BOX HEATER INCLUDING A PERFORATED FLAME HOLDER

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Abstract

An enclosed heater includes a plurality of tubes (or a continuous serpentine tube) and a perforated flame holder within an interior volume. The plurality of tubes carries a working fluid. The perforated flame holder supports a combustion reaction of fuel and oxidant within the perforated flame holder and radiates heat to the tubes to heat the working fluid.
FIG. 4

1. PROVIDE START-UP ENERGY AT PERFORATED FLAME HOLDER

2. IS \( T \geq T_s \) ?

   - NO
   - YES

3. PROVIDE FUEL AND OXIDANT MIXTURE TO PERFORATED FLAME HOLDER

4. HOLD COMBUSTION REACTION WITH PERFORATED FLAME HOLDER

5. OUTPUT HEAT FROM PERFORATED FLAME HOLDER

6. SENSE COMBUSTION

7. IS COMBUSTION STABLE?

   - NO
   - YES

8. CHANGE COMBUSTION PARAMETERS?

    - NO
    - YES

9. CHANGE COMBUSTION PARAMETERS

10. EXECUTE ERROR PROCEDURE
FIG. 7

700

706

708

712

726

724a

102a

102b

724b

726
FIG. 8

800

OUTPUT FUEL AND OXIDANT

802

SUPPORT COMBUSTION REACTION WITHIN PERFORATED FLAME HOLDER

804

PASS WORKING FLUID THROUGH TUBES

806

TRANSFER HEAT FROM PERFORATED FLAME HOLDER TO WORKING FLUID

808
BOX HEATER INCLUDING A PERFORATED FLAME HOLDER

CROSS-REFERENCE TO RELATED APPLICATIONS


SUMMARY

[0002] According to an embodiment, an enclosed heater includes a plurality of walls forming an enclosure. The enclosure defines an interior volume. A plurality of tubes are (or a continuous serpentine tube is) positioned along the walls within the interior volume. A working fluid flows through the tubes. A perforated flame holder is also positioned within the interior volume. A fuel and oxidant source outputs fuel and oxidant onto the perforated flame holder. The perforated flame holder supports a combustion reaction of the fuel and oxidant within the perforated flame holder. The perforated flame holder absorbs heat from the combustion reaction and radiates heat to the tubes, thereby transferring heat from the combustion reaction to the working fluid within the tubes. According to an embodiment, the enclosed heater can include a box heater, a cabin heater, or a vertical cylinder heater.

[0003] According to an embodiment, a method includes outputting fuel and oxidant onto a first perforated flame holder positioned within an interior of an enclosed heater. The enclosed heater includes one or more walls defining the interior. The method further includes supporting a majority of a combustion reaction of the fuel and oxidant within the first perforated flame holder, passing one or more working fluids through a plurality of tubes lining one or more walls within the interior, and transferring heat from the first perforated flame holder to the one or more working fluids.

[0004] According to an embodiment, a box heater including an enclosure and a tube including a first segment positioned external to the enclosure, a second segment positioned within the enclosure, and a third segment positioned external to the enclosure, the second segment connecting the first segment to the third segment. The tube is configured to pass a working fluid from the first segment, through the second segment, to the third segment. The box heater further includes a fuel and oxidant source positioned within the enclosure and configured to output fuel and oxidant, and a perforated flame holder positioned to receive the fuel and oxidant, to sustain a combustion reaction of the fuel and oxidant within the perforated flame holder, and to transfer heat from the combustion reaction to the working fluid as the working fluid passes through the second segment positioned within the enclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] FIG. 1 is a diagram of an enclosed heater, according to one embodiment.
[0006] FIG. 2 is a simplified perspective view of a burner system including a perforated flame holder, according to an embodiment.
[0007] FIG. 3 is a side sectional diagram of a portion of the perforated flame holder of FIGS. 1 and 2, according to an embodiment.
[0008] 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.
[0009] FIG. 5A is a perspective view of a cabin heater, according to an embodiment.
[0010] FIG. 5B is a top view of the cabin heater of FIG. 5A, according to an embodiment.
[0011] FIG. 5C is a cross-section of the cabin heater of FIG. 5A, according to an embodiment.
[0012] FIG. 5D is a side view of an interior of the cabin heater of FIG. 5A, according to an embodiment.
[0013] FIG. 6 is a side view of an interior of a box heater including multiple perforated flame holders, according to an embodiment.
[0014] FIG. 7 is a side view of the interior of a box heater including multiple perforated flame holders, according to an embodiment.
[0015] FIG. 8 is a flow diagram of a process for operating an enclosed heater including a perforated flame holder, according to an embodiment.

DETAILED DESCRIPTION

[0016] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. Other embodiments may be used and/or other changes may be made without departing from the spirit or scope of the disclosure.

[0017] FIG. 1 is a block diagram of an enclosed heater burner system 100, according to one embodiment. The enclosed heater burner system 100 includes a wall 110 enclosing an enclosed heater interior volume 112. A perforated flame holder 102 is positioned within the enclosed heater interior 112. A fuel and oxidant source 104 is positioned to output fuel and oxidant onto the perforated flame holder 102. Tubes 106 carry a working fluid 108.

[0018] According to an embodiment, the fuel and oxidant source 104 outputs fuel and oxidant onto the perforated flame holder 102. The perforated flame holder 102 supports a combustion reaction of the fuel and oxidant within the perforated flame holder 102. The perforated flame holder 102 absorbs heat from the combustion reaction within the perforated flame holder 102. The perforated flame holder 102 radiates heat to the tubes 106 lining the wall 110 of the enclosed heater burner system 100. The working fluid 108 is passed through the tubes 106. Heat is transferred from the tubes 106 to the working fluid 108. In this way, heat is transferred from the perforated flame holder 102 to the working fluid 108. The working fluid 108 is passed via the tubes 106 to the exterior of the enclosed heater burner system 100 and is used to provide heat to an external apparatus. According to an embodiment, the working fluid 108 transfers heat to crude oil flowing through a crude oil pipeline. In another embodiment the crude oil itself can be used as the working fluid 108. Even and predictable radiative heating provided by the perforated flame holder 102 can substantially prevent coking and other infirmities of conventional flame heaters. This may be used to simplify the design to allow even an inconsistent working fluid, such as crude oil with an asphaltene component, to avoid coking in the tubes 106. Moreover, whether or not a conventional 2-step working fluid-to-heat sink transfer is used, the perforated flame holder 102 provides very low output of oxides of nitrogen (NOx) and carbon monoxide (CO).
According to an embodiment, the enclosed heater defines an interior volume that is between 5 and 30 feet in height, length, and width.

According to an embodiment, the enclosed heater burner system 100 is a box heater such as a cabin heater including a peaked roof. According to an alternative embodiment, the enclosed heater burner system 100 incorporates a vertical cylindrical heater. Those of skill in the art will recognize, in light of the present disclosure, that a perforated flame holder 102 can be utilized in a large variety of types of enclosed heaters in accordance with principles of the present disclosure. All types of enclosed heaters fall within the scope of the present disclosure.

FIG. 2 is a simplified diagram of a burner system 200 including a perforated flame holder 102 configured to hold a combustion reaction, according to an embodiment. As used herein, the terms perforated flame holder, perforated reaction holder, porous flame holder, porous reaction holder, duplex, and duplex tile shall be considered synonymous unless further definition is provided.

Experiments performed by the inventors have shown that perforated flame holders 102 described herein can support very clean combustion. Specifically, in experimental use of systems 200 ranging from pilot scale to full scale, output of oxides of nitrogen (NOx) was measured to range from low single digit parts per million (ppm) down to undetectable (less than 1 ppm) concentration of NOx at the stack. These remarkable results were measured at 3% (dry) oxygen (O2) 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 extremities that may be required for conventional burners to even approach such clean combustion.

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.

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 202 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 201 are configured to collectively hold a combustion reaction 302 supported by the fuel and oxidant mixture 206.

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 (H2), and methane (CH4). In another application the fuel can include natural gas (mostly CH4) or propane (C3H8). 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.

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 201 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.

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.
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 D₂. 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.

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 304. 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.

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 ½ and ¾ 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.

The perforated flame holder body 208 may 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.

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.

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.

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).

[0035] The perforated flame 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.

[0036] 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.

[0037] 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 D2 between the fuel nozzle 218 and the perforated flame holder. 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 oxidant and the oxidant mixture 206 as the fuel jet and oxidant travel along a path to the perforated flame holder through the dilution distance D2, between the fuel nozzle 218 and the perforated flame holder. Additionally or alternatively, the fuel nozzle 218 can be configured to entrain flue gas as the fuel jet travels through the dilution distance D2 between the fuel nozzle 218 and the face 212 of the perforated flame holder 102.

[0038] 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 D2 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 D2 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.

[0039] 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.

[0040] 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.

[0041] 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.

[0042] 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.

[0043] 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 cementitious, and/or ceramic refractory material. In another embodiment, the plurality of adjacent perforated flame holder sections can be joined with a fiber reinforced refractory cement.

[0044] 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.

[0045] 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).

[0046] 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 than a standard reference quenching distance.

[0047] 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.

[0048] 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 the 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.

[0049] 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.

[0050] 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.

[0051] 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.

[0052] 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.

[0053] 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.

[0054] 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.

[0055] 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.

[0056] The inventors contemplate various explanations for why burner systems including the perforated flame holder 102 provide such clean combustion.

[0057] 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 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.).

[0058] The perforated flame holder 102 may be formed from 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% O2, i.e. an equivalence ratio of ~0.87. Use of even leaner mixtures is possible, but may result in elevated levels of O2. 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.

[0059] 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.

[0060] 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.

[0061] According to a simplified description, the method 400 begins with step 402, wherein the perforated flame holder is preheated to a start-up temperature, Tp. 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.

[0062] 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, Tp. 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.

[0063] Step 404 may be broken down into several discrete steps, at least some of which may occur simultaneously.

[0064] 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.

[0065] Proceeding to step 412, the combustion reaction is held by the perforated flame holder.

[0066] 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.

[0067] 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, a 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.

[0068] 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.

[0069] 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.

[0070] 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.

[0071] 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) adjac-
cent 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.

[0072] 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 ≥ Tₐ₁).

[0073] 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.

[0074] 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.

[0075] 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 Halsstahammar, 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.

[0076] 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.

[0077] 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).

[0078] 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.

[0079] FIG. 5A is a perspective view of a cabin heater 500, according to an embodiment. The cabin heater 500 includes sidewalls 510a-510d, though only sidewalls 510a, 510b are visible in FIG. 5A. The cabin heater 500 further includes sloped roof portions 514a-514d (only 514a and 514b are visible), and a flat roof peak portion 516. A flue vent 518 is positioned on roof peak 516. The flue vent 518 vents flue gases from an interior of the cabin heater 500 to an exterior of the cabin heater 500. A first tube 506a passes through the sidewalk 510 into the interior of the cabin heater 500. A second tube 506b also passes from the exterior of the cabin heater 500 to the interior of the cabin heater 500. A working fluid 108 passes into the tube 506a via an input 520a. A working fluid 108 passes into the tube 506b via a secondary input 520b.

[0080] FIG. 5B is a top view of the cabin heater 500, according to one embodiment. All four of the sloped roof portions 514a-514d and the roof peak 516 are visible in the top view of FIG. 5B. Additionally, output portions 522a, 522b of the tubes 506a, 506b are visible. In particular, the working fluid 108 is passed from the tube 506a via an output 522a. The working fluid 108 is passed from the tube 506b via the output 522b.
FIG. 5C is a cross-section of the cabin heater 500 taken along cross-section lines 5C from FIG. 5B, according to an embodiment. FIG. 5C illustrates that the tube 506a lines the sidewall 510a and the sloped roof portion 514a within the interior volume 512 of the cabin heater 500. Multiple portions of the tube 506a are visible in FIG. 5C because the tube 506a runs in a serpentine manner along the sidewall 510a and the sloped roof portion 514a, as is further apparent with reference to FIG. 5D. The tube 506b lines the sidewall 510b and the sloped roof portion 514b. Multiple portions of the tube 506b are visible in FIG. 5C because the tube 506b runs in a serpentine manner along the sidewall 510b and the sloped roof portion 514b as is further apparent with reference to FIG. 5D. A perforated flame holder 102 is positioned in the interior volume 512 between the tubes 506a and 506b and above a fuel and oxidant source 524.

The fuel and oxidant source 524 outputs fuel and oxidant 526 onto the perforated flame holder 102. The perforated flame holder 102 supports a combustion reaction of the fuel and oxidant 526 within the perforated flame holder 102. The perforated flame holder 102 absorbs heat from the combustion reaction of the fuel and oxidant 526. The perforated flame holder 102 radiates heat to the tubes 506a, 506b. As the working fluid 508 passes through the multiple serpentine portions of the tubes 506a, 506b, heat from the perforated flame holder 102 is transferred to the working fluid 508 in the tubes 506a, 506b. When the working fluid 508 passes from the outputs 522a, 522b the working fluid has absorbed a large amount of heat. In this way, the working fluid 508 transfers heat from the combustion reaction of the fuel and oxidant 526 to the exterior of the cabin heater 500.

According to an embodiment, the working fluid 508 is crude oil. Alternatively, the working fluid 508 can include natural gas, other hydrocarbon products, water, glycol water, air, or regeneration gas. Those skilled in the art will recognize, in light of the present disclosure, that the working fluid 508 can include many other fluids.

According to an embodiment, the fuel and oxidant source 524 protrudes through the floor of the cabin heater 500. Only the portion of the fuel and oxidant source 524 that is positioned within the cabin heater 500 is shown in FIG. 5C and FIG. 5D.

FIG. 5D is a side view of the interior volume 512 of the cabin heater 500 viewed from the cross-section lines 5D of FIG. 5B. The perforated flame holder 102 and the fuel and oxidant source 524 are visible in the foreground. The tube 506a is visible in the background. In particular, the serpentine layout of the tube 506a is more readily apparent in the side view of FIG. 5D.

Although a cabin heater 500 has been shown with respect to FIGS. 5A-5D, those of skill in the art will recognize, in light of the present disclosure, that many types of box heaters can implement a perforated flame holder 102. For example, a box heater can have a cylindrical outer wall with one or more tubes lining the inside of the wall and a perforated flame holder 102 positioned in an interior volume of the box heater.

According to an embodiment, multiple tubes 506 can be positioned on each wall of the cabin heater 500. The multiple tubes 506 can be wound about each other. Those skilled in the art will recognize, in light of the present disclosure, that many other configurations for tubes 506 within the cabin heater 500 are possible. All such other configurations fall within the scope of the present disclosure.

FIG. 6 is a side view of an interior volume 612 of a box heater 600, according to an embodiment. Multiple perforated flame holders 102a-102c are positioned in the interior volume 612 of the box heater 600. A tube 606 carrying a working fluid 608 is positioned in a serpentine manner along the wall of the box heater 600. Each perforated flame holder 102a-102c is positioned above a respective fuel and oxidant source 624a-624c. The perforated flame holders 102a-102c support a combustion reaction of the fuel and oxidant output from the fuel and oxidant sources 624a-624c. The perforated flame holders 102a-102c absorb heat from the combustion reactions and radiate heat to the tube 606. A working fluid 608 within the tube 606 receives heat from the tube 606. Thus, as the working fluid 608 progresses through the tube 606 it is heated by the heat radiated from the perforated flame holders 102a-102c. The working fluid 608 is then passed from the interior volume 612 of the box heater 600 to an exterior of the box heater 600.

According to an embodiment, the box heater 600 includes one or more partitions (not shown) positioned within the interior volume 612 between the first and second perforated flame holders 102a, 102b, and/or between the second and third perforated flame holders 102b, 102c. According to an embodiment, the one or more partitions can separate the first perforated flame holder 102a from the second perforated flame holder 102b along a line of sight between the first and second perforated flame holders 102a, 102b. According to an embodiment, the partition is configured to receive heat from the first and second perforated flame holders 102a, 102b, reach an elevated temperature, and radiate heat energy to the tube 606. The partition can be a partial partition that does not define two completely separated portions of the interior volume 612. Alternatively, the partition can be a full partition that defines two completely separated portions of the interior volume 612.

FIG. 7 is a side view of an interior volume 712 of a box heater 700, according to one embodiment. Perforated flame holders 102a, 102b are positioned laterally from respective fuel and oxidant sources 724a, 724b. The fuel and oxidant sources 724a, 724b output fuel and oxidant onto the perforated flame holders 102a, 102b. The perforated flame holders 102a, 102b support a combustion reaction of the fuel and oxidant within the perforated flame holders 102a, 102b. A tube 706 is positioned along a wall of the box heater 700 in a serpentine fashion. A working fluid 708 passes through the tube 706. The perforated flame holders 102a, 102b radiate heat to the tube 706, thereby heating the working fluid 708 within the tube 706. The working fluid 708 therefore absorbs heat as it passes through the tube 706 within the interior 712 of the heater 700.

According to an embodiment, the box heater 700 includes a partition (not shown) positioned within the interior volume between the first and second perforated flame holders 102a, 102b. According to an embodiment, the partition separates the first perforated flame holder 102a from the second perforated flame holder 102b along a line of sight between the first and second perforated flame holders 102a, 102b. According to an embodiment, the partition is configured to receive heat from the first and second flame holders 102a, 102b, reach an elevated temperature, and radiate heat energy to the tube 706. The partition can be a partial partition that does not define two completely separated portions of the interior vol-
Alternatively, the partition can be a full partition that defines two completely separated portions of the interior volume.

Fig. 8 is a flow diagram of a process for operating a box heater, according to an embodiment. At 802, fuel and oxidant are output from a fuel and oxidant source onto a perforated flame holder. At 804, the perforated flame holder supports a combustion reaction of the fuel and oxidant within the perforated flame holder. At 806, working fluid is passed through one or more tubes within an interior of the box heater. At 808, heat is transferred from the perforated flame holder to the working fluid within the one or more tubes.

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

1. An enclosed heater, comprising:
   - one or more walls defining an interior volume;
   - a plurality of tubes positioned within the interior volume along one or more of the walls and configured to carry a working fluid;
   - a first fuel and oxidant source configured to output fuel and oxidant; and
   - a first perforated flame holder positioned to receive the fuel and oxidant, the first perforated flame holder being configured to support a majority of a combustion reaction of the fuel and oxidant within the first perforated flame holder and to transfer heat to the tubes.

2. The enclosed heater of claim 1, wherein the first perforated flame holder includes:
   - an input face proximal to the first fuel and oxidant source;
   - an output face opposite the flame holder; and
   - a plurality of perforations extending from the input face to the output face and configured to receive the mixture of fuel and oxidant and to support the majority of the combustion reaction within the perforations.

3. The enclosed heater of claim 2, wherein the first perforated flame holder is positioned laterally from the first fuel and oxidant source.

4. The enclosed heater of claim 2, wherein the first perforated flame holder is positioned vertically from the first fuel and oxidant source.

5. The enclosed heater of claim 1, comprising:
   - a second fuel and oxidant source configured to output fuel and oxidant; and
   - a second perforated flame holder positioned to receive the fuel and oxidant from the second fuel and oxidant source, the second perforated flame holder configured to support a majority of a combustion reaction of the fuel and oxidant from the second fuel and oxidant source within the second perforated flame holder and to transfer heat to the tubes.

6. The enclosed heater of claim 5, wherein:
   - the first perforated flame holder is positioned laterally from the first fuel and oxidant source;
   - the second perforated flame holder is positioned laterally from the second fuel and oxidant source; and
   - the first and second perforated flame holders are positioned to transfer heat to each other.

7. The enclosed heater of claim 5, further comprising:
   - a partial partition separating the first perforated flame holder from the second perforated flame holder along a line of sight between the first and second perforated flame holders; wherein the partial partition is configured to receive heat from the first and second flame holders, reach an elevated temperature, and radiate heat energy to the tubes.

8. The enclosed heater of claim 5, wherein:
   - the first perforated flame holder is positioned above the first fuel and oxidant source; and
   - the second perforated flame holder is positioned above the second fuel and oxidant source.

9. The enclosed heater of claim 1, wherein the working fluid is crude oil.

10. The enclosed heater of claim 1, wherein the enclosed heater is a crude oil pipeline heater.

11. The enclosed heater of claim 1, wherein the plurality of tubes are joined together as a single tube.

12. The enclosed heater of claim 11, wherein the single tube is positioned along the one or more walls in a serpentine fashion.

13. The enclosed heater of claim 1, including four walls and a roof.

14. The enclosed heater of claim 13, including a peaked roof.

15. The enclosed heater of claim 13, wherein a portion of one or more of the plurality of tubes is positioned along a ceiling of the enclosed heater.

16. The enclosed heater of claim 13, including a flue vent in the roof configured to pass flue gas from the combustion reaction from the interior volume to an exterior of the enclosed heater.

17. The enclosed heater of claim 13, wherein the first fuel and oxidant source includes one or more fuel nozzles configured to output the fuel and oxidant onto the first perforated flame holder.

18. The enclosed heater of claim 13, wherein the first fuel and oxidant source includes a premix chamber in which the fuel and oxidant are mixed prior to being output to the first perforated flame holder.

19. The enclosed heater of claim 1 wherein the enclosed heater is a cabin heater.

20. The enclosed heater of claim 1 wherein the enclosed heater is a cylindrical enclosed heater.

21. A method comprising:
   - outputting fuel and oxidant onto a first perforated flame holder positioned within an interior of an enclosed heater, the enclosed heater including one or more walls defining the interior;
   - supporting a majority of a combustion reaction of the fuel and oxidant within the first perforated flame holder;
   - passing one or more working fluids through a plurality of tubes lining the one or more walls within the interior; and
   - transferring heat from the first perforated flame holder to the working fluid.

22. The method of claim 21, wherein the perforated flame holder includes an input face, an output face, and a plurality of perforations extending between the input and output faces.

23. The method of claim 22, wherein the perforated flame holder supports a majority of a combustion reaction of the fuel and oxidant within the perforations.
24. The method of claim 21, comprising:
outputting fuel and oxidant onto a second perforated flame
holder positioned within the interior of the enclosed heater;
supporting a second combustion reaction within the second
perforated flame holder; and
transferring heat from the second perforated flame holder
to the working fluid.
25. The method of claim 21 wherein the working fluid includes a fossil fuel.
26. The method of claim 21 wherein the working fluid includes water.
27. The method of claim 21 wherein the enclosed heater is a box heater.
28. The method of claim 21 wherein the enclosed heater is a cylindrical enclosed heater.
29. The method of claim 21 wherein the enclosed heater is a cabin heater.
30. A box heater, comprising:
an enclosure;
a tube including:
a first segment positioned external to the enclosure;
a second segment positioned within the enclosure; and
a third segment positioned external to the enclosure, the second segment connecting the first segment to the third segment, the tube being configured to pass a working fluid from the first segment, through the second segment, to the third segment;
a fuel and oxidant source positioned within the enclosure and configured to output fuel and oxidant; and
a perforated flame holder positioned to receive the fuel and oxidant, to sustain a combustion reaction of the fuel and oxidant within the perforated flame holder, and to transfer heat from the combustion reaction to the working fluid as the working fluid passes through the second segment positioned within the enclosure.
31. The box heater of claim 30 wherein the enclosure includes one or more walls, the second segment being positioned adjacent to one or more of the one or more walls.
32. The box heater of claim 30, wherein the second segment winds in a serpentine fashion within the enclosure.
33. The box heater of claim 30 wherein the enclosure includes a vent configured to pass flue gas from within the enclosure to an exterior of the enclosure.