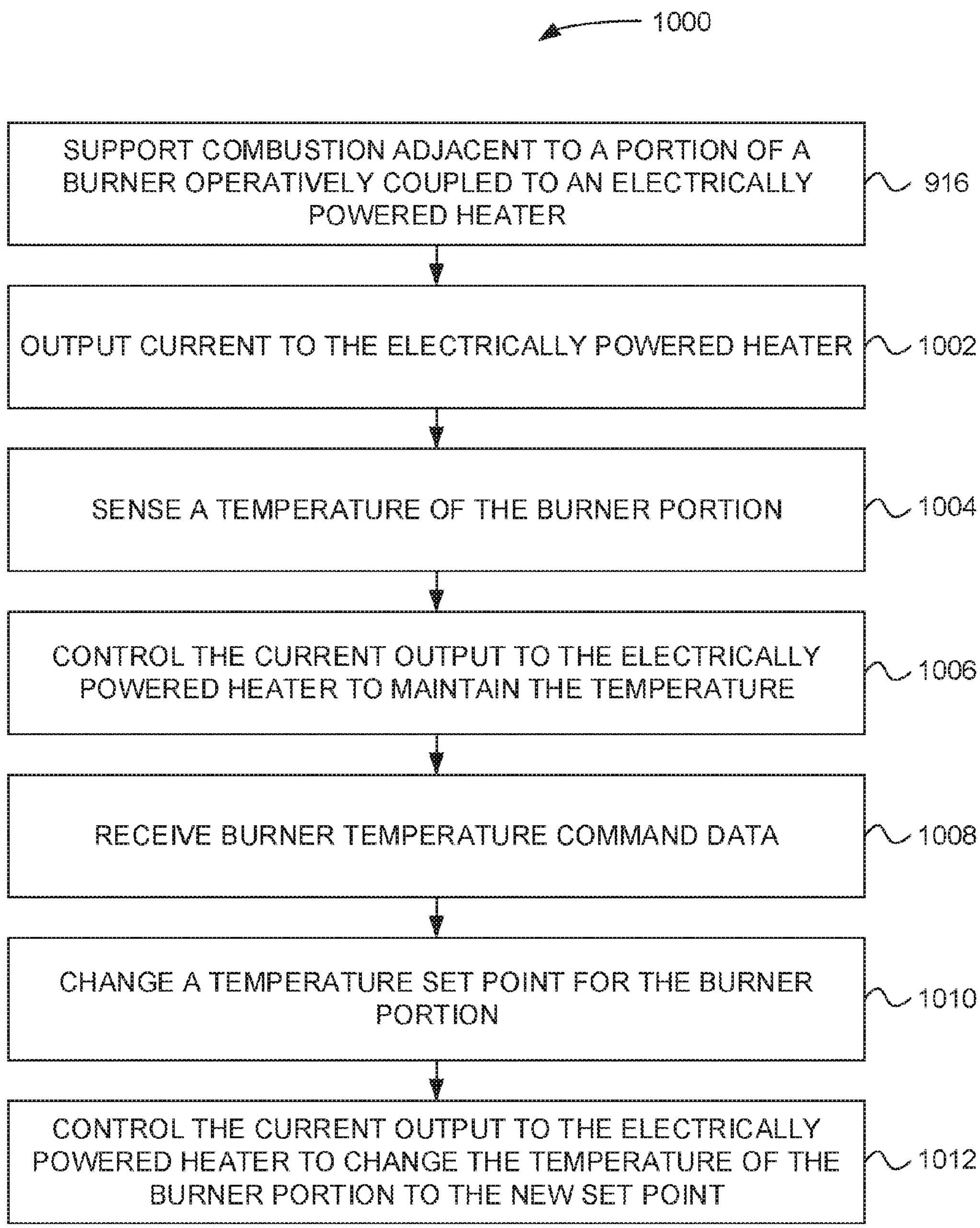

900
RECEIVE BURNER START-UP COMMAND DATA
902
ENABLE A RELAY TO OUTPUT A DRIVE VOLTAGE
904
OUTPUT THE DRIVE VOLTAGE TO AN ELECTRICALLY POWERED HEATER
906
CAUSE A TEMPERATURE RISE IN AT LEAST A PORTION OF A BURNER
908
SENSE THE TEMPERATURE RISE IN THE PORTION OF THE BURNER
910
ENABLE AN IGNITION SOURCE IN THE BURNER
912
ENABLE A FUEL VALVE TO OUTPUT FUEL AT A FUEL NOZZLE
914
SUPPORT COMBUSTION ADJACENT TO THE PORTION OF THE BURNER
916

FIG. 10


1000
SUPPORT COMBUSTION ADJACENT TO A PORTION OF A BURNER OPERATIVELY COUPLED TO AN ELECTRICALLY POWERED HEATER
916
OUTPUT CURRENT TO THE ELECTRICALLY POWERED HEATER
1002
SENSE A TEMPERATURE OF THE BURNER PORTION
1004
CONTROL THE CURRENT OUTPUT TO THE ELECTRICALLY POWERED HEATER TO MAINTAIN THE TEMPERATURE
1006
RECEIVE BURNER TEMPERATURE COMMAND DATA
1008
CHANGE A TEMPERATURE SET POINT FOR THE BURNER PORTION
1010
CONTROL THE CURRENT OUTPUT TO THE ELECTRICALLY POWERED HEATER TO CHANGE THE TEMPERATURE OF THE BURNER PORTION TO THE NEW SET POINT
1012

ELECTRICALLY HEATED BURNER

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a U.S. Continuation-in-Part application which claims priority benefit under 35 U.S.C. §120 (pre-AIA) of co-pending International Patent Application No. PCT/US2015/016456, entitled "ELECTRICALLY HEATED BURNER," filed Feb. 18, 2015 (docket number 2651-267-04). Co-pending International Patent Application No. PCT/US2015/016456 claims priority benefit from U.S. Provisional Patent Application No. 62/104,028, entitled "ELECTRICALLY HEAT ANY FLAME HOLDER," filed Jan. 15, 2015 (docket No. 2651-267-02). Co-pending International Patent Application No. PCT/US2015/016456 claims priority to International Application No. PCT/US2014/016632, entitled "FUEL COMBUSTION SYSTEM WITH A PERFORATED REACTION HOLDER," filed Feb. 14, 2014 (docket number 2651-188-04). The present application is also a Continuation-in-Part of co-pending U.S. patent application Ser. No. 14/763,271, entitled "PERFORATED FLAME HOLDER AND BURNER INCLUDING A PERFORATED FLAME HOLDER," filed Jul. 24, 2015 (docket number 2651-172-03). Co-pending U.S. patent application Ser. No. 14/763,271 claims priority benefit to International Patent Application No. PCT/US2014/016628, entitled "PERFORATED FLAME HOLDER AND BURNER INCLUDING A PERFORATED FLAME HOLDER," filed Feb. 14, 2014 (docket number 2651-172-04). International Patent Application No. PCT/US2014/016628 claims the benefit of U.S. Provisional Patent Application No. 61/765,022, entitled "PERFORATED FLAME HOLDER AND BURNER INCLUDING A PERFORATED FLAME HOLDER," filed Feb. 14, 2013 (docket number 2651-172-02). The present application is also a Continuation-in-Part of co-pending U.S. patent application Ser. No. 15/215,401, entitled "LOW NO_X FIRE TUBE BOILER," filed Jul. 20, 2016 (docket number 2651-205-03). Co-pending U.S. patent application Ser. No. 15/215,401 claims priority benefit to International Patent Application No. PCT/US2015/012843, entitled "LOW NO_X FIRE TUBE BOILER," filed Jan. 26, 2015 (docket number 2651-205-04). International Patent Application No. PCT/US2015/012843 claims the benefit of U.S. Provisional Patent Application No. 61/931,407, entitled "LOW NO_X FIRE TUBE BOILER," filed Jan. 24, 2014 (docket number 2651-205-02). Each of the international patent applications, U.S. patent applications, and U.S. provisional patent applications listed in this paragraph are, to the extent not inconsistent with the disclosure herein, incorporated by reference.

SUMMARY

[0002] According to an embodiment, an electrically heated burner includes a burner portion configured for contact with at least one of a fuel stream or a flame and an electrically powered heater operatively coupled to the burner portion. A power supply can be operatively coupled to the electrically powered heater. A controller can be configured to control a flow of current from the power supply to the electrically powered heater. The electrically powered heater can be configured to output heat energy to the burner portion to cause a temperature of the burner portion to be controlled proportional to the controlled current flow.

[0003] According to an embodiment, a burner includes a fuel and oxidant source configured to cooperate to produce a fuel and oxidant stream that includes a range of fuel concentrations. A body is disposed to receive the fuel and oxidant stream, configured to maintain combustion within perforations of the body, and to exchange heat energy with the combustion reaction therein. An electrically powered heater is operatively coupled to the body. A current source powers the electrically powered heater. A thermostatic control circuit selectively couples the current source to the electrically powered heater to hold the body at a selected temperature.

[0004] According to another embodiment, a conventional flame holder body is disposed adjacent to a fuel and oxidant stream and is configured to initiate and maintain vortices in the fuel and oxidant stream. An electrically powered heater is configured to raise the conventional flame holder body to an elevated temperature. The conventional flame holder body is configured to exchange heat energy with an adjacent combustion reaction supported by the fuel and oxidant stream.

[0005] According to another embodiment, a method of combustion includes outputting fuel into a combustion volume, admitting air into the combustion volume, and allowing the fuel and air to mix in the combustion volume to form a fuel and air jet having a range of mixtures. An igniter ignites the fuel and air jet to initiate combustion. A flame holder is supported adjacent to the fuel and air jet or to receive the fuel and air jet so has to hold the combustion reaction in a predetermined position. The flame holder is electrically heated. Ignition of the fuel and air mixture is maintained by heat exchange with the electrically heated flame holder.

[0006] According to another embodiment, a control system controls dynamics of a flame. The control system includes a source of electric current and an electrically-heated flame holder positioned to be in contact with the flame and operatively coupled to the source of electric current. The source of electric current induces electric current flow in an electrical heater operatively coupled to the electrically-heated flame holder. A temperature-responsive current controller coupled to the current source and the electrically-heated flame holder adjusts the electric current flow through the electrically-heated flame holder to drive the electrically-heated flame holder to a predetermined temperature.

[0007] According to an embodiment, a method for operating an electrically heated burner includes supporting combustion adjacent to at least a portion of an electrically heated industrial or commercial burner, outputting electrical current from a power supply to an electrically powered heater, causing the electrically powered heater to dissipate heat energy responsive to outputting the electrical current, and raising a temperature of the portion of the electrically heated burner with the heat energy.

[0008] According to another embodiment, a method for operating an electrically heated burner includes receiving start-up command data into a controller via a data interface, enabling a relay to output a drive voltage on at least one node of a power supply, receiving the drive voltage at an electrically powered heater, outputting heat energy from the electrically powered heater to a component of an industrial or commercial burner to cause a sensible temperature rise in the burner component and contacting a fuel stream or a flame supported by the fuel stream with the burner component.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a diagram of an electrically heated burner, according to an embodiment.

[0010] FIG. **2** is a simplified perspective view of a burner system including a perforated flame holder, according to an embodiment.

[0011] FIG. **3** is a side sectional diagram of a portion of the perforated flame holder of FIGS. **1** and **2**, according to an embodiment.

[0012] 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.

[0013] FIG. **5** is a partially schematic, partially cross-sectional diagram of a system for controlling electric heating of a flame holder, according to an embodiment.

[0014] FIG. **6** is an elevational, partially cross-sectional diagram of a flame-holding burner tile with controllable fuel and air feeds, according to an embodiment.

[0015] FIG. **7** is a cross-sectional diagram of a flame holder with an electric heater element inserted therethrough, according to an embodiment.

[0016] FIG. **8** is a diagrammatic perspective view of a combustion system in a furnace with feedback control of fuel flow and electric heating, according to an embodiment.

[0017] FIG. **9** is a flow chart showing a method for operating an electrically heated burner, according to an embodiment.

[0018] FIG. **10** is a flow chart showing a method for operating an electrically heated burner, according to another embodiment.

DETAILED DESCRIPTION

[0019] 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.

[0020] FIG. **1** is a diagram of an electrically heated burner **100**, according to an embodiment. Various embodiments of the electrically heated burner **100** are contemplated. For ease of understanding, FIG. **1** depicts a sectional view, augmented by a block diagram, of an electrically heated burner **100** including an otherwise conventional burner tile **104** with an added electrically powered heater **106**, according to an embodiment.

[0021] The burner tile **104** can be a type that can be used to heat a furnace, duct, oven, or boiler volume **108** arranged to receive combustion heat from the electrically heated burner. The burner tile **104** can be of a type that is typically formed from a refractory material such as a fiber-reinforced refractory or cementatious material formed as a bluff body flame holder configured to hold a combustion reaction **110**, shown as a flame, in the furnace, duct, oven, or boiler volume **108**. According to embodiments, primary fuel nozzles **112** and secondary fuel nozzles **114** are arranged to respectively impinge at least partially on interior and exterior surfaces **116**, **118** of an axially symmetric burner tile **104**. The burner may receive combustion air through a central natural or forced draft air source **120** and/or from other sources of combustion air. As is known to the art, the conventional aspects of the burner **100** support staged combustion as an attempt to control output of undesirable combustion products such as oxides of nitrogen (NOx) and carbon monoxide (CO).

[0022] One function of the burner tile **104** can be to provide flame holding for the combustion reaction **110**. The inventors note that, especially in low NOx burners, flame holding can be somewhat tenuous and tricky to maintain. Other shortcomings are apparent to those skilled in the art.

[0023] To address the shortcomings and design trade-offs of burners **100** used in commercial and industrial applications, the inventors believe that electrically heating a portion of the burner **100** such as the burner tile **104** offers performance, capital cost, and/or operating cost advantages. The inventors contemplate use of the electrically powered heater **106** during system start-up, for example, to reduce time during which the burner **100** must be held at a low heat output. The inventors contemplate use of the electrically powered heater **106** during steady-state operation, for example, to improve stability of flame **110** holding by the burner tile **104**. For example, the inventors have noted a tendency for flame lift-off and other asymmetries in existing burners under some operating conditions. For another example, the inventors contemplate use of the electrically powered heater **104** to improve system turn-down range. Conventional burners can exhibit a limitation with respect to the minimum amount of heat output compared to maximum heat output, especially in “low NOx” and “ultra low NOx” burners (both of which typically output far more NOx and/or more CO than a burner **200** with perforated flame holder **102** described in FIGS. **2**-**3** below). In an embodiment, electrically heating the burner tile **104** can help to maintain stable combustion even when fuel flow rate is reduced to a level insufficient to maintain a preferred operating temperature of the burner tile **104**. In some embodiments, the inventors contemplate use of the electrically powered heater **106** to maintain the burner **100** in a “warm stand-by” mode wherein fuel flow is stopped during periods of low demand for heat release. This approach can afford the ability to start up the burner **100** more quickly to respond to an increase in power demand, process throughput, etc.

[0024] During start up, an igniter **122**, such as a hot surface igniter, electrical discharge igniter, pilot flame, etc. can be used to ignite the primary fuel stream from the primary fuel nozzles **114**. In typical prior art systems, only primary fuel is output for a time sufficient to heat the surface, and particularly a flame-holding surface **124** sufficiently to hold a larger flame supported by secondary fuel from the secondary fuel nozzles **114**. During this time, the burner **100** cannot respond as quickly as may be desired to surge demand and/or the concentration of undesirable combustion products such as NOx and CO can be elevated.

[0025] According to an embodiment, during start up, a controller **126** controls an electrical current source **128** to energize a primary fuel igniter **122** and to energize the electrically powered heater **106**. The additional heat output by the electrically powered heater **106** causes extra heat energy to be dissipated to the burner tile, and allows for faster start up. In an embodiment, the primary fuel igniter

122 and the electrically powered heater **106** can be energized at different and/or overlapping periods of time. In an embodiment, the controller **126** causes the electrical current source **128** to energize the electrically powered heater **106** upon receipt of a start up command via a data interface **130**. A timer and/or optional one or more sensor(s) **132** operatively coupled to the controller can determine when the burner tile **104**, and especially a flame holding surface **124** of the burner tile **104** is heated sufficiently for optimum ignition of the primary flame. Upon reaching a start up temperature, the controller **126** can cause the current source **128** to energize the igniter **122** and can cause a primary fuel valve **134** to open to supply fuel flow to the primary fuel nozzles **114** and ignite a primary flame. At a later time or simultaneously, the controller **126** can cause a secondary fuel valve **136** to open to supply fuel flow to the secondary fuel nozzles **114**. Owing to the electrical heating of the burner tile **104** by the electrically powered heater **106**, the time delay between receiving a start up command via the data interface **130** and igniting primary and secondary combustion **110** can be decreased, compared to a non electrically heated burner.

[0026] According to an embodiment, during steady-state operation, the controller can receive a temperature signal from temperature sensor(s) **132** (which may optionally be embedded in the burner tile **104** and/or embodied as an electrical resistance measurement across the power supply nodes **138**, **140**) and cause output of current from the current source **128** to maintain a desired temperature. In this way, the controller **126** and sensor(s) **132** can operate as a thermostat that maintains a temperature of at least the flame holding surface **124** of the burner tile **104**.

[0027] According to an embodiment, a thermostat is configured to sense the temperature of the burner portion(s) and control current delivered from the power supply to the electrically powered heater to maintain a range of temperatures near a temperature set point. In one embodiment the thermostat has a precision of plus or minus 5 degrees F. In another embodiment, the thermostat has a precision of plus or minus 2 degrees F. In another embodiment, the thermostat has a precision that is poorer than plus or minus 2 degrees F.

[0028] According to an embodiment, the temperature sensor is operatively coupled to the burner portion and the controller, and configured to measure a temperature of the burner portion, and to output a temperature signal or data corresponding to the measured temperature to the controller.

[0029] According to another embodiment, the controller includes a timer circuit, a non-transitory computer readable medium carrying data corresponding to a duty cycle set point, and a signal generator operatively coupled to the timer circuit and configured to generate an electrical heater control signal having a duty cycle corresponding to the duty cycle set point. The controller can thus be configured to control the current flow from the power supply to the electrically powered heater according to the electrical heater control signal.

[0030] While the description corresponding to FIG. **1** was directed to an embodiment wherein the electrically powered heater **106** was operatively coupled to an otherwise conventional burner tile, the inventors contemplate additionally or alternatively providing an electrically powered heater to a perforated flame holder **102**, described in more detail below in conjunction with FIGS. **2-4**.

[0031] 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.

[0032] 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.

[0033] 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**.

[0034] 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**.

[0035] 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.

[0036] 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**.

[0037] 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**.

[0038] 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.

[0039] 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**.

[0040] 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**.

[0041] 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.

[0042] 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.

[0043] 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.

[0044] 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).

[0045] 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**.

[0046] 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.

[0047] 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**.

[0048] 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.

[0049] 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.

[0050] 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**.

[0051] 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.

[0052] 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**.

[0053] 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.

[0054] 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**.

[0055] 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).

[0056] 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.

[0057] 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.

[0058] 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.

[0059] 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.

[0060] 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.

[0061] 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.

[0062] 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.

[0063] 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.

[0064] 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.

[0065] 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.

[0066] The inventors contemplate various explanations for why burner systems including the perforated flame holder **102** provide such clean combustion.

[0067] 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.).

[0068] 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.

[0069] 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**.

[0070] 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.

[0071] 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.

[0072] 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.

[0073] Step **404** may be broken down into several discrete steps, at least some of which may occur simultaneously.

[0074] 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.

[0075] Proceeding to step **412**, the combustion reaction is held by the perforated flame holder.

[0076] 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.

[0077] In optional 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, 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.

[0078] 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. 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.

[0079] 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**.

[0080] 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**.

[0081] 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**.

[0082] 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 $T \geq T_S$).

[0083] 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.

[0084] 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.

[0085] 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.

[0086] 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.

[0087] 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).

[0088] 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**.

[0089] FIG. **5** is a schematic diagram of a fuel and oxidant source **202** in conjunction with an electrically powered heater **502** combined with a flame holder body **208**, according to an embodiment. The body **208** may be made of a refractory material, such as for example ceramic, fire brick, etc., and may be part of an industrial furnace or heater. The body **208** may, according to an embodiment, exclude metals such as stainless steel, except possibly as attachments or auxiliary parts (e.g., swirlers, vanes, supports, bolts, etc.) that are not part of the body **208** proper, which may be less than 0.5, 0.4, 0.3, 0.2, 0.1, 0.05, or 0.01 of the body structure or the body proper by weight; or in other words, the body may substantially comprise a non-metal or consist substantially of non-metallic material. The fuel and oxidant source **202** comprises a fuel jet nozzle **218** configured to emit a jet of fuel and an oxidant **206** as a combined stream, for example, by the jet of fuel entraining air (or other oxidant). The fuel and oxidant source **202** may optionally be configured so as not to comprise or constitute a fuel/air mixer, i.e., a device or system that premixes fuel and air for delivery to the region of a combustion reaction **302**.

[0090] The flame holder body **208** may be disposed adjacent to the fuel and oxidant stream **206** at a predetermined position at which it may be configured to initiate and maintain vortices of turbulence T in the fuel and oxidant stream **206**. Optionally, to induce more local turbulence and/or vortices, and thereby assist in flame holding, the body **208** may includes a vortex generator **502**, that may be shaped as a ramp or projection as illustrated, or may be shaped in some other way that will produce additional turbulence, or vortices, or otherwise assist with flame holding; or, the body **208** may act as a bluff body that induces additional turbulence without being shaped specifically for that purpose (e.g., without a specific vortex generator), but rather does so by being placed in a predetermined position in the flow of mixture and/or in the combustion reaction or flame **302**. The body may act either by disrupting streamlines that would otherwise be present, or by the Coanda effect, or by its motion, or by some other mechanism.

[0091] A body that generates vortices and/or turbulence thereby promotes heat transfer between the body and fluid with which it interacts. The body **208** may also increase such heat transfer by having a larger surface area. For example, if the vortex generator **502** were perforated with through-holes, then it might create more turbulence, but its heat transfer rate would be increased even if the amount of turbulence did not increase, due to the larger surface area. Heat transfer between a body and fluid is a concern of the applicants.

[0092] While not shown in FIG. **5**, it will be understood that the illustrated portion of flame-holder body **208** may be merely representative of a differently shaped or longer body, and in particular might schematically represent a curved flame-holder body that curves circumferentially around the combustion reaction **302**, and or an axis of the nozzle **218**.

[0093] The body **208** receives heat from an adjacent diffusion-limited combustion reaction or flame **302** supported by the fuel and oxidant stream **206**. The heat of the flame raises the body **208** to an elevated temperature, after the flame is well established and the body **208** has time to heat up. However, in the early stages of combustion, especially, the body **208** may not have reached its steady state or equilibrium temperature, and as a result the dynamics of the flame or reaction **302** are affected. To more quickly bring the body **208** to an operating temperature, and/or to maintain that temperature during steady-state operation (or, to maintain a more-elevated temperature), an electrically powered heater **502** is arranged and deployed to conduct at least a majority of heat electrically generated in the heater **502** into the flame holder body and, at most, a minority of the generated heat to the fuel and oxidant stream **206**.

[0094] The oxidant source **220** may be illustrated as a mere pipe conducting the oxidant. The oxidant may be air, although any oxidizer, such as gaseous oxygen or liquid oxidants may be used. The oxidant source **220** may include a natural-draft or forced-draft arrangement, such as a blower **506** configured to provide a flow of combustion air. Conventional devices may be used for the fuel and oxidant source **202**.

[0095] In an embodiment, the electrically powered heater **502** constitutes an electrical resistance heating element, and may be made from conventional materials suitable for low or high-temperature devices, such as tungsten for example; it may have insulation, like the burner of an electric-stove element, or it may be bare or otherwise covered. In FIG. **5**, the two ends of the heater **502** are coupled, by a schematically-illustrated wire **508**, to a voltage supply, power supply, or current source **510** (shown schematically by a battery symbol).

[0096] A control system **512** may include a controller **514** (which may be, for example, a processor, relay arrangement, or other device), a temperature sensor **234** that is coupled to the controller **514**, and a device **516** for varying the electric current through the heater element **502**; in FIG. **5**, this device is shown schematically as a variable resistance, but any other current-varying device, such as a transistor, can be used. The control system may use input signals from the temperature sensor **234** for feedback to control the current-control device **516**; thus, in one embodiment the control system **512** comprises a thermostat. The temperature sensor **234** may detect the temperature directly (as by infrared detector, thermocouple, thermopile, or the like) or indirectly (as by combustion products).

[0097] A schematically-illustrated known electrically powered hot-surface igniter **518** is shown in FIG. **5**, with a hot end thereof disposed in the flow of fuel and oxidant. The hot-surface igniter is not a flame holder and is used only for ignition of the fuel in the flow of entrained air (e.g., starting a flame). Because it only needs to heat a local region to above the flammability point, a hot-surface igniter is often small and does not affect the flow or create substantial vortices.

[0098] The flame holder body **208** may be disposed in relation to the heater **502** in such a way that a majority of the heat generated by electric current in the heater **502** flows into the flame holder body, rather than flowing directly into the environment of the flame holder body and the electrically powered heater **502**, and therefore bypassing the flame holder body. When a majority of the electric-current heat flows into the body **208**, then the body **208** will more quickly reach its desired operating temperature, and a steady-state dynamic of the combustion reaction **302** will more quickly be reached. If heat is not being removed from the combustion reaction **302** into the body **208**, as it is when the body **208** is cold, then the flame dynamic is not disturbed and, e.g., flame "lifting" or even extinguishing of the flame, is made less likely.

[0099] Heat, as is well known in physics, moves from a place of higher temperature to a place of lower temperature via three primary mechanisms: conduction, convection, and radiation. In conduction, heat is transferred via molecular impacts; in convection, heat is transferred via bulk motion of hot or cold fluid; and in radiation, heat is transferred via photons (electromagnetic radiation).

[0100] In all three types, the rate of heat transfer is substantially dependent on surface area. In radiation, for example, a hot object such as a glowing ember in a fire emits a certain amount of radiation, carrying a corresponding certain amount of heat energy away from the ember; and two such embers, having twice the surface area, will emit two times the amount of heat. Similarly, two similar cold objects in the path of the ember's heat radiation will absorb twice the heat that one would. In conduction, a similar correspondence exists, because heat transfer through a slab of material is directly proportional to the area of that slab (the other factors are the thickness, the heat conductivity of the slab material, and the temperature difference between the two sides). Convection is more complicated, because fluid flow is itself more complicated—the flows are usually deterministically chaotic, and heat transfer from a moving fluid to a surface depends on local flow conditions near the surface. However, the same general dependence on area exists for convection also, in part because the heat path of convection usually starts and stops on respective solid surfaces that bound the convective fluid.

[0101] FIG. **5** typifies that an electrically powered heater **502** may be disposed substantially within a flame holder body **208**, which may be one way of causing heat to flow from the hotter body (the heated wire) to the colder body (the flame holder), rather than to flow somewhere else (i.e., the environment, which may be the fuel and oxidant stream **206**, ambient air, nearby or attached objects, etc.). If a majority of the area of the heater is in contact with, or close to, the flame holder body **208**, this will tend to cause a majority of the heat generated in the heater to flow directly into the flame holder body **208**, by any or all of the three heat-transfer mechanisms.

[0102] However, this is not a necessary condition. In the case where an electrically powered heater wire or elongated element is in contact with a planar part of the surface of the flame holder body (not shown in FIG. 5), the body may not substantially surround the heater, but it may still absorb most of the heat generated in the heater because conduction through the contact region will pass more energy than radiation and convection will pass to the environment.

[0103] One of the inventors' objects is to pre-heat a flame holder body, which may for example be done to quickly normalize a combustion process. In an ongoing combustion process, the flame holder body has achieved a certain overall or average temperature by absorbing heat generated in a flame, and this temperature may be a steady-state temperature if the fuel and oxidant flows are steady-state. However, when the flame holder body is cold, for example when combustion is started, the flame conditions are different from these steady-state conditions; and then, adjustment of the flame conditions (for example by adjusting the fuel or oxidant flow) cannot be performed directly for steady-state conditions. The steady-state conditions corresponding to mixture flow settings will not result from the adjustment, due to the cold flame holder; the operator must guess. Thus, operation of a boiler, furnace, jet engine, or other fuel-burning device, may be simplified by electrically heating a flame holder.

[0104] FIG. **6** illustrates an embodiment in which the flame-holding body may be associated with a burner tile **602** that has an internal ridge or ledge **604**. The burner tile **602** is shown in cross section, as if sawn down its axis. Curved arrows around the ridge or ledge **604** indicate toroidal vortices which may comprise a substantially toroidal pattern of vortices (i.e., there is an overall toroidal swirl pattern regardless of non-toroidal turbulence superimposed on the more-prevalent toroidal swirl pattern). The ridge or ledge **604** comprises a ramp shape, which is one shape for a projection into the moving portion of a flame; the vortex generator **502** is another projection shape.

[0105] A burner tile can be described as a flame holder, since it affects the flow of fuel/oxidant mixture and because a flame may be attached to a rim of the burner tile, except during the undesirable condition of flame "lift-off" (which a flame holder can prevent). A burner tile may also include specific flame-holding structures such as the illustrated internal ledge **604** that acts as a flame holder, and may also include a separate flame stabilizer or flame holder disposed within, that may be considered as a part of the burner tile (see, e.g., *The John Zink Hamworthy Combustion Handbook,* 2nd ed., Vol. 2, FIGS. 6-10 and 6-11).

[0106] An electrically powered heater wire **502** is shown embedded inside the burner tile **602**, in a position near to the ledge **604**. In the illustrated predetermined position, a majority of the heat generated in the heater wire **502** will appear at the internal surface of the burner tile **602** and cause an elevated temperature at the ledge **604**. The wire **502** may be cast in place in the burner tile **602**. If the burner tile **602** is assembled from segments, then the embedded section may be electrically connected at their ends to form a complete circuit, or, a partial circuit may have its ends connected to a current source. If the wire **502** forms a complete circuit, then current may be magnetically induced in it. The figure shows a multi-turn induction coil **606** on the outside of the burner tile **602**. If the material of the burner tile may be non-conductive (e.g., non-metallic), then magnetic fields generated by the induction coil **606** will induce current in the wire **502** when an AC voltage is impressed across it. As in any transformer, more current will be induced in the coil with fewer turns (wire **502** in FIG. **6**), and a higher current causes more electric heating. Thus, a multi-turn induction coil may be capable of inducing large heating effects in a single-turn coil such as wire **502**.

[0107] It may be noted that at least a portion of the body of the burner tile **602** forms a conical surface, and the electrical heater wire **502** is wrapped around the conical interior surface, though separated from it (it may also be wrapped around an exterior conical surface, as are the wires of the coil **606** in FIG. **6**). In alternative embodiments (not illustrated) the heater wire **502** may be deployed in contact with a conical surface of a refractory body, either on the outside of an exterior or interior conical surface, in a groove formed in an otherwise conical surface, or against a ridge protruding from a conical surface.

[0108] According to various embodiments, the burner tile **602** may comprise a dielectric body formed by casting refractory material a mold cavity (not shown), and the wire or wires **502** may be supported in the mold cavity during the formation of the dielectric body. During such formation, refractory material can flow or pack around the wire **502**, causing the wire **502** to be cast into the body of the burner tile **602** when the refractory material is hardened. The mold cavity can include at least one via for wire supports and/or, when the burner tile **602** is assembled from segments, for portions of the wire **502** that extend to an outer or inner surface for electrical connection to the wire **502** of an adjacent burner tile segment (or to a power supply or current source even when there are no segments). In such a case, the wire **502** in each segment might be shaped as a partial arc of a circle, with radial extensions at either end that protrude through the outer surface of the burner tile **602** for electrical connection to the wire **502** of the adjacent segment when the refractory material is hardened (not illustrated).

[0109] The heater wire **502** may be configured to provide tensile reinforcement of the dielectric body of the burner tile **602**. According to various embodiments, burner tile **602** segments can be formed in a mold cavity with one or more inserts (not shown) configured to establish mechanical fastener locations, as well as electrical connections. According to various other embodiments, the burner tile **602** or burner tile segments can be formed by sand casting the refractory material. The cast refractory material can include a cement-bonded material, phosphate-bonded materials, fiber reinforcement, and/or an aggregate particle distribution.

[0110] In another embodiment, the refractory tile can include cast passages for allowing electrodes to be inserted, taken out, or interchanged as needed. Cast passages can be formed during manufacturing of refractory tile according to the dimensions, shapes, and desired applications of electrodes within the structure. Cast passages can allow metal parts to be inserted and taken out of the burner tile **602**. In general, castable materials can be used for a refractory body in order to minimize cost when manufacturing complex shapes that can integrate one or more electrodes, resistance heating elements, or other parts.

[0111] Forming a refractory tile, with or without cast passages, can involve known refractory manufacturing processes which can include mixing raw materials and forming into desired shapes and dimensions under wet or moist conditions; followed by heating the refractory material to high temperatures in a periodic or continuous tunnel kiln to form the ceramic bond that gives the refractory tile its refractory properties; and concluding with a final processing stage that can involve milling, grinding, and sandblasting of the refractory tile.

[0112] In FIG. **6**, the oxidant source or pipe **220** includes an air-flow control, shown as a damper plate **608** for example, while the fuel source or jet-forming pipe **218** includes a fuel-concentration adjustment (a device for varying the ratio of fuel and oxidant flowing into the combustion reaction **302**, for example by varying the flow rate of fuel, of oxidant, or of both). In FIG. **6**, the fuel-concentration adjustment is shown as an exemplary adjustable valve **610** (a variable-fuel-flow-rate pump/motor is an alternative; such a device can use a variable-speed motor and/or a variable-flow pump). The valve **610** can adjust the fuel concentration even without providing any airflow control such as the plate **608**. These adjustment devices may, individually or in a combined manner, be coupled to respective actuators **612** and **614**, which may be step motors, for example, and the actuators **612** and **614** may in turn be coupled to a control system (they may also be manual, or both manual and automatic). Only one motor may be needed if the adjustment devices are combined, or is only one of them is provided. For example, they may be coupled by wires **616**, **618** to the controller **514** of FIG. **5** (or some other automatic controller). The characteristics of the combustion reaction **302** are determined in part by the proportion and flow rates of the fuel and oxidant.

[0113] FIG. **7** is a cross-sectional diagram of a flame holder with an electric heater element inserted therethrough, according to an embodiment. FIG. **7** relates to a flame holder body **208** that may be of arbitrary shape in cross section and has an elongated central passage **702** through which the heater wire **502** passes. If the heater **502** passes along a central passage, then virtually all of the heat generated in the heater will pass into the body **208**. FIG. **7** illustrates the fact that the flame holder body **208** is not limited to any specific shapes.

[0114] A particular example of such an arrangement might be in a gas fireplace of the type in which a gas flame impinges on non-flammable (e.g., ceramic) "logs." These fireplaces require a warm-up period both to achieve mimicry of a wood fire, and also to begin to throw radiant heat, most of which comes from the heated "logs" once they are hot. If the "logs" include electric heaters according to the Applicants' construction, then the fireplace will more rapidly reach the desired condition of resembling a wood fire and giving off radiant heat. (The "logs" act as a flame holder because they give heat back to the fuel/air mixture, and thereby maintain complete combustion, and also because their irregular shape causes turbulence. Such a "log" body **208**, though not commonly denoted as a "flame holder" in the art, is so termed herein by the applicants and the phrase covers such a "log" in the following claims.)

[0115] In the case of the fireplace, and also in other cases such as metallurgical and industrial applications, the flame holder may eventually reach a temperature at which even high-temperature heating elements deteriorate, oxidize, or even melt; the flame holder may be constructed of ceramic, refractory material, or other non-metallic materials that can withstand temperatures higher than those tolerable to metals such as stainless steels. If so, then the heater element can be surrounded by a layer of insulation, anti-oxidant, or other covering **704** as shown, but can also be exposed to a force flow of outside air. For example, if there is an air gap between the heater **502** and the passage wall, then air can be pumped through that passage, and keep the temperature of the heater **502** below that of the flame holder body **208**. The air can then be released into the environment, or recycled to an air pump. In a fireplace, a small air pump (not illustrated) can send air into the "logs" by metal pipes to pass through the air gap passage and thence out into the fire.

[0116] FIG. **8** is a diagrammatic perspective view of a combustion system or burner system, according to an embodiment in which the flame holder body **208** is embodied as a perforated flame holder, a flame holder including perforations **210** that allow the passage of fuel and oxidant and/or combustion reactants and/or combustion products from an input face **212** of the perforated flame holder **102** to an output face **214** thereof, and which may support flames inside the perforations **210** of the perforated flame holder **102**. The perforations **210**, and also the edges of the perforated flame holder **102**, may induce turbulence in a flow of mixture or combustion products.

[0117] In FIG. **8**, the electrically powered heater **502** is exemplified by an electrically resistive heating element in the form of a wire that is interleaved in and out through some of the plurality of perforations **210** (which may include through-bores or through-passages. The electrically powered heater **502** may, for example, be formed from KANTHAL® wire (available from Sandvik Materials Technology division of Sandvik AB of Hallstahammar, Sweden) threaded through at least a portion of elongated perforations **210** formed of the perforated flame holder **102**. (Alternatively, the flame holder **102** can be heated by an inductive heater, a high energy (e.g. microwave or laser) beam heater, a frictional heater, or other types of heating technologies.)

[0118] The heating element **502** is, in an embodiment, operatively coupled to a voltage supply **510** via wires **508**, and the voltage supply **510** may be coupled to a controller or control unit **514** by a bus, wire, or wireless means. The control unit **514** may control the current flowing through the heating element **502** so as to vary the temperature of the perforated flame holder **502**, or portions thereof.

[0119] Although only a single heating element **502** is illustrated, it will be understood that plural heating elements **502** with associated plural pairs of wires **508** may be arranged from the voltage supply **510** (or from respective plural voltage supplies **510**) all under the control of the controller **514**, or, of plural controllers. In such an arrangement, the control unit **514** may control the different heating units differentially or individually according to an algorithm, sequence, or timing schedule, and can also determine a distribution pattern of heat in the perforated flame holder **102**. The voltage supply **510** may be replaced by a current supply or some other electrical heat driver.

[0120] The nozzle **218** is shown located in an aperture **806** in a plate **808**, which schematically represents a furnace, or a furnace wall or wall portion. The nozzle **218** may, in an embodiment, be coaxial with an axis A of the perforated flame holder as shown. The nozzle **218** emits a fuel jet or stream **206** and is supplied from a fuel supply **802**, a fluid line **804**, and a fuel control valve **610**, which may in an embodiment be under the control of the control unit **514**. (In an alternative embodiment, the valve **610** includes a sensor that informs the control unit **514** of the rate at which fuel is being delivered to the nozzle **218**.) The control unit **514** may further be coupled to a temperature sensor **234** that is capable of detecting a temperature or temperature distribution of the upper second face **214** of the perforated flame holder **102** (for example, by infrared detection or imaging, although any other temperature or heat-measuring sensor may be used).

[0121] Because of these connections, the control unit **514** is capable, in an embodiment, of adjusting both the flow of fuel and the electrical heating of the perforated flame holder **102** in such as way as to maintain a predetermined temperature and/or temperature distribution of the perforated flame holder, or to make other adjustments related to the fuel rate and the temperature, such as controlling a rate of temperature change. Such adjustment can extend the turndown ratio, and/or compensate for lower flame-holder temperature during cold starting.

[0122] During a startup procedure, the system control unit **514** may control the voltage supply **510** to apply a voltage potential (or current) across the ends of the heating element **502**. The resistance value of the heating element **502** and the magnitude of the voltage potential may be selected to generate sufficient heat to raise the temperature of the portion of the flame holder **102** in the vicinity of the heating element **502** to beyond a startup threshold within a few seconds, after which the system control unit **514** controls valve **610** to open, while controlling the voltage supply **510** to remove the voltage potential from the heating element **502**. When the fuel stream **206** contacts the heated portion of the flame holder **502**, auto-ignition occurs, and a stable flame is established in the flame holder **502**.

[0123] The stream of fuel **206** ejected from the nozzle **218** toward the first face **212** of the flame holder **102** disperses from the nozzle **218** in a conical spray at an angle that is typically about 7.5 degrees from the longitudinal axis A, resulting in a solid conical angle of about 15 degrees. As the fuel stream **206** disperses, it entrains air, and eventually reaches a flammable proportion of fuel and air. By selection of the nozzle orifice diameter and the pressure at which fuel is ejected, the velocity at which the fuel stream **206** ejected from the nozzle **218** is preferably selected to be much higher than the flame propagation speed of the particular type of fuel employed, so that, on the one hand, the fuel stream is prevented from supporting a flame near the nozzle, and on the other hand, by the time the dispersing fuel stream **206** has slowed to near the flame propagation speed, the fuel stream has entrained enough air that the mixture is too lean for combustion at the temperature of the fuel stream.

[0124] A nozzle-produced fuel jet such as **206** may have greater velocity near the axis A and may have fuel/oxidant ratios changing with the radial distance from the axis A. Therefore, a wire heating element **502** may be placed generally at a selected distance from the axis A where an ignition temperature might be reached more quickly due to jet characteristics, or, where it might cause adjacent areas to more quickly reach ignition temperature, or where some combination of flame characteristics are optimized. As mentioned above, plural heating elements can be used, and these plural elements can be placed at generally different radial distances from the axis A.

[0125] After ignition and some time of combustion, the flame holder **102** is held at a much higher temperature because of the ongoing combustion. The higher temperature of the flame holder **102** is sufficient to maintain combustion of a lean fuel mixture. A stable flame can thus be maintained by the flame holder **102**. The flame is held primarily within the perforations **210**, although the flame may extend a short distance beyond either or both faces **212**, **214** of the flame holder **102**. The fuel stream **206** is able to continually feed the combustion, and the flame holder **102** is able to support a leaner flame than could be maintained in a conventional burner system.

[0126] The inventors have recognized that, although the flame holder **102** is able to support combustion with a very lean fuel mixture during steady-state operation, startup of combustion is problematic. The fuel mixture at any particular distance of the perforated flame holder **102** from the nozzle **218** is flammable only at elevated temperatures, and because the flame holder **102** may be at ambient temperature at startup, conventional ignition methods or devices are not generally effective for startup of combustion.

[0127] The applicants' apparatus and method are, however, also useful for steady-start operation, following the start-up phase. This is because heating of the applicants' apparatus or via the applicants' methods cannot only more quickly achieve steady-state operation, but also can widen the so-called "turndown ratio." The turndown ratio may be defined as the ratio of maximum heat release to minimum heat release, with maintenance of stable flames (see *The John Zink Hamworthy Combustion Handbook,* 2nd Ed., Volume 1, ¶10.7.1.3 and FIG. 17.15).

[0128] Loss of flame stability can result from too much or from too little fuel flow to a flame holder. Depending on the geometry of the flame holder and other factors such as the type of fuel, the flame will go out when there is not enough fuel to support the combustion (this may occur at the lower end of the range of heat that defines the turndown ratio); and when there is too much flow, the flame will move up away from the flame holder (which may correspond to the upper end of the range of heat that defines the turndown ratio). In general, a flame will move "upstream" as the fuel rate or flow rate decreases, and will move "downstream" as the fuel rate or flow rate increases.

[0129] As mentioned, too little fuel will hinder combustion. Aside from fuel, the other two main requirements of fire are oxidant and high-enough temperature. In a flame holder, the temperature of the fuel/air mixture must be sufficient to reach combustion if the flame is to be stable. If the flow is too great, then the temperature of the flame holder will be lowered by the relatively cool un-burned mixture, and eventually the flame will leave the flame holder. Once that happens, flame stability is greatly decreased. In general, a flame will move "upstream" as the fuel rate or flow rate decreases, and will move "downstream" as the fuel rate or flow rate increases.

[0130] The applicants electrically heat the flame holder at both ends of the range which determines the turndown ratio.

[0131] If, for example, the valve **610** informs the controller **514** that the fuel flow rate is too low to support a stable flame (or, when the controller shuts the valve to a certain point), then the controller may in response send electric current to the heating element **502**, which will have the effect of producing flame stability. As explained above, a leaner mixture can be burned when the flame holder is heated.

[0132] If, on the other hand, the sensor **234** detects a drop in flame holder temperature, perhaps due to too-rapid flow of unburned mixture, then the control unit **514** might electrically heat the flame holder so as to bring the combustion "upstream" and thereby prevent the flame from "lifting." Or, the controller might electrically heat the flame holder whenever it has instructed the valve **610** to open beyond a predetermined threshold. (The controller **514** may also detect fuel pressure and/or air flow and use them as factors in determining when to initiate flame-holder heating.)

[0133] The discussion above is equally applicable to a perforated flame holder and a non-perforated flame holder, or to a flame holder that includes a vortex generator **210** that is not a perforation.

[0134] FIG. **9** is a flow chart showing a method **900** for operating an electrically heated burner, such as the electrically heated burner **100** of FIG. **1**, according to an embodiment. Beginning at step **902**, start-up command data is received into a controller via a data interface. The controller processes the instruction and, in step **904**, enables a relay to output a drive voltage on at least one node of a power supply. Proceeding to step **906**, the output drive voltage is coupled to an electrically powered heater configured to cause a sensible temperature rise in a component of an industrial or commercial burner, the component being disposed so as to contact a fuel stream and/or a flame supported by the fuel stream.

[0135] In step **908**, the electrically powered heater causes a temperature rise in at least a portion of a burner. Optionally, the method **900** can include step **910** to sense the temperature rise in the portion(s) of the burner. The method **900** can the proceed to optional step **912** to enable an ignition source in the burner, and then to optional step **914** to enable a fuel valve to output fuel at a fuel nozzle.

[0136] Proceeding to step **916**, the electrically heated burner supports combustion adjacent to the portion(s) of the burner.

[0137] FIG. **10** is a flow chart showing a method **1000** for operating an electrically heated burner, such as the electrically heated burner **100** of FIG. **1**, according to another embodiment.

[0138] In step **916**, combustion is supported adjacent to at least a portion of an electrically heated industrial or commercial burner operatively coupled to an electrically powered heater. In step **1002**, current is output from a power supply to the electrically powered heater. The output current causes the electrically powered heater to dissipate energy, such as by electrical resistance or electrical inductance. The dissipated energy enters the portion(s) of the electrically heated burner.

[0139] Proceeding to step **1004**, a temperature of the burner portion(s) is sensed. Proceeding to step **1006**, the current output to the electrically powered heater is controlled to maintain the temperature. Additionally or alternatively, the controller can operate a timer and cause application of electrical current to the electrically powered heater according to a duty cycle set point.

[0140] Proceeding to step **1008**, burner temperature command data is received via a data interface. Responsive to the command data, an electronic controller, in step **1010**, changes a temperature set point for the burner portion(s). In step **1012**, the controller controls the current output from the power supply to the electrically powered heater to change the temperature of the burner portion to the new set point. Additionally or alternatively, the controller can change a heater duty cycle set point and control the current output according to the new duty cycle set point. The new duty cycle set point can change the temperature of the burner portion(s).

[0141] Above, and in the following claims, "substantially within" indicates that, at room temperature or some other start-up temperature, most (a majority of) heat generated by the electrically powered heater due to electric current flowing therethrough passes into the flame holder body, rather than passing directly into the environment (e.g., fuel/air mixture) while by-passing the flame holder body; or, conversely, that at most a minority of electrically-generated heat passes directly to the fuel and oxidant stream.

[0142] 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 burner, comprising:

a fuel and oxidant source configured to provide a fuel and oxidant stream that includes a range of fuel concentrations to support a combustion reaction;

a body disposed adjacent to the fuel and oxidant stream and configured to exchange heat energy with the fuel and oxidant stream; and

an electrically powered heater arranged to convey at least a portion of electrically generated heat to the body.

2. The burner of claim **1**, wherein the electrically powered heater is arranged to conduct a majority of electrically generated heat to the body.

3. The burner of claim **1**, wherein the body comprises a vortex generator.

4. The burner of claim **1**, wherein the body comprises a perforated flame holder body; and

wherein being disposed adjacent to the fuel and oxidant stream comprises being disposed to receive the fuel and oxidant stream into a plurality of perforations defined by the perforated flame holder body.

5. The burner of claim **1**, wherein the electrically powered heater includes an electrical resistance heating element.

6. The burner of claim **3**, wherein the vortex generator is configured to generate vortices aligned circumferentially around the fuel and oxidant stream.

7. The burner of claim **1**, wherein the body comprises at least one non-flammable log.

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

a thermostat operatively coupled to the electrically powered heater, the thermostat including a temperature sensor and an electronic controller operatively coupled to the temperature sensor;

wherein the thermostat is configured to cause the electrically powered heater to maintain the body at a selected temperature.

9. The burner of claim **8**, wherein the electronic controller is configured to cause the electrically powered heater to raise the temperature of the body to the selected temperature before causing a fuel valve to open to provide the fuel and oxidant stream; and

wherein the electronic controller is configured to cause the fuel valve to open to provide the fuel and oxidant stream after the temperature of the body reaches the selected temperature.

10. The burner of claim **8**, wherein the selected temperature is preselected to be equal to or greater than an autoignition temperature of the fuel.

11. The burner of claim **8**, wherein the thermostat is configured to increase a rate of heating by the electrically powered heater when a rate of fuel flow is reduced, and to decrease the rate of heating by the electrically powered heater when the rate of fuel flow is increased.

12. The burner of claim **1**, wherein the electrical heater includes at least a portion embedded in the body.

13. The burner of claim **12**, wherein the body defines one or more hollow passages formed within the body; and

wherein the electrical heater is carried within the one or more hollow passages.

14. The burner of claim **12**, wherein at least a portion of the body forms a conical surface; and

wherein the electrical heater is wrapped around the conical surface.

15. The burner of claim **1**, wherein the body defines one or more grooves formed in a surface of the body; and

wherein the electrical heater is disposed in the one or more grooves.

16. The burner of claim **1**, further comprising:

an electronic controller operatively coupled to the electrically powered heater, the electronic controller including a timer; and

a fuel flow rate sensor operatively coupled to the electronic controller;

wherein the electronic controller is configured to respond to the timer to cause the electrically powered heater to dissipate heat at a duty cycle inversely proportional to a rate of fuel flow sensed by the fuel flow rate sensor.

17. The burner of claim **1**, further comprising an igniter.

18. The burner of claim **17**, wherein the igniter is configured to be turned off after ignition.

19. The burner of claim **17**, wherein the electrically powered heater is configured to at least selectively remain powered during combustion.

20. The burner of claim **17**, wherein the igniter is separate and distinct from the electrically powered heater and the body.

21. A method of increasing a turndown ratio of combustion, comprising:

outputting fuel into a combustion volume;

admitting air into the combustion volume;

allowing the fuel to at least partially entrain the air in the combustion volume to form a fuel and air jet having a range of mixtures;

supporting a flame holder adjacent to the fuel and air jet in a position predetermined to promote vortex formation in the mixture;

igniting the fuel and air mixture to form a combustion reaction; and

electrically heating the flame holder to maintain stable ignition of the fuel and air mixture within the vortices promoted by the flame holder.

22. The method of combustion of claim **21**, wherein maintaining ignition includes at least intermittently transferring electrically-generated heat from the flame holder to the vortices.

23. The method of combustion of claim **21**, wherein at least a majority of the electrically-generated heat flows to the turbulent portion of the mixture via a body of the flame holder.

24. The method of combustion of claim **21**, further comprising starting the combustion reaction with an igniter.

25. The method of combustion of claim **21**, wherein supporting a flame holder includes supporting a hollow cylindrical refractory body peripheral to a fuel nozzle and an air source; and

wherein supporting a flame holder adjacent to the fuel and air jet in a position predetermined to promote vortex formation in the mixture includes supporting the hollow cylindrical refractory body to receive at least a portion of the fuel and air jet through the hollow portion of the cylinder and supporting a vortex-formation surface at an end of the flame holder perpendicular to a nominal direction of fuel and air flow.

26. The method of combustion of claim **25**, wherein the vortex-formation surface is configured to cause toroidal vortices to form such that hot combustion products are recycled from the combustion reaction to the fuel and air jet.

27. The method of combustion of claim **25**, wherein allowing the fuel to at least partially entrain the air in the combustion volume to form a fuel and air jet having a range of mixtures further comprises adjusting at least one of a fuel flow rate and an air flow rate.

28. The method of claim **21**, wherein electrically heating the flame holder includes passing an electric current through an electrically powered heater.

29. The method of claim **21**, wherein electrically heating the flame holder includes passing an electric current through the flame holder.

30. A control system for controlling dynamics of a flame, comprising:

a source of electric current;

an electrically heated flame holder immersed in the flame and coupled to the source, wherein the source induces electric current flow therethrough;

a temperature-responsive current controller coupled to the source and the electrically heated flame holder to adjust the electric current flow through the electrically heated flame holder toward a predetermined temperature of the electrically heated flame holder.

31. The control system for controlling dynamics of a flame of claim **30**, wherein the temperature-responsive current controller further comprises a temperature sensor.

32. The control system for controlling dynamics of a flame of claim **30**, wherein the temperature-responsive current controller further constitutes a thermostat.

33. The control system for controlling dynamics of a flame of claim **30**, wherein the temperature-responsive current controller further comprises a processor.

34. The control system for controlling dynamics of a flame of claim **30**, wherein the flame holder comprises at least one vortex-forming structure.

35. The control system for controlling dynamics of a flame of claim **34**, wherein the vortex-forming structure includes a projection into a moving portion of the flame.

36. The control system for controlling dynamics of a flame of claim **35**, wherein the projection further comprises a ramp.

37. The control system for controlling dynamics of a flame of claim **30**, wherein the control system further comprises an electrically heated surface igniter used only to start the flame.

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