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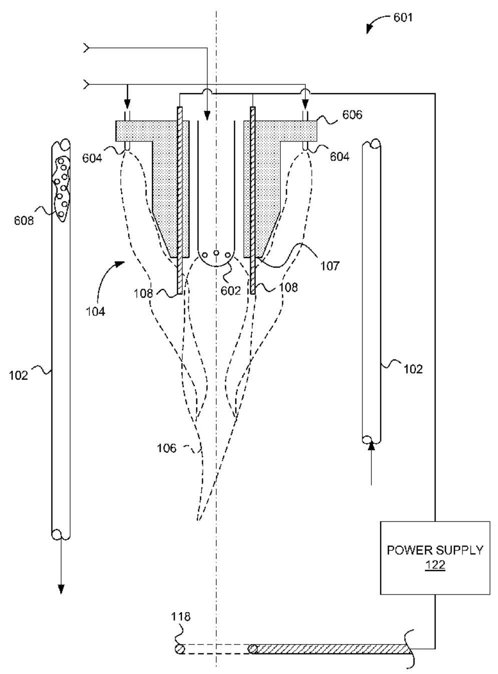
(54) **Title**: ELECTRICALLY STABILIZED DOWN-FIRED FLAME REACTOR

FIG. 6



(57) Abstract: A down-fired flame burner including a flame charger and one or more field electrodes configured to control flame shape and/or heat transfer to a chemical reactor is presented. Also described is a method for providing process heat includes projecting a down-fired flame in a heating volume, electrically charging the flame to carry a majority charge, and applying an electric field proximate the down-fired flame to control flame shape, heat transfer from the flame, or flame shape and heat transfer from the flame, and applying heat from the flame to a chemical reactor.

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ELECTRICALLY STABILIZED DOWN-FIRED FLAME REACTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority benefit from U.S. Provisional Patent Application No. 61/660,684, entitled "ELECTRICALLY STABILIZED DOWN-FIRED FLAME REACTOR", filed June 15, 2012; which, to the extent not inconsistent with the disclosure herein, is incorporated by reference.

BACKGROUND

Steam-methane reforming is a process whereby methane (CH_4) is converted to hydrogen (H_2) by the addition of steam (H_2O) and heat over a catalyst. Although the chemistry for CH_4 is illustrated, other light hydrocarbons can be used as well. This process is usually accomplished in two phases. The first reaction occurs in a primary reformer where a flame is used to supply the necessary heat to convert methane to carbon monoxide and hydrogen via reaction 1:

1) $CH_4 + H_2O \rightarrow CO + 3\ H_2$.

The second reaction is slightly exothermic and occurs in shift reactors outside the primary reformer where carbon monoxide is further converted carbon dioxide to liberate additional hydrogen using the water-gas shift reaction 2:

2) $CO + H_2O \rightarrow CO_2 + H_2$.

Thus, the overall reaction is shown in reaction 3:

3) $CH_4 + 2\ H_2O \rightarrow CO_2 + 4\ H_2$.

The primary reformer portion of the reaction, where reaction 1 occurs, typically uses burners to drive the endothermic reaction. Reaction 1 typically occurs in catalyst-filled reaction tubes heated externally by the burners.

Two kinds of primary reformers are in use. A side-fired reactor uses a plurality of burners fired against a refractory wall. Each burner is configured to disburse its heat in substantial radial-symmetry along the plane of the wall. Two mutually parallel walls are so configured and enclose a bank of vertical catalyst-containing tubes through which the steam and methane are fed. The second kind of primary reformer is a down-fired reactor. A down-fired reactor has columns of catalyst tubes interleaved by vertically down-fired burners. In this design, alternating columns of tubes and burners allow for a more modular design that can be expanded to very large sizes. For this reason, the down-fired reactor may be preferred in modern installations.

Down-fired combustion suffers from several infirmities. The first is that the fired direction is contrary to the direction of natural buoyancy. Owing to particulars of the process, the fuel pressure may be relatively low and the fuel may include impurities from a pressure-swing adsorption system often used later in the process to purify the end product. Thus, the flames are fired against the buoyant direction with low momentum. If the combustion process is not finished before the fuel and air momentum are substantially exhausted, then the flame will bend and ultimately reverse direction. Inasmuch as the catalyst tubes are in close proximity to the burners, such bending leads to flame impingement on the catalyst tube. If the flame impinges on the catalyst tube, it will generate create a carbonaceous deposit on the inside tube furnace known as coke. The effect of coke deposition is to insulate the tube from the process fluid. Since the process fluid cools the tube wall, coke deposits act to insulate the tube wall, and the tube may develop hot spots as localized overheating on the fired side of the tube.

In an effort to counter the normal buoyant force with greater momentum and to reduce the flame length and increase the speed of fuel burning, sometimes a high-pressure line of refinery gas is added to supplement the main combustion of low-pressure gas. However, this adds significant expense in that an additional and independent supply of fuel gas must be plumbed, controlled, and maintained. Moreover, even with a high-pressure fuel line, flame impingement can still be a problem. Coking can be removed from the inside of a tube using special methods referred to a "de-coking." However, the de-coking cycle can last days, during which the unit cannot produce hydrogen product.

What is needed is an effective method of flame control that does not exclusively rely on fuel momentum or require the complexity of adding high-pressure fuel gas.

SUMMARY

According to an embodiment, an electrically stabilized down-fired flame reactor includes a plurality of catalyst-packed tubes extending vertically in a heating volume, one or more downward-fired burners configured to project one or more flames downward to heat the plurality of catalyst-packed tubes, one or more flame charge electrodes respectively associated with each downward-fired burner and configured to cause each of the flames to carry one or more majority charge species, and one or more field electrodes operatively coupled to each tube and configured to electrically interact with the majority charge species in the one or more flames to control heat transfer from the one or more flames to the tubes. The field electrode(s) may include one or more shield electrodes carrying a voltage to repel the flame from contact with the catalyst tubes. The field electrode(s) can additionally or alternatively include one or more attraction

electrodes configured to attract the flame downward in opposition to flame buoyancy.

According to another embodiment, a method for providing process heat includes projecting a down-fired flame in a heating volume, electrically charging the flame to carry a majority charge, and applying an electric field proximate the down-fired flame to control flame shape, heat transfer from the flame, or flame shape and heat transfer from the flame. Heat from the flame can be applied to a chemical reactor such as a vertical tube catalyst-packed reactor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing an electrically stabilized down-fired flame reactor, according to an embodiment.

FIG. 2 is a block diagram showing an electrically stabilized down-fired flame reactor, according to another embodiment.

FIG. 3 is a block diagram showing an electrically stabilized down-fired flame reactor, according to another embodiment.

FIG. 4 is a block diagram showing an electrically stabilized down-fired flame reactor, according to another embodiment.

FIG. 5 is a flowchart showing a method for providing process heat with an electrically stabilized down-fired flame, according to an embodiment.

FIG. 6 is a diagram showing an electrically stabilized down-fired flame reactor, according to another embodiment.

FIG. 7 is a perspective view of an electrically stabilized down-fired burner, according to another embodiment.

FIG. 8 is a perspective view of multiple electrically stabilized down-fired flame reactors, according to another embodiment.

DETAILED DESCRIPTION

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.

FIG. 1 is a block diagram showing an electrically stabilized down-fired flame reactor 101, according to an embodiment. For example, the down-fired reactor 101 may include a steam methane reformer.

In an embodiment, the electrically stabilized down-fired flame reactor 101 includes a plurality of catalyst-packed tubes 102 extending vertically in a heating volume 103. One or more downward-fired burners 104 receive fuel from a fuel source 105 and emit one or more fuel jets downwardly, in a direction substantially in opposition to flame buoyancy. A flame holder 107 anchors a flame 106 supported by the fuel. Each downward-fired burner 104 is configured to project a flame 106 downward to heat the catalyst-packed tubes 102. According to an embodiment, one or more flame charge electrodes 108 are respectively associated with each downward-fired burner 104 and are configured to cause each of the flames 106 to carry a majority charge species 112. The majority charge carried by the flame 106 can be expressed as a voltage carried by the flame 106. In some embodiments, the flame charge electrode 108 can act as a depletion electrode configured to remove a portion of charged particles 110 opposite in polarity to the majority charge species 112 to leave the majority charge species 112. For example, when the majority charge species 112 is positive polarity, the flame charge electrode 108 carries a positive voltage and produces the positive polarity by removing electrons 110 from the flame 106. In embodiments where the flame is charged negatively (i.e., where the flame 106 carries negative majority charge species 112), the flame charge electrode 108 carries a negative voltage and outputs electrons to the flame 106. It is believed that relatively massive and easily charged species such as H_30^+ and OH^- may respectively be responsible for carrying positive and negative charges in the flame.

One or more field electrodes 114 are disposed to carry a voltage that interacts with the majority charge (which may be expressed as voltage) carried by the flame 106. The interaction of the voltage carried by the field electrodes 114 with the majority charge carried by the flame 106 causes the flame 106 to respond by adopting a shape corresponding to instantaneous electrostatic attraction or repulsion of the majority charge species by the voltage carried by the field electrodes 114.

The electrical interaction of the field electrode 114 voltage with the majority charge species 112 in the flames 106 can be used to control heat transfer from the flames 106 to the catalyst-packed tubes 102. According to embodiments, one or more field electrodes 114 include one or more shield (repulsion) electrode(s) 116 or one or more attraction electrode(s) 118. According to embodiments, one or more field electrodes 114 include one or more shield (repulsion) electrode(s) 116 and one or more attraction electrode(s) 118.

The term “shield electrode” 116 refers to an electrode disposed between the catalyst-packed tube 102 and a flame 106 that is configured to be at least transiently held at a voltage having a same polarity as the majority charge species 112 in the flame 106. The same-polarity voltage carried by a shield electrode 116 causes the flame 106 to be repelled from the shield electrode 116. It is believed that the same-polarity voltage carried by a shield electrode 116 repels the majority charge species and, by a momentum cascade, neutral particles carried in the flame 106. The electrical repulsion reduces direct impingement of the flame 106 on a catalyst-packed tube 102 with which the shield electrode is associated. Electrical repulsion of the flame 106 reduces or eliminates coking and hot spots on the catalyst-packed tubes 102 and may allow an extended maintenance schedule.

FIG. 2 is a diagram of an electrically stabilized down-fired flame reactor, according to another embodiment 201. **FIG. 3** is a diagram of an electrically stabilized down-fired flame reactor, according to another embodiment 301. As indicated in the embodiment 201 compared to the method 301, relative location(s) of shield electrode(s) 116 can be varied.

Alternatively or additionally, the field electrodes 114 may include one or more attraction electrodes 118. The term “attraction electrode” 118 refers to an electrode that is positioned below and distal from the flame holder 107 that is configured be at least transiently held at a voltage having a polarity opposite to the polarity of the majority charge species 112 carried by the flame 106.

Referring again to **FIG. 1**, in one embodiment, the attraction electrode(s) 118 is disposed between a catalyst packed tube tube 102 and a flame 106 at a relatively distal location along the flame 106 (farther below than nearer to the flame holder 107). In an embodiment, the distal location is at least about 0.62 times a maximum flame extension below the flame holder 107 or about 0.62 times the distance from the flame holder 107 to a U-bend at a lower end of the catalyst packed tubes. As described above, the attraction electrode(s) 118 are at least transiently held at a voltage having an opposite polarity from the majority charge species 112 in the flame 106. In some applications, an attraction electrode 118 can receive heat from the flame 106 and radiate the heat to its associated catalyst packed tube. The attraction electrodes 118 can optionally be thermally coupled to a catalyst packed tube 102 with which the electrode is associated by a thermal coupling 120. The thermal coupling 120 can be configured as an electrical insulator or high impedance electrical conductor.

FIGS. 2 and 4 illustrate embodiments 201, 401 where the attraction electrode(s) 118 are in different locations. As indicated in the embodiment 201, the relative location(s) of attraction electrode(s) 118 may be varied. For example, the attraction electrode(s) 118 can be positioned to attract the flame 106 toward a distal location not immediately adjacent to a catalyst tube 102.

The catalyst-packed tubes 102 can be arranged in flow-coupled pairs via a tube fitting or bend 204 at lower ends of each flow-coupled pair. Each flow-coupled pair is configured to receive reactants through an input end and output reaction products through an output end near a ceiling 126 of the heating volume 103. According to the embodiments 201, 401, the attraction electrode(s) 118 can be arranged to attract the majority charge 112b and thereby the flame 106 to a location between catalyst-packed tubes 102. Optionally, the attraction electrode(s) 118 can be aligned to draw a buoyancy-dominated flame downward between catalyst-filed tube reactor such that the visible flame 106 substantially doesn't touch the catalyst-packed tubes 102 during operation.

Referring to **FIGS. 1, 2, and 4**, the voltage carried by the attraction electrodes 118 is selected to increase heat transfer to the catalyst-packed tubes 102 at attraction electrode 118 distal locations along a down-fired flame 106 compared to systems that do not have attraction electrodes 118. For example, the attraction electrodes 118 can be energized to draw the flame 106 down toward a bottom end of the catalyst-packed tubes 102. In an embodiment, flame contact with an attraction electrode 118 or attraction electrode segment is controlled to be momentary by operatively coupling the attraction electrode 118 to a power supply 122 via a current limiting device (not shown). For example, the current limiting device can be a resistor having an electrical resistance higher than the electrical resistance of the flame 106. For example, a current-limiting resistor of between 6 and 8 mega-ohms resistance can be used to operatively couple the attraction electrode 118 to a power supply 122.

Referring to **FIGS. 1 to 4**, variations are contemplated.

According to an embodiment, the flame charge electrode 108 is formed integrally with each downward-fired burner 104. Alternatively, the flame charge electrode can be formed separately from the downward-fired burners 104.

One or more power supplies 122 are configured to apply electrical potentials to the one or more flame charge electrode 108. The power supply(ies) 122 can apply a substantially constant voltage such as a DC voltage. Alternatively, or at a time-varying voltage According to an embodiment, an electrode controller 124 is configured to drive the one or more power supplies 122 with a waveform corresponding to the constant voltage or the time-varying voltage. For example, the electrode controller 124 can be configured to drive the one or more power supplies 122 to intervals with positive voltage and intervals with negative voltage. The one or more power supplies 122 can be configured to apply one or more electrical potentials to the one or more field electrodes 114 at either a substantially constant voltage or at a time-varying voltage.

According to an embodiment, the flame charge electrode(s) 108 can be configured to be driven synchronously with the one or more field electrodes 114. For example, when the flame charge electrode 108 is driven positive to contain or remove negative charges (primarily electrons), the flame 106 has a positive majority charge species 112. Shield electrodes 116 can be driven synchronously in phase with the one or more flame charge electrode(s) 108 such that the shield electrode(s) 116 instantaneously carry a positive voltage that repels the positive majority charge species 112 in the flame 106.

Similarly, the attraction electrode(s) 118 can be driven about 180° out of phase to the flame charge electrode(s) 108 such that the attraction electrode(s) 118 instantaneously carries a negative voltage that attracts the positive majority charge species 112 in the flame 106. At another instant, the polarities of the flame charge electrode(s) 108, shield electrode(s) 116, and attraction electrode(s) 118 can be inverted, but still maintain similar repelling and attracting functions. Optionally, phase of the shield electrode(s) 116 and/or the attraction electrode(s) 118 can be adjusted to allow for transit time or capacitance of majority charge species 112 in the flame 106.

The power supply(ies) 122 can be an amplifier, such as a multi-stage amplifier, for example. In an embodiment, the power supply 122 includes a voltage multiplier. In an embodiment, the power supply(ies) 122 is (are) configured to deliver between 1000 volts and 150,000 volts magnitude to the flame charge electrode(s) 108 and the field electrode(s) 114.

In an embodiment, the power supply 122 applies a DC voltage of between +15,000 and +150,000 volts to the flame charge electrode 108. For example, the power supply 122 can be configured to deliver about +40,000 volts to the flame charge electrode 108. The power supply 122 can apply a DC voltage of between

+15,000 and +150,000 volts to a shield electrode 116. For example, the power supply 122 can be configured to deliver about +40,000 volts to the shield electrode 116. Optionally, the flame charge electrode 108 and the shield electrode 116 can be driven from the same power rail of the power supply 122. The power supply 122 can apply a DC voltage of between -15,000 and -150,000 volts to an attraction electrode 118. For example, the power supply 122 can be configured to deliver about -40,000 volts to the attraction electrode 118.

In another embodiment, the power supply 122 applies an AC voltage of between 15,000 and 150,000 volts to the flame charge electrode 108. For example, the power supply 122 can be configured to deliver about 40,000 volts AC to the flame charge electrode 108. The power supply 122 can apply a synchronous AC voltage of between 15,000 and 150,000 volts to a shield electrode 116. For example, the power supply 122 can be configured to deliver about 40,000 volts AC to the shield electrode 116. Optionally, the flame charge electrode 108 and the shield electrode 116 can be driven from the same AC power rail of the power supply 122. The power supply 122 can apply a 180° out-of-phase synchronous AC voltage of between 15,000 and 150,000 volts to an attraction electrode 118. For example, the power supply 122 can be configured to deliver about 40,000 volts AC to the attraction electrode 118.

Optionally, the attraction electrode(s) 118 can be omitted. **FIG. 3** is a diagram of an electrically stabilized down-fired flame reactor, according to another embodiment 301. As indicated in the embodiment 301 compared to the embodiments 101 and 201, relative location(s) of shield electrode(s) 116 are varied.

Also as indicated in the embodiment 301, the attraction electrode(s) 118 can be omitted. In the embodiment 301, the field electrode(s) 114 includes only shield electrode(s) 116. The shield electrode(s) 116 applies electrical pressure on the majority charges 112a in the flame 106 to substantially prevent the flame 106 from touching the catalyst-packed tubes 102. Flame inertia cooperates with the shield electrode(s) 116 to carry the flame downward to heat substantially the entirety of the vertical extent of the catalyst-packed tubes 102.

A field electrode 302 can be disposed relative to the shield electrodes 116 to form an electric field between the shield electrodes 116 and the field electrode 302. The field electrode 302 can be held at relatively low voltage having the same polarity as the shield electrodes 116. Alternatively, the field electrode 302 can be held at a voltage ground. Alternatively, the field electrode 302 can be held at a voltage opposite in polarity to a DC voltage carried by the shield electrodes 116 or 180° out of phase from an AC voltage carried by the shield electrodes 116. The voltage contrast between the field electrode 302 and the shield electrodes 116 creates an electric field gradient for driving the majority charge species 112 toward an intended centerline of the flame 106. Optionally, the field electrode 302 can be electrically insulated from the flame 106. Various high temperature refractory and/or ceramic coatings can be used to provide at least partial electrical insulation around the field electrode 302.

Optionally, shield electrode(s) 116 can be omitted. **FIG. 4** is a diagram of an electrically stabilized down-fired flame reactor, according to another embodiment 401. As indicated in the embodiment 401, the shield electrode(s) 116 is omitted.

Also as indicated in the embodiment 401, the field electrode(s) 114 includes substantially only attraction electrodes 118. For example, the attraction electrode(s) 118 is positioned to attract the flame 106 toward a distal location not immediately adjacent to a catalyst tube 102. A plurality of catalyst-packed tubes 102 are arranged in flow-coupled pairs via a tube fitting or bend 204 at lower ends of each flow-coupled pair. Each flow-coupled pair is configured to receive reactants through an input end and output reaction products through an output end near a ceiling 126 of the heating volume 103.

According to an embodiment, the attraction electrode(s) 118 is arranged to attract the majority charge 112b and thereby the flame 106 to a location between catalyst-packed tubes 102. Optionally, the attraction electrode(s) 118 can be aligned to draw a buoyancy-dominated flame downward between catalyst-filed tube reactor such that the visible flame 106 substantially doesn’t touch the catalyst-packed tubes 102 during operation. The cooperation between the majority charge species 112 and the attraction electrode(s) 118 stabilizes the flame 106 and substantially prevents the flame 106 from touching the catalyst-packed tubes 102.

FIG. 5 is a flowchart showing a method 501 for providing process heat with a down-fired flame, according to an embodiment. The method 501 begins with step 502, wherein a down-fired flame is projected in a heating volume. Step 502 includes emitting a fuel jet in a downward direction and anchoring a flame supported by the fuel jet at a. The fuel may include a light hydrocarbon and/or a process gas such as a mixture of carbon monoxide and hydrogen.

Proceeding to step 504, a voltage is applied to the flame to produce a majority charge carried by the flame. Optionally, in step 504, a voltage can be applied to a charge-ejecting electrode in a dielectric upstream from the flame, and the charges produce thereby can travel to the flame and be incorporated by the flame. Optionally, applying the voltage to the flame can include removing a portion of charged particles from the flame to produce a majority charge species remaining in the flame.

In step 506, an electric field is applied near the down-fired flame to control flame shape and/or heat transfer from the flame.

In step 508, heat from the flame is applied to a chemical reactor. For example, the chemical reactor can include a steam methane reformer.

Referring to step 502, projecting a down-fired flame in a heating volume may include projecting a plurality of down-fired flames. In such a case, step 508 includes applying heat from the plurality of flames to a plurality of substantially vertical catalyst-packed tubes forming the chemical reactor.

According to an embodiment, the vertical tubes contain a catalyst packing. Reactants and one or more products flow through the tubes and the catalyst packing. For example, in endothermic reactions, it is advantageous to apply heat from a burner in a controlled manner. The electrical stabilization of the flame helps to control the application of the heat.

Referring to step 504, a voltage is applied to the flame to produce a majority charge carried by the flame includes applying an electric potential having a same sign as the majority charge species to a flame charging electrode proximate an upper end of the flame. For example, the depletion electrode can be formed at least in part by a burner that projects the down-fired flame in step 502. Applying a voltage to the flame to produce a majority charge carried by the flame can include modulating voltage to produce a modulated majority charge species concentration in the flame. For example, modulating the flame charge electrode can include modulating the flame charge electrode through positive and negative potentials to produce majority charge species having a modulated polarity. For example, modulating the polarity can include changing the polarity from positive to negative, and back again in time-varying manner. Alternatively, applying the voltage to the flame to produce a majority charge carried by the flame can include applying a substantially constant voltage to the flame charge electrode to produce charged particles in the flame at a substantially constant rate to produces a substantially constant concentration of majority charge species having a single polarity.

Referring to step 506, applying an electric field near the down-fired flame to control one or more of flame shape or heat transfer from the flame includes causing the applied electric field to electrically interact with chemical species or electrons carrying the majority charge species in the flame. Step 506 may include shielding a portion of the chemical reactor from the flame with a shield electrode at least transiently carrying an electrical potential having a same polarity as the majority charge species. Additionally or alternatively, step 506 also may include attracting the flame toward a portion of the chemical reactor by at least transiently applying to one or more attraction electrodes a voltage having an opposite polarity from the majority charge species in the flame. Step 506 can include attracting the flame toward a distal location below a location from which the flame is projected by at least transiently applying to one or more attraction electrodes a voltage having an opposite polarity from the majority charge species in the flame.

The method 501 may include operating one or more power supplies to apply a flame energizing voltage to a flame charge electrode and operating the operating the one or more power supplies to apply a repelling voltage to a shield electrode. The method 501 may include operating one or more power supplies to apply a flame energizing voltage to a flame charge electrode and operating the operating the one or more power supplies to apply an attracting voltage to an attraction electrode.

The method 501 may include operating an electrode controller to cause the one or more power supplies to apply a time-varying voltage to a flame charge electrode to produce a time-varying majority charge species and to apply one or more time varying voltages to field electrodes proximate the down-fired flame to control the one or more of flame shape and heat transfer from the flame. Operating the electrode controller may include synchronously driving flame charge electrodes and field electrodes proximate the down-fired flame.

FIG. 6 is a sectional diagram of an electrically stabilized down-fired flame reactor, according to another embodiment 601. The electrically stabilized down-fired flame reactor 601 can include a primary fuel nozzle 602 configured to operate at low pressure. Secondary fuel nozzles 604 can be configured to operate at high pressure. Optionally, a single pressure fuel may be used, and a majority of downward momentum on the flame 106 can be provided by electrical attraction between charged particles in the flame and a voltage carried by an attraction electrode 118. In such a case, the secondary fuel nozzles 604 may be omitted.

A flame holder 107 may be formed from a refractory material such as a refractory tile 606. The flame charge electrode(s) 108 can be formed integrally with the refractory tile 606. In an embodiment, flame charge electrodes 108 are formed from steel rebar pieces that are cast into and extend through the refractory tile. In the embodiment 601, the flame attraction electrode 118 is formed as a steel ring disposed below and peripheral to the primary nozzle, at a distance at or beyond a normal vertical flame extension. A power supply 122 applies opposite polarity high voltages to the flame charge electrodes 108 and the flame attraction electrode 118.

Reactor tubes 102 containing a catalyst 608 are disposed adjacent to the down-fired flame 106.

The burner and electrode assemblies described herein may be used for applications other than heating of vertical reactor tubes 102.

FIG. 7 is a perspective view of an electrically stabilized down-fired burner 701, according to an embodiment. As indicated in the embodiment 701, the downward-fired burner 104 is fired from a ceiling 126 of a furnace. According to an embodiment, the ceiling 126 supports a refractory tile 606 forming a flame holder 107. A primary fuel nozzle 602 is located along a centerline of the burner 701. Optional secondary fuel nozzles 604 are located around the refractory tile 606. Flame charge electrodes 108 extend through the refractory tile 606 and are held in contact with the flame 106 such that a high voltage placed on the flame charge electrodes 108 is imparted onto the flame 106.

An attraction electrode (not shown) can be supported below the refractory tile 606. The attraction electrode may be configured to carry a voltage at a polarity opposite to the polarity of the voltage carried by the flame charge electrodes 108 and the flame 106. Alternatively, the attraction electrode may be configured to carry a voltage ground.

In an embodiment where there are no grounded conductive surfaces nearby, an attraction electrode can be formed from a floor of the furnace (not shown) held at voltage ground.

FIG. 8 is a perspective view of multiple electrically stabilized down-fired flame reactors 801, according to another embodiment. The multiple electrically stabilized down-fired flame reactors 801 are inserted into a furnace volume from a furnace ceiling 126. The furnace ceiling 126 includes refractory tile 606, according to an embodiment. The down-fired burners and reactor tubes 102 can be arrayed in a checkerboard pattern, wherein each down-fired flame 106 primarily heats four adjacent reactor tubes 102, and wherein each reactor tube 102 is heated by four adjacent down-fired flames 106.

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.

CLAIMS

What is claimed is:

1. An electrically stabilized down-fired flame reactor, comprising:

a plurality of catalyst-packed tubes extending vertically in a heating volume;

one or more downward-fired burners configured to project one or more flames downward to heat the plurality of catalyst-packed tubes;

one or more flame charge electrodes respectively associated with each downward-fired burner and configured to cause the one or more flames to carry a majority charge species; and

one or more field electrodes operatively coupled to each tube and configured to electrically interact with the majority charge species in the one or more flames to control heat transfer from the one or more flames to the tubes.

2. The electrically stabilized down-fired flame reactor of claim 1, wherein the one or more field electrodes include one or more shield electrodes.

3. The electrically stabilized down-fired flame reactor of claim 2, wherein the one or more shield electrodes include one or more electrodes disposed between each tube and a proximal flame, the one or more shield electrodes being at least transiently held at a voltage having a same polarity as the majority charge in the flame.

4. The electrically stabilized down-fired flame reactor of claim 2, wherein the one or more shield electrodes are configured to reduce direct impingement of the flame on the respective tubes.

5. The electrically stabilized down-fired flame reactor of claim 2, wherein the one or more shield electrodes are configured to reduce or eliminate hot spots on the tubes.

6. The electrically stabilized down-fired flame reactor of claim 1, wherein the one or more field electrodes include one or more attraction electrodes.

7. The electrically stabilized down-fired flame reactor of claim 6, wherein the one or more attraction electrodes include one or more electrodes disposed between each tube and a proximal flame, the one or more attraction electrodes being at least transiently held at a voltage having an opposite polarity from the majority charge species in the flame.

8. The electrically stabilized down-fired flame reactor of claim 6, wherein the one or more attraction electrodes are thermally coupled to a respective tube by a thermal coupling.

9. The electrically stabilized down-fired flame reactor of claim 8, wherein each thermal coupling is configured as an electrical insulator or high impedance electrical conductor.

10. The electrically stabilized down-fired flame reactor of claim 6, wherein the one or more attraction electrodes are configured to increase heat transfer to the tubes compared to tubes not including the one or more attraction electrodes.

11. The electrically stabilized down-fired flame reactor of claim 6, wherein the one or more attraction electrodes are configured to draw the flame down toward a bottom end of the tubes.

12. The electrically stabilized down-fired flame reactor of claim 1, wherein the one or more flame charge electrodes include a flame charge electrode respectively formed integrally with each burner.

13. The electrically stabilized down-fired flame reactor of claim 1, further comprising one or more power supplies configured to apply one or more electrical potentials to the one or more flame charge electrodes.

14. The electrically stabilized down-fired flame reactor of claim 13, wherein the one or more power supplies are configured to apply a substantially constant voltage to the plurality of flame charge electrodes.

15. The electrically stabilized down-fired flame reactor of claim 13, wherein the one or more power supplies are configured to apply a time-varying voltage to the plurality of flame charge electrodes.

16. The electrically stabilized down-fired flame reactor of claim 15, wherein one or more field electrodes are configured to be driven synchronously with the plurality of flame charge electrodes.

17. The electrically stabilized down-fired flame reactor of claim 15, further comprising an electrode controller configured to drive the one or more power supplies with a waveform corresponding to the time-varying voltage.

18. The electrically stabilized down-fired flame reactor of claim 15, wherein the time-varying voltage includes intervals with positive voltage and intervals with negative voltage.

19. The electrically stabilized down-fired flame reactor of claim 1, further comprising one or more power supplies configured to apply one or more electrical potentials to the one or more field electrodes.

20. The electrically stabilized down-fired flame reactor of claim 19, wherein the one or more power supplies are configured to apply a substantially constant voltage to the one or more field electrodes.

21. The electrically stabilized down-fired flame reactor of claim 19, wherein the one or more power supplies are configured to apply a time-varying voltage to the one or more field electrodes.

22. The electrically stabilized down-fired flame reactor of claim 21, wherein one or more field electrodes are configured to be driven synchronously with the one or more flame charge electrodes.

23. The electrically stabilized down-fired flame reactor of claim 21, further comprising an electrode controller including a waveform generator configured to drive the one or more power supplies with a waveform corresponding to the time-varying voltage.

24. The electrically stabilized down-fired flame reactor of claim 21, wherein the time-varying voltage includes intervals with positive voltage and intervals with negative voltage.

25. The electrically stabilized down-fired flame reactor of claim 1, wherein the one or more field electrodes include one or more shield electrodes and one or more attraction electrodes.

26. The electrically stabilized down-fired flame reactor of claim 1, comprising a steam methane reformer.

27. The electrically stabilized down-fired flame reactor of claim 1, wherein the plurality of catalyst-packed tubes are arranged in flow-coupled pairs via a tube fitting or bend at lower ends of each flow-coupled pair, each flow-coupled pair being configured to receive reactants through an input end and output reaction products through an output end near a ceiling of the heating volume

28. The electrically stabilized down-fired flame reactor of claim 1, wherein the one or more field electrodes comprise one or more flame attraction electrodes, and

further comprising:

a power supply operatively coupled to the one or more flame charge electrodes and to the one or more flame attraction electrodes, the power supply being configured to output a flame charge voltage to one or more flame charge electrodes and to output an attraction voltage opposite in polarity from the flame charge voltage to the one or more flame attraction electrodes; and

a current limiting device operatively coupled between the power supply and each flame attraction electrode.

29. The electrically stabilized down-fired flame reactor of claim 28, wherein the current limiting device includes a resistor.

30. The electrically stabilized down-fired flame reactor of claim 29, wherein the resistor has a resistance of about 6 mega-ohms to 8 mega-ohms.

31. A method for providing process heat, comprising:

projecting a down-fired flame in a heating volume;

applying a voltage to the flame to produce a majority charge in the flame;

applying an electric field proximate the down-fired flame to control flame shape, heat transfer from the flame, or flame shape and heat transfer from the flame; and

applying heat from the flame to a chemical reactor.

32. The method for providing process heat of claim 31, wherein projecting a down-fired flame in a heating volume includes projecting a plurality of down-fired flames; and

wherein applying heat from the plurality of flames to a chemical reactor includes heating a plurality of substantially vertical tubes containing catalyst-packing and flowing reactants and one or more products.

33. The method for providing process heat of claim 31, wherein applying a voltage to the flame to produce a majority charge in the flame includes applying an electric potential having a same sign as the majority charge to a charge depletion electrode proximate an upper end of the flame.

34. The method for providing process heat of claim 31, wherein applying a voltage to the flame to produce a majority charge in the flame includes applying the voltage with a flame charge electrode formed integrally with a flame holder.

35. The method for providing process heat of claim 31, wherein applying a voltage to the flame to produce a majority charge in the flame includes modulating the voltage to produce a modulated majority charge in the flame.

36. The method for providing process heat of claim 35, wherein applying a voltage to the flame to produce a majority charge in the flame includes modulating a flame charge electrode through positive and negative potentials to produce a modulated majority charge including a modulated polarity.

37. The method for providing process heat of claim 31, wherein applying a voltage to the flame to produce a majority charge in the flame includes applying a substantially constant voltage to a flame charge electrode to produce a substantially constant concentration of majority charge species having a single polarity.

38. The method for providing process heat of claim 31, wherein applying an electric field proximate the down-fired flame to control one or more of flame shape and heat transfer from the flame includes causing the applied electric field

to electrically interact with chemical species or electrons carrying the majority charge in the flame.

39. The method for providing process heat of claim 31, wherein applying an electric field proximate the down-fired flame to control one or more of flame shape and heat transfer from the flame includes shielding a portion of the chemical reactor from the flame with a shield electrode at least transiently carrying an electrical potential having a same polarity as the majority charge.

40. The method for providing process heat of claim 31, wherein applying an electric field proximate the down-fired flame to control one or more of flame shape and heat transfer from the flame includes attracting the flame toward a portion of the chemical reactor by at least transiently applying a voltage having an opposite polarity from the majority charge in the flame to one or more attraction electrodes.

41. The method for providing process heat of claim 31, wherein applying an electric field proximate the down-fired flame to control one or more of flame shape and heat transfer from the flame includes attracting the flame toward a distal location below a location from which the flame is projected by at least transiently applying to one or more attraction electrodes a voltage having an opposite polarity from the majority charge in the flame.

42. The method for providing process heat of claim 31, wherein applying an electric field proximate the down-fired flame to control one or more of flame shape and heat transfer from the flame includes:

shielding a first portion of the chemical reactor from the flame with a shield electrode at least transiently carrying an electrical potential having a same potential as the majority charge; and

attracting the flame toward a second portion of the chemical reactor or toward a distal location below a location from which the flame is projected by at least transiently applying to one or more attraction electrodes a voltage having an opposite polarity from the majority charge in the flame.

43. The method for providing process heat of claim 31, further comprising:

operating one or more power supplies to apply a voltage to a flame charge electrode and to one or more field electrodes.

44. The method for providing process heat of claim 43, further comprising:

operating an electrode controller to cause the one or more power supplies to apply a time-varying voltage to a flame charge electrode to produce a time varying majority charge in the flame; and

operating the electrode controller to apply one or more time varying voltages to one or more field electrodes near the down-fired flame to control the one or more of flame shape and heat transfer from the flame.

45. The method for providing process heat of claim 44, wherein operating the electrode controller includes synchronously driving the flame charge electrode and the one or more field electrodes.

46. The method for providing process heat of claim 31, wherein the chemical reactor includes a steam methane reformer.

47. A down-fired burner, comprising:

a fuel nozzle configured to emit a fuel jet in a downward direction;

a flame holder disposed adjacent to the fuel nozzle and configured to anchor a flame supported by the fuel jet;

a power supply configured to output a high magnitude voltage;

a flame charge electrode operatively coupled to receive the high magnitude voltage from the power supply and configured to apply the high magnitude voltage to the flame; and an attraction electrode below and distal from the fuel nozzle and the flame holder, the attraction electrode being configured to carry an electrical potential selected to electrostatically attract the high magnitude voltage.

48. The down-fired burner of claim 47, wherein the flame holder is formed from a refractory material; and

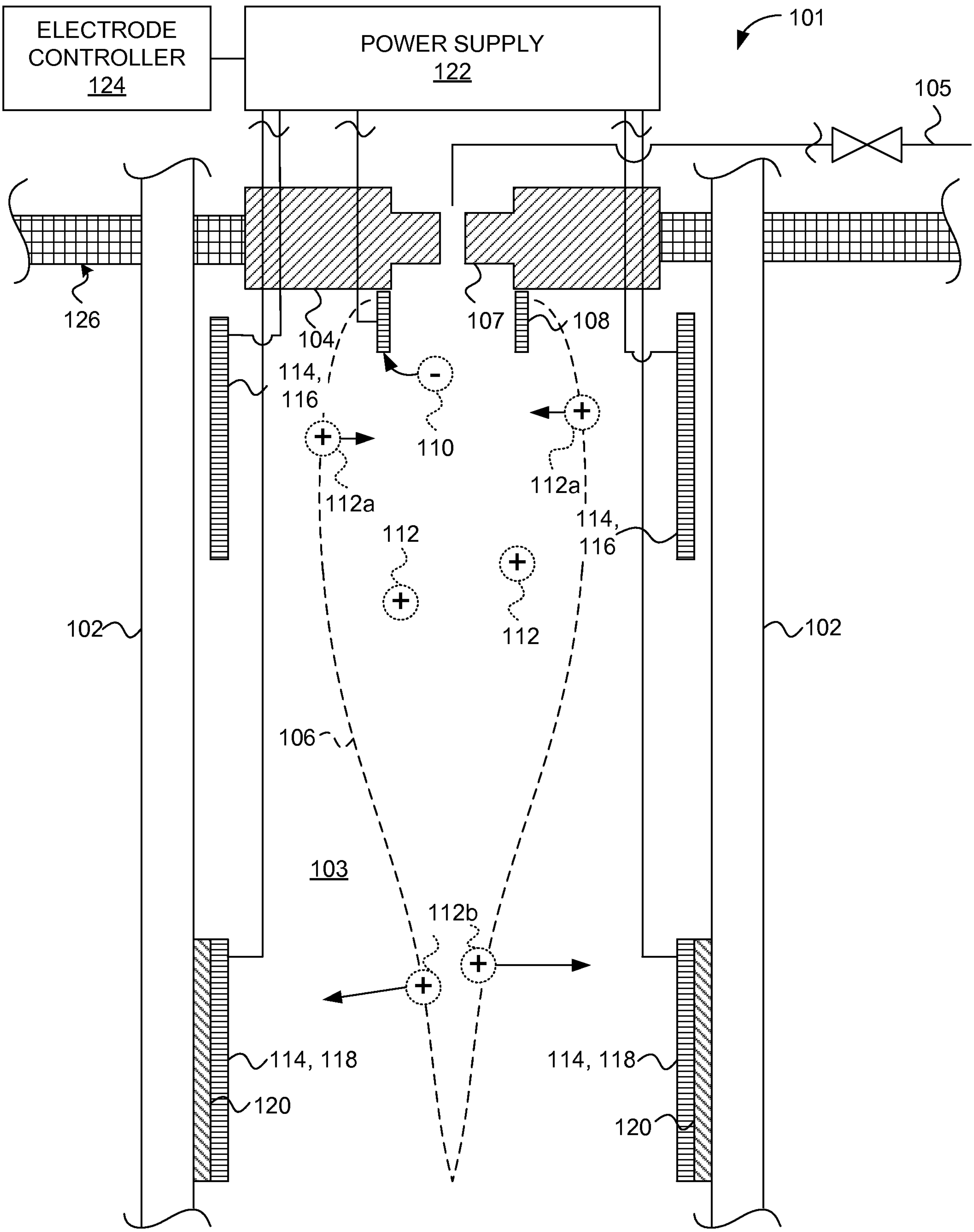
wherein the flame charge electrode includes a plurality of flame charge electrodes extending through the flame holder.

49. The down-fired burner of claim 47, further comprising:

a current limiter operatively coupled between the power supply and the attraction electrode, the current limiter being configured to limit electrical current when the flame comes into electrical continuity with the attraction electrode.

50. The down-fired burner of claim 49, wherein the current limiter includes a resistor.

FIG. 1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120

FIG. 2

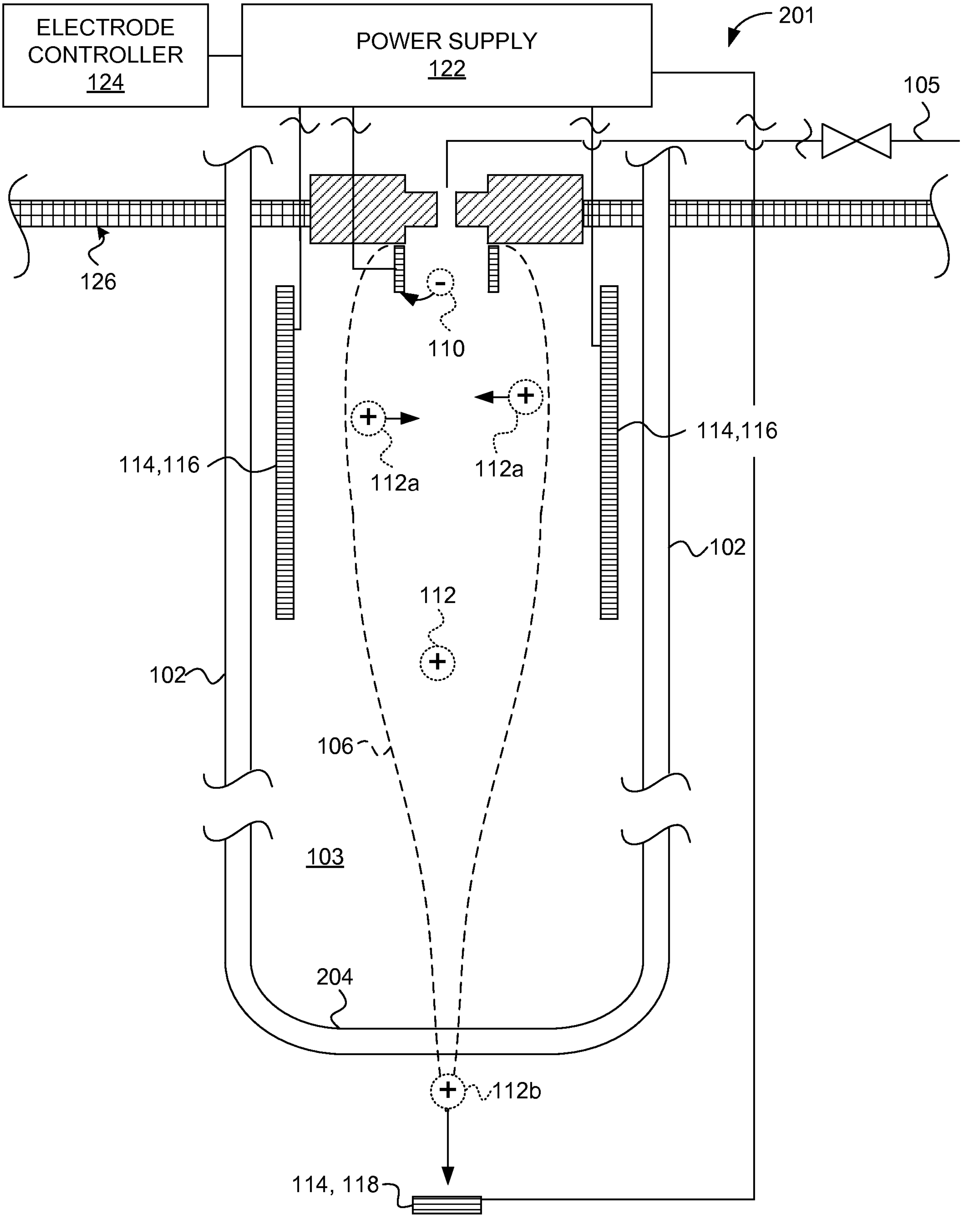
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FIG. 3

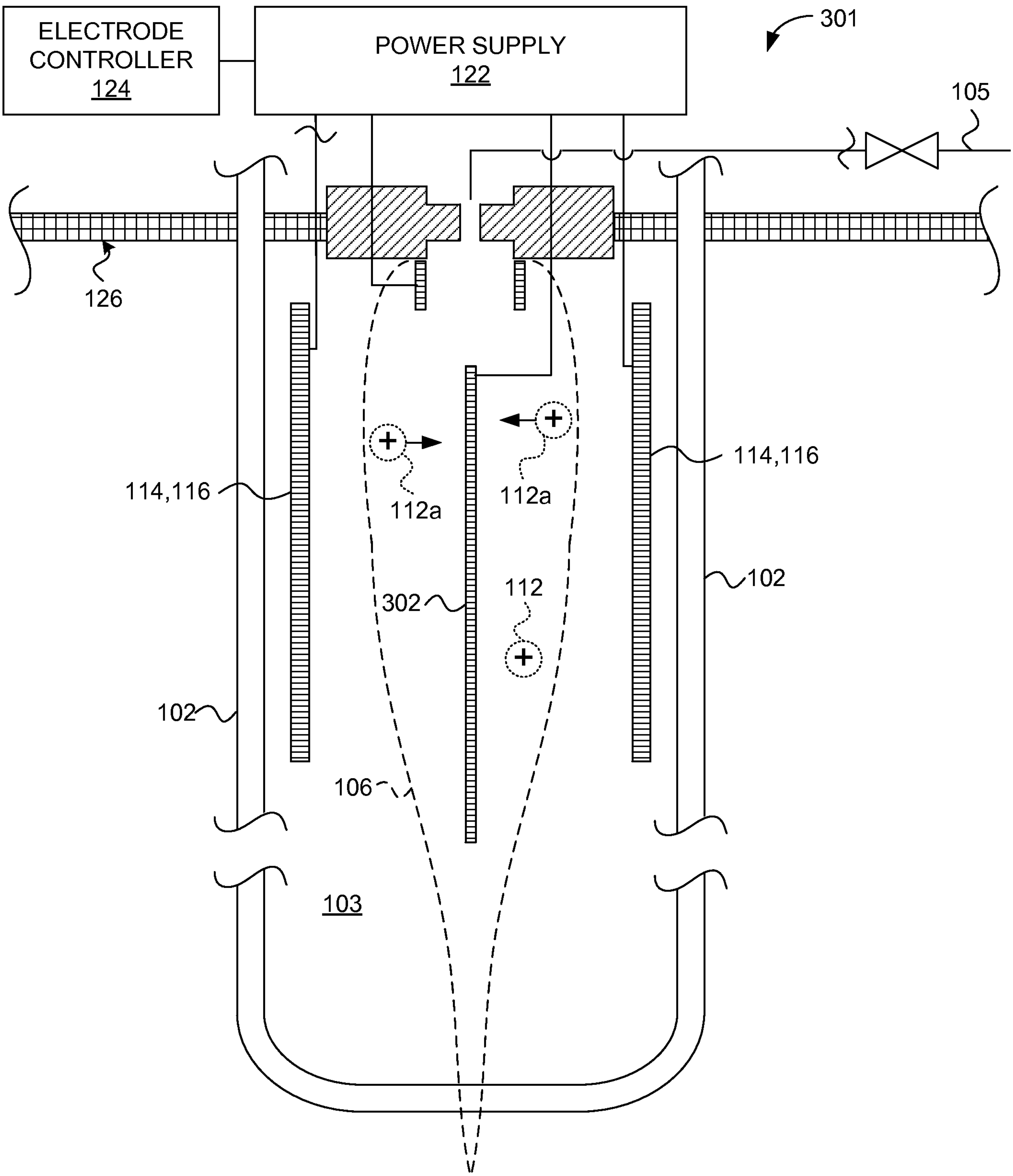
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FIG. 4

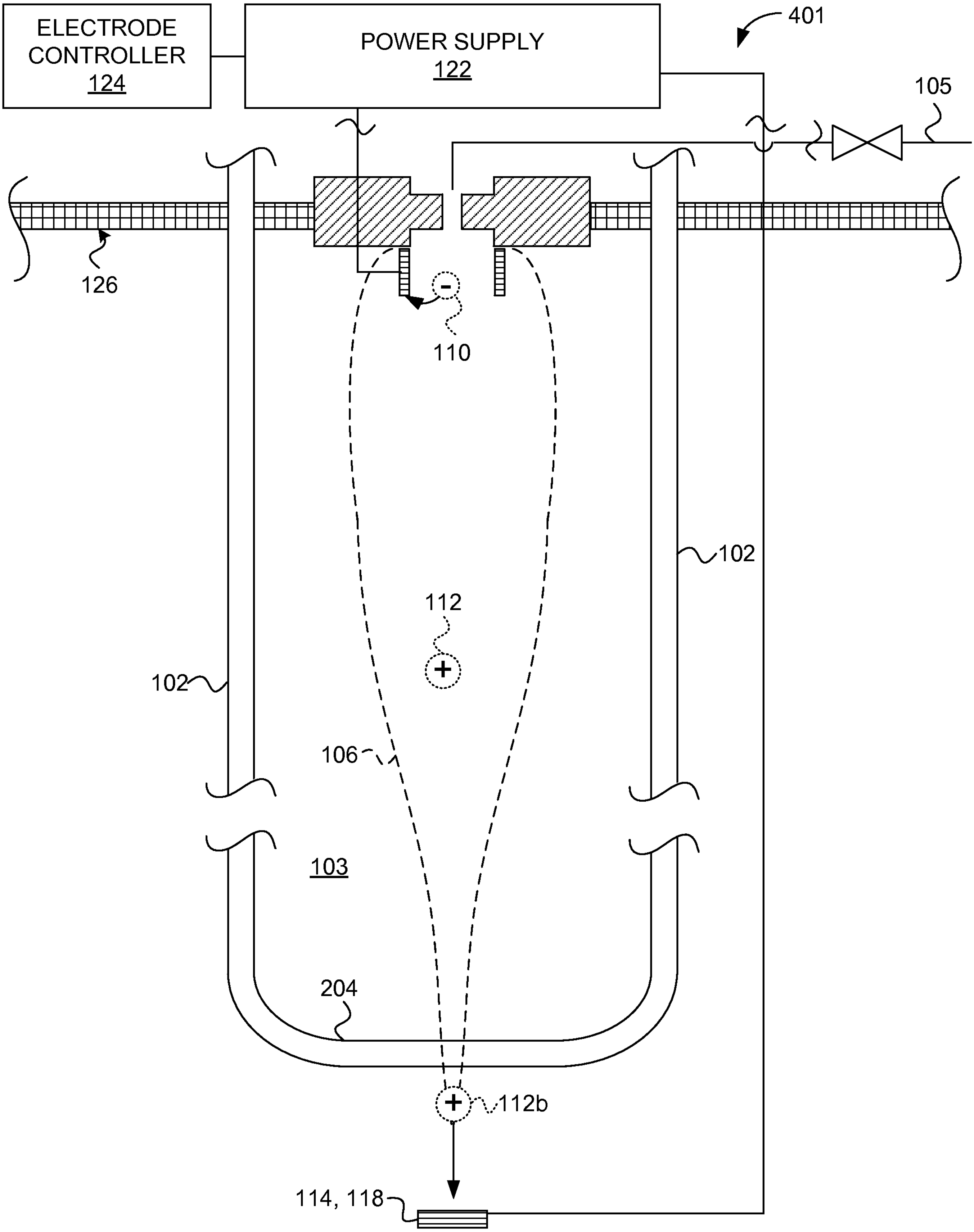
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FIG. 5

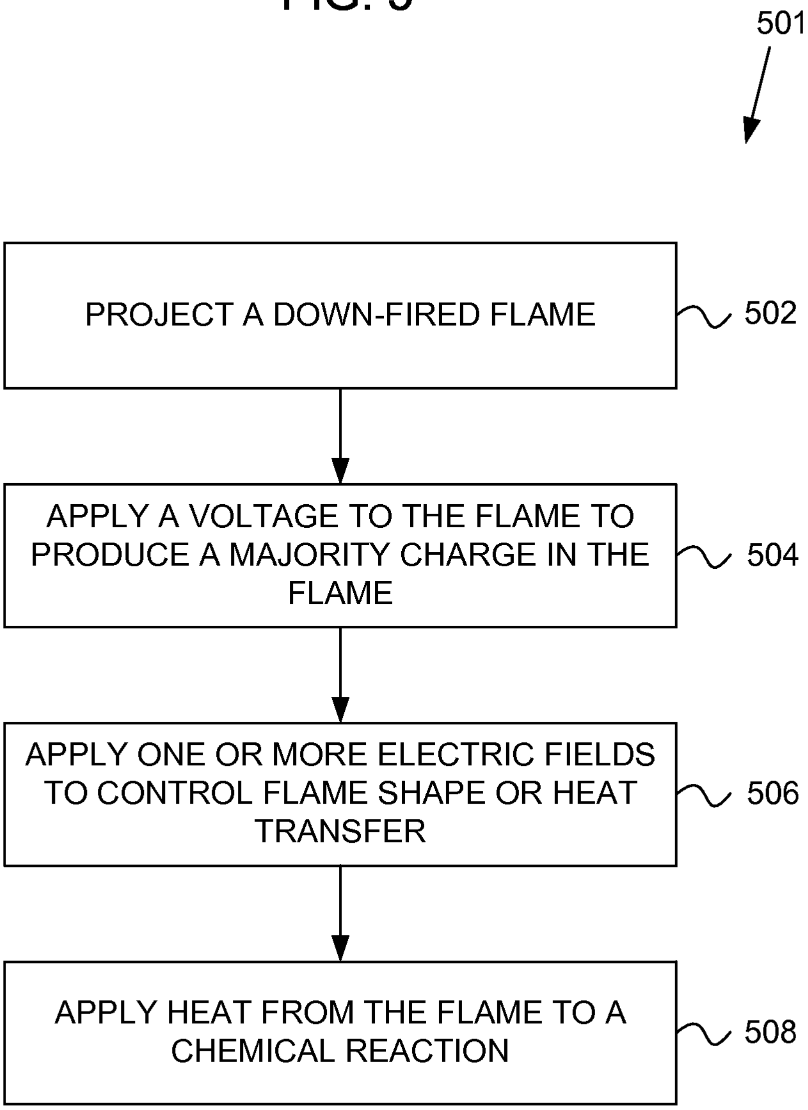
501
PROJECT A DOWN-FIRED FLAME
502
APPLY A VOLTAGE TO THE FLAME TO PRODUCE A MAJORITY CHARGE IN THE FLAME
504
APPLY ONE OR MORE ELECTRIC FIELDS TO CONTROL FLAME SHAPE OR HEAT TRANSFER
506
APPLY HEAT FROM THE FLAME TO A CHEMICAL REACTION
508

FIG. 6

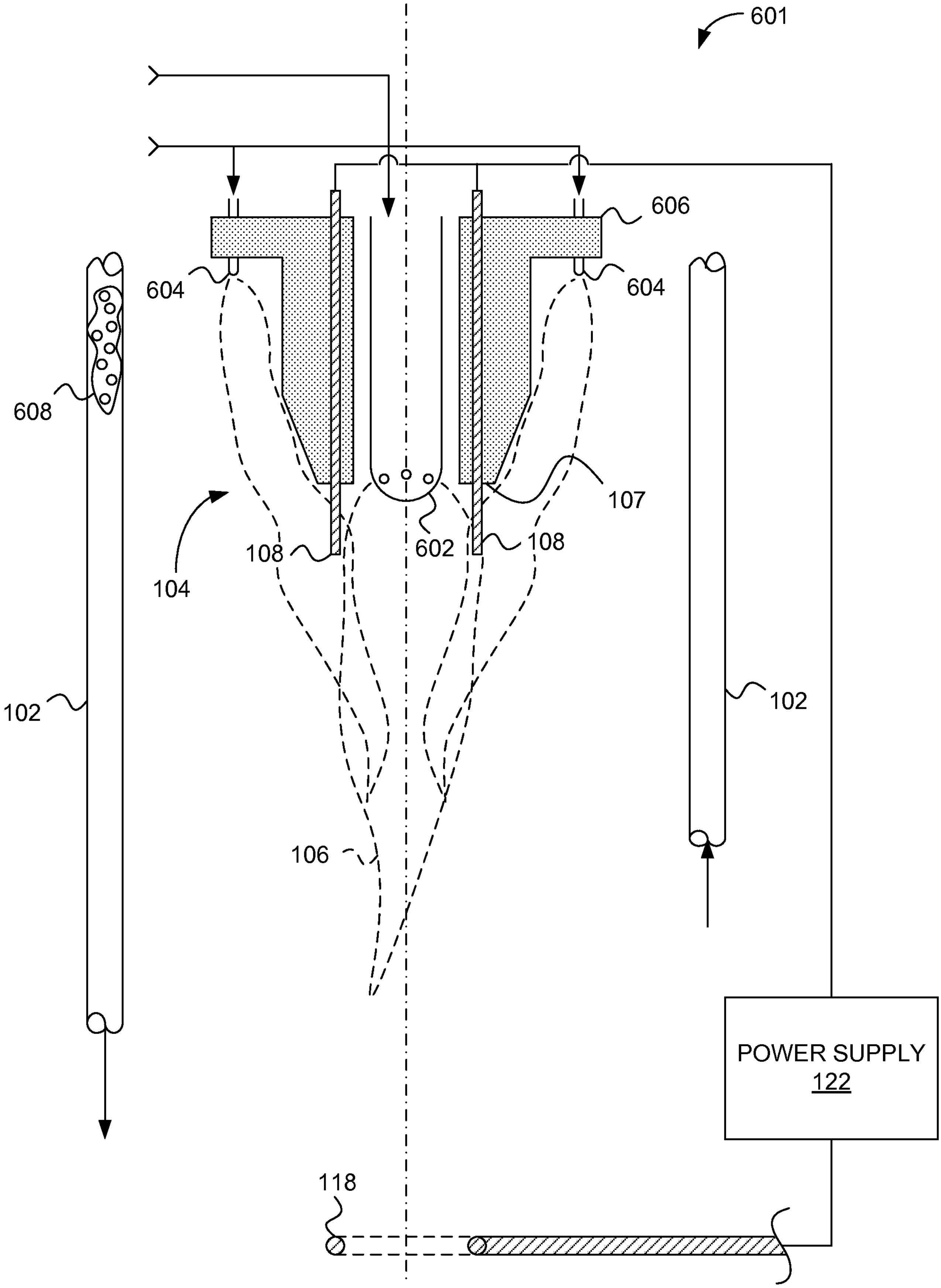
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FIG. 7

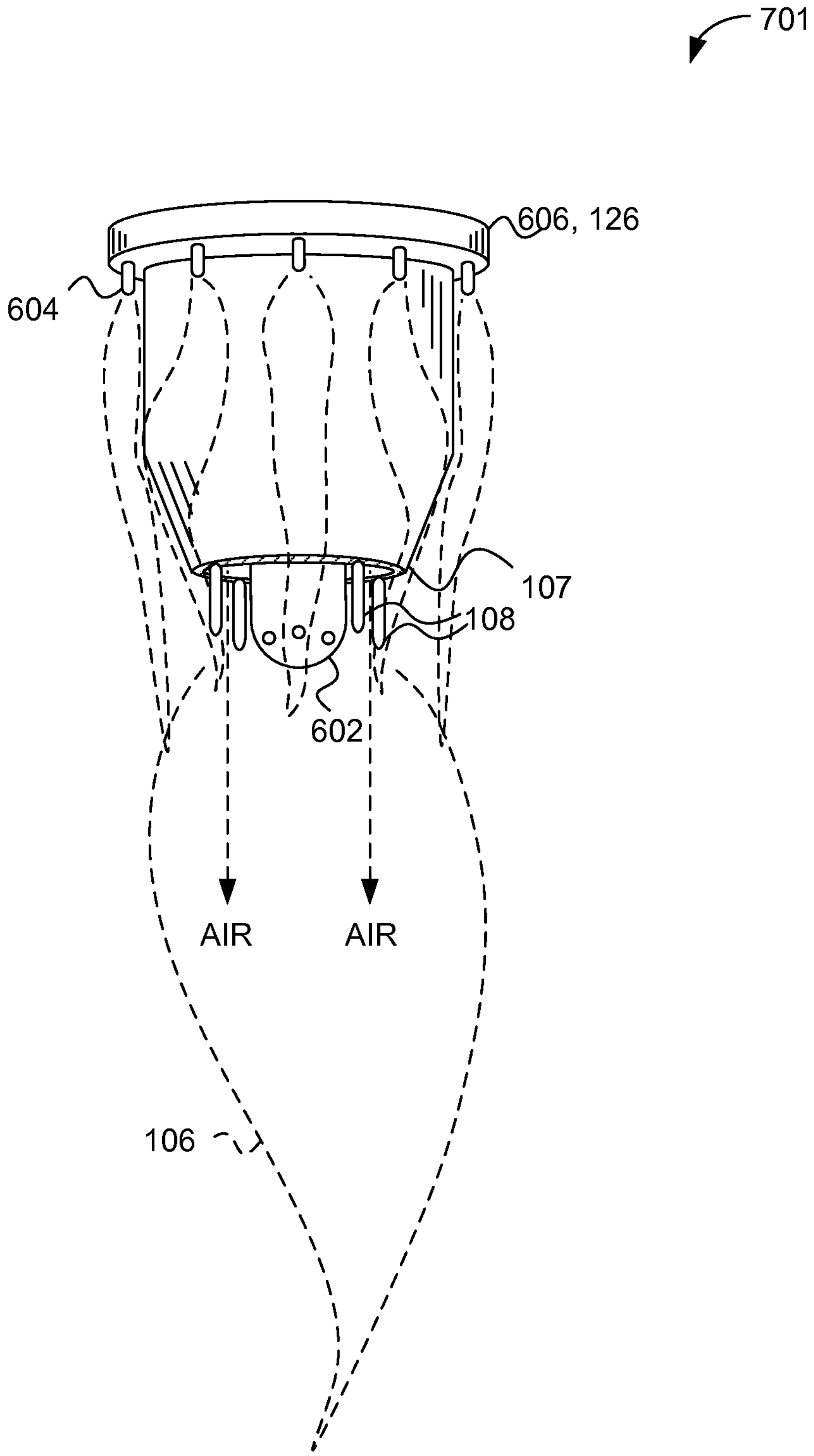
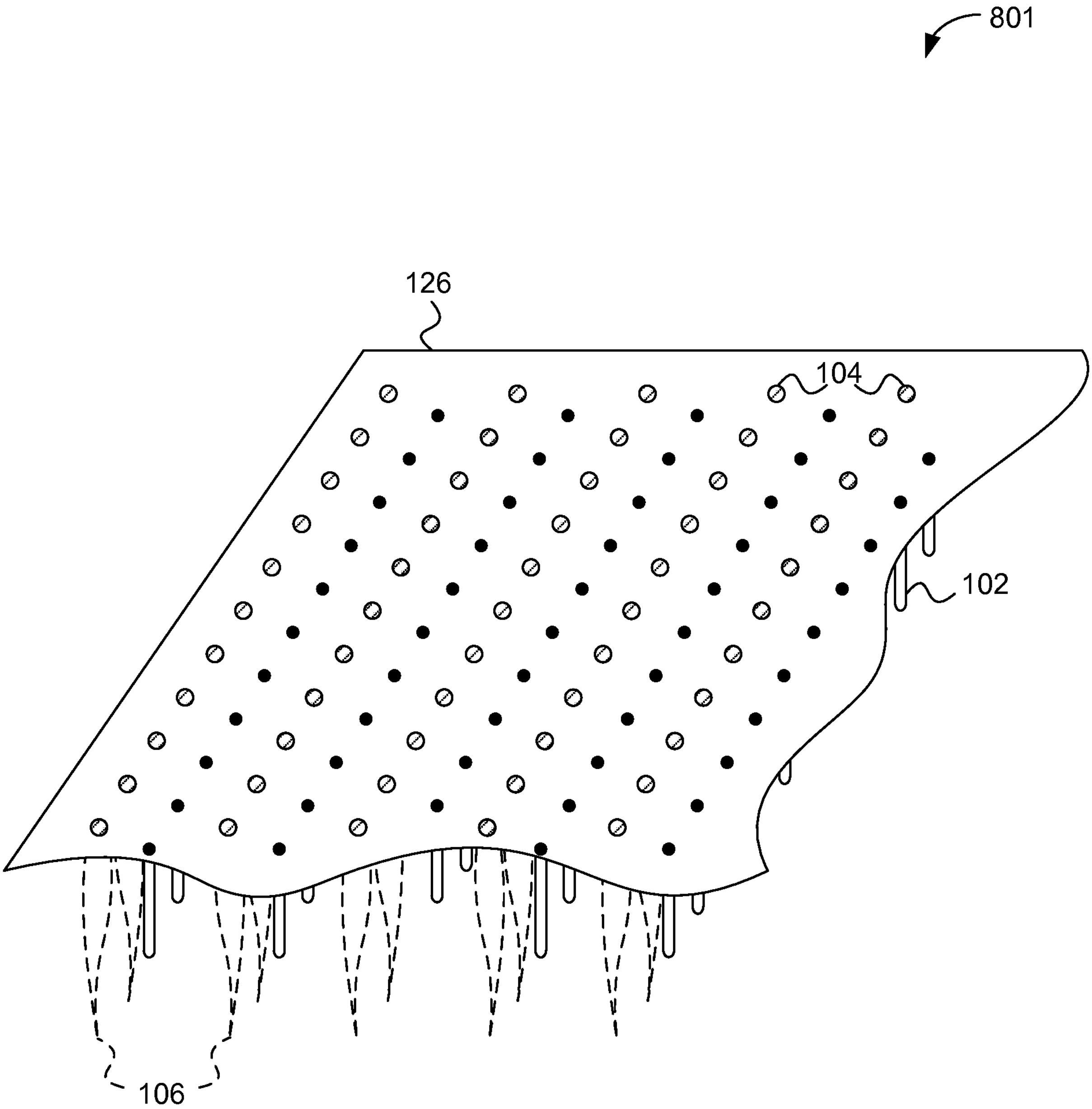


FIG. 8



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/046202

A. CLASSIFICATION OF SUBJECT MATTER

B01J 19/08(2006.01)i, B01J 19/26(2006.01)i, F23C 5/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B01J 19/08; H01M 8/04; C01B 3/32; H01M 8/06; C01B 3/38; F15B 21/00; F28F 13/00; B01J 19/26; F23C 5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: down-fired, flame, electrical, burner, electrode, shield, attraction

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	JP 06-215787 A (TOKYO GAS CO., LTD.) 05 August 1994 See Ffigure 1 and paragraph [0011].	1,13-24,31-32,38-42,47-50 2-12,25-30,33-37,43-46
Y A	US 2011-0203771 A1 (GOODSON, D. et al.) 25 August 2011 See claims 1, 19; Figures 1-2; and paragraph [0023].	1,13-24,31-32,38-42,47-50 2-12,25-30,33-37,43-46
A	JP 07-011136 Y2 (FUJI ELECTRIC CO.) 15 March 1995 See Figures 1-2.	1-50
A	JP 2011-207700 A (ENEOS CELLTECH CO., LTD.) 20 October 2011 See Figure 2.	1-50
A	KR 10-2010-0058899 A (SAMSUNG SDI CO., LTD.) 04 June 2010 See abstract; claim 1; and Figures 3, 6.	1-50

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 October 2013 (22.10.2013)	**23 October 2013 (23.10.2013)**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea	KIM, Dong Seok
Facsimile No. +82-42-472-7140	Telephone No. +82-42-481-8647

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/046202

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Invention Group I (claims 1-30): An electrically stabilized down-fired flame reactor, comprising: a plurality of catalyst-packed tubes; one or more downward-fired burners; one or more flame charge electrodes; and one or more field electrodes.

Invention Group II (claims 31-46): A method for providing process heat, comprising: projecting a down-fired flame in a heating volume; applying a voltage to the flame to produce a majority charge in the flame; applying an electric field proximate the down-fired flame; and applying heat from the flame to a chemical reactor.

Invention Group III (claims 47-50): A down-fired burner, comprising: a fuel nozzle; a flame holder; a power supply; a flame charge electrode; and an attraction electrode.

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2013/046202

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 06-215787A	05/08/1994	None	
US 2011-0203771 A1	25/08/2011	AU 2011-205254 A1	02/08/2012
		CA 2787234 A1	21/07/2011
		CN 102782297 A	14/11/2012
		EP 2524130 A2	21/11/2012
		JP 2013-517453 A	16/05/2013
		KR 20120129907 A	28/11/2012
		WO 2011-088250 A2	21/07/2011
		WO 2011-088250 A3	22/12/2011
JP 7011136 Y2	15/03/1995	JP 2102428 U	15/08/1990
JP 2011-207700 A	20/10/2011	None	
KR 10-2010-0058899 A	04/06/2010	US 2010-0126070 A1	27/05/2010
		US 8197563 B2	12/06/2012