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(54) METHODS FOR GENERATION OF SUBSURFACE HEAT FOR TREATMENT OF A HYDROCARBON CONTAINING FORMATION

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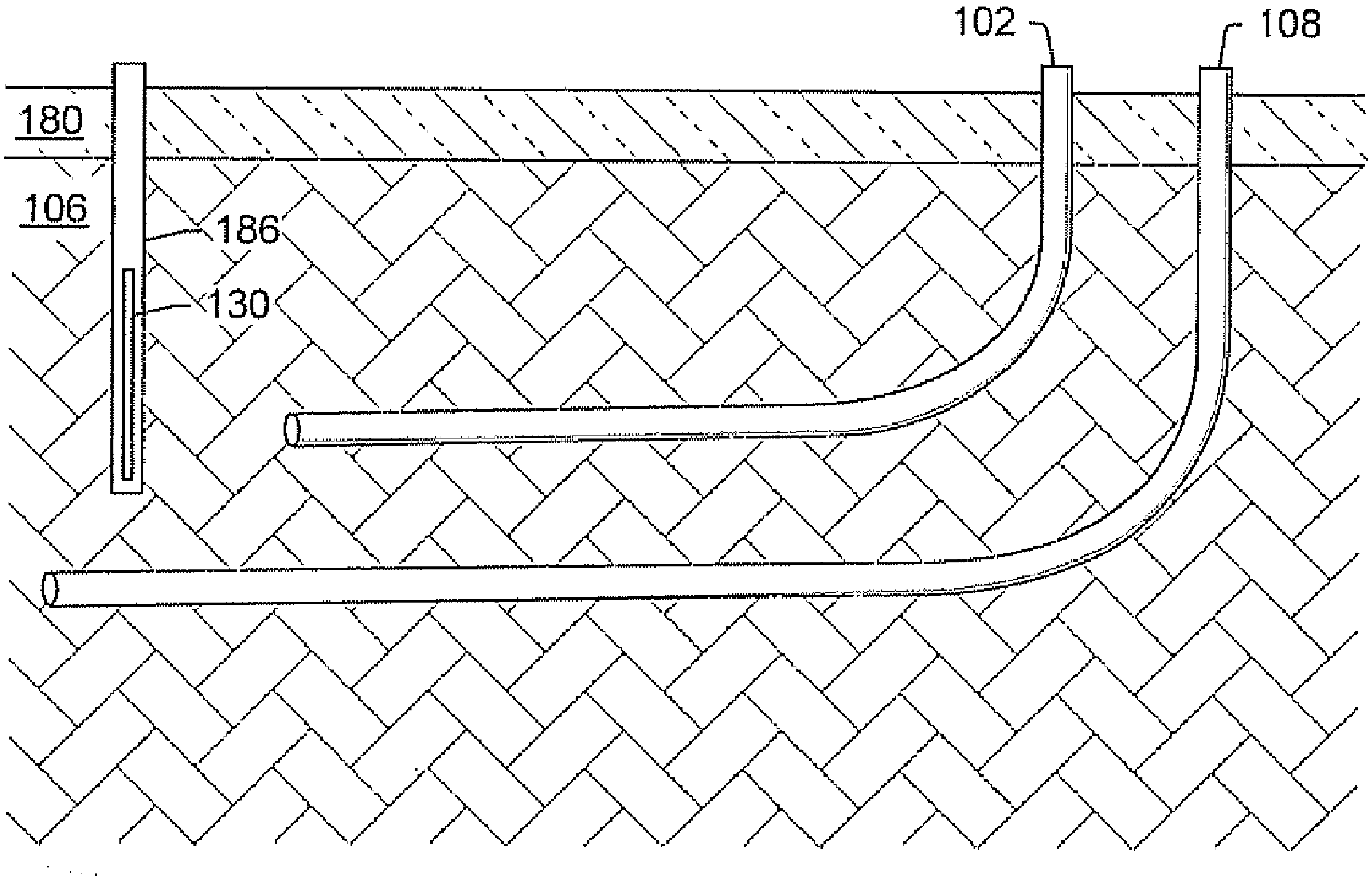
(57) ABSTRACT

Methods of generating subsurface heat for treatment of a hydrocarbon containing formation are described herein. Steam is provided to at least a portion of a hydrocarbon containing formation from a plurality of substantially horizontal steam injection wells. A mixture comprising hydrogen sulfide and an oxidant is combusted in one or more flameless distributed combustors positioned in one or more substantially vertical wellbores to generate heat. At least one of the substantially vertical wellbores is within ten meters of an end of at least one of the substantially horizontal steam injection wells, and at least a portion of the generated heat is transferred to a portion of the hydrocarbon containing formation located between at least one of the substantially horizontal steam injection wells and at least one of the substantially vertical heater wells to mobilize formation fluids for recovery.



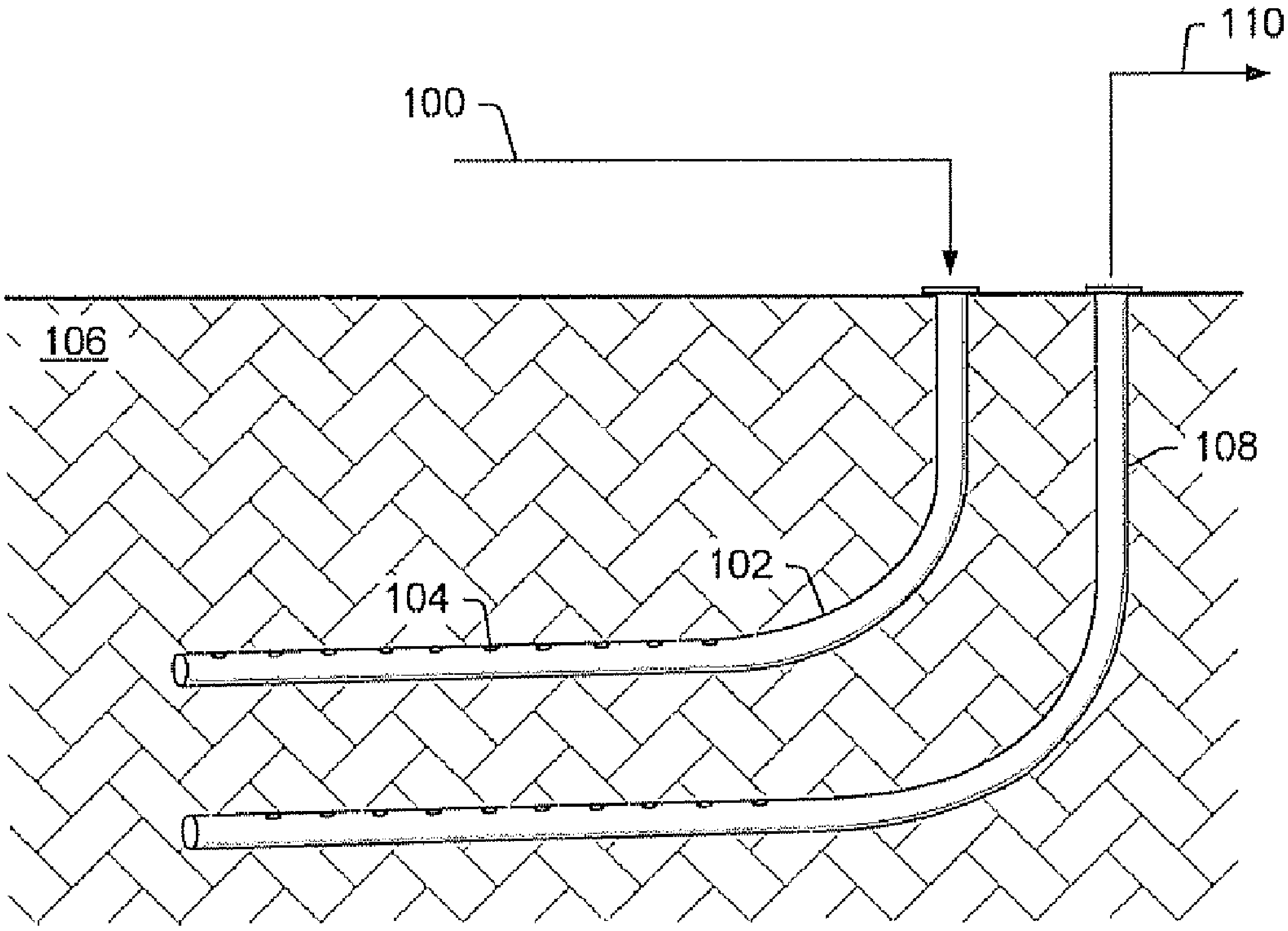

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FIG. 1

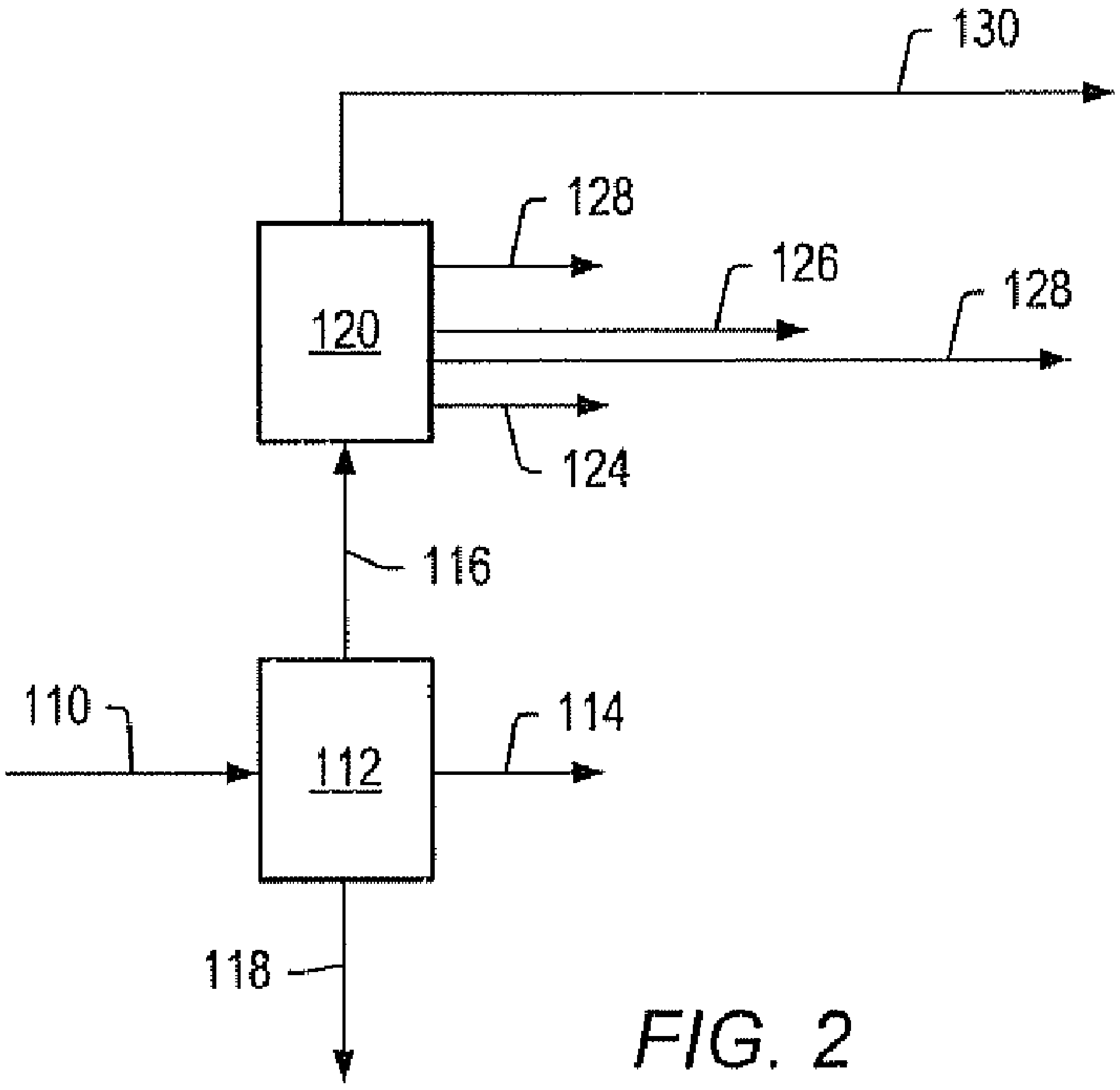
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FIG. 2

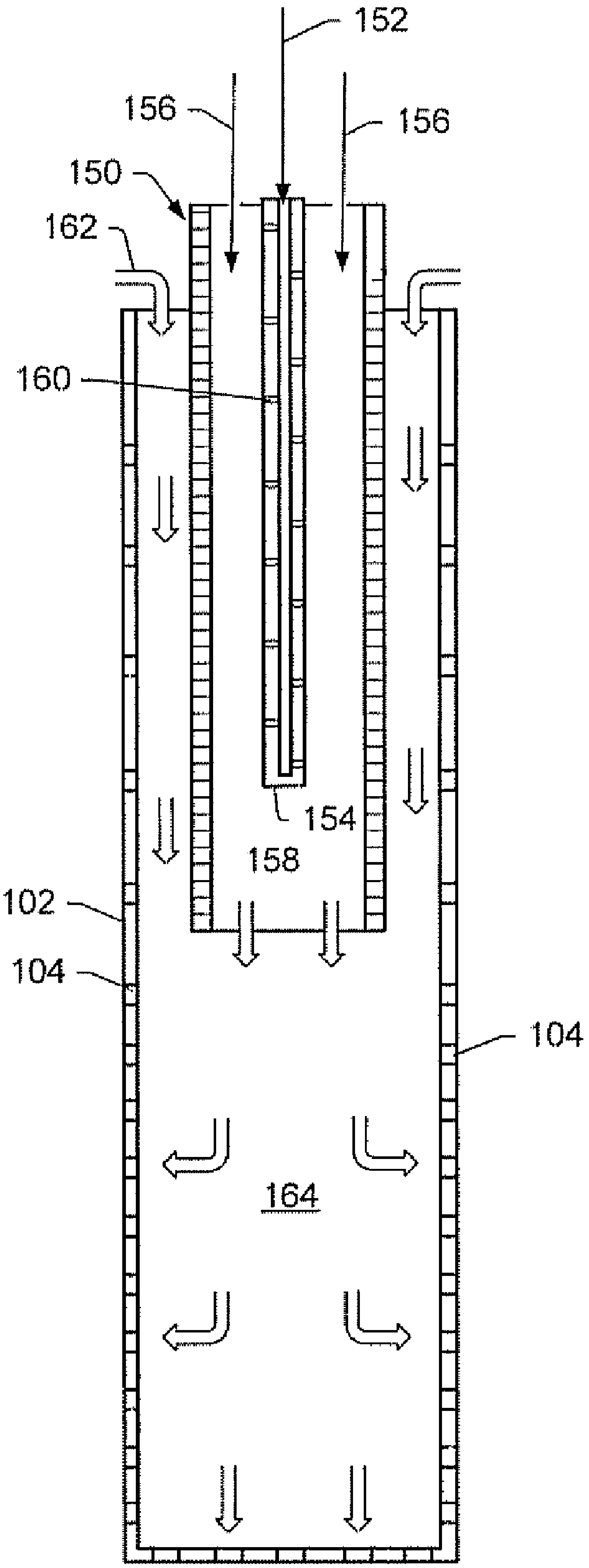

FIG. 3

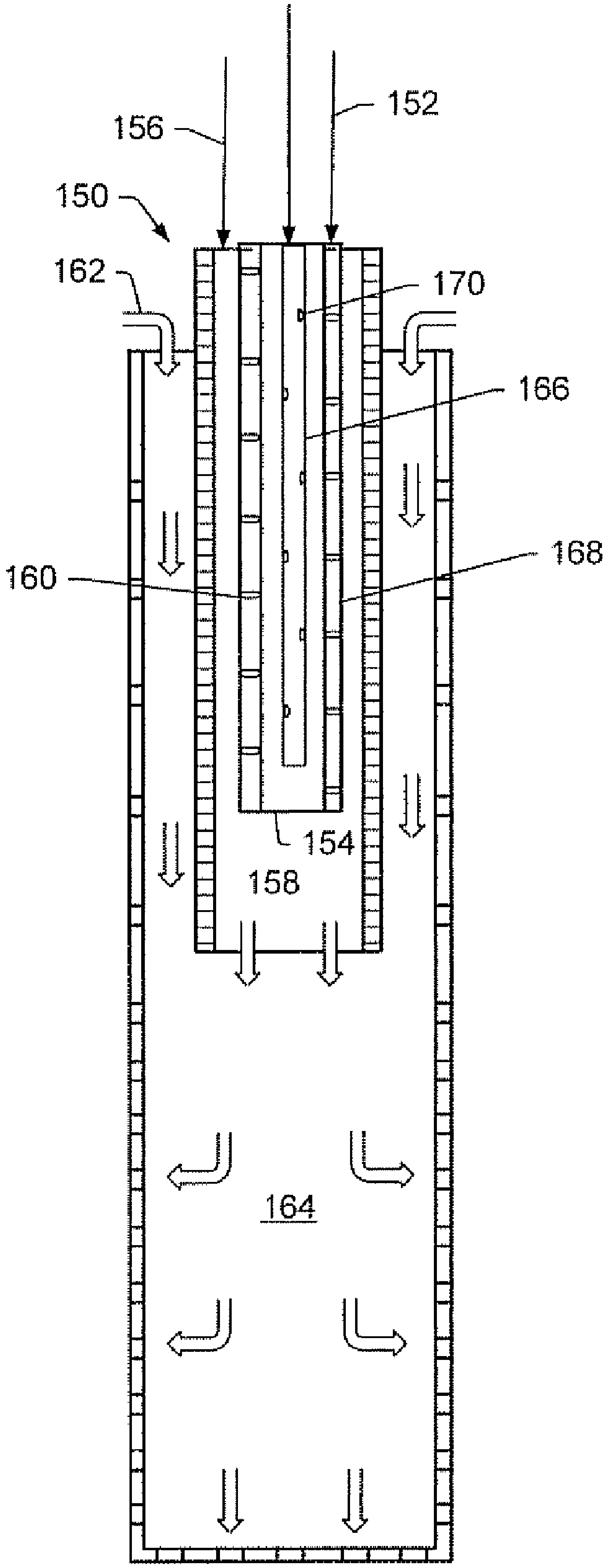

FIG. 4

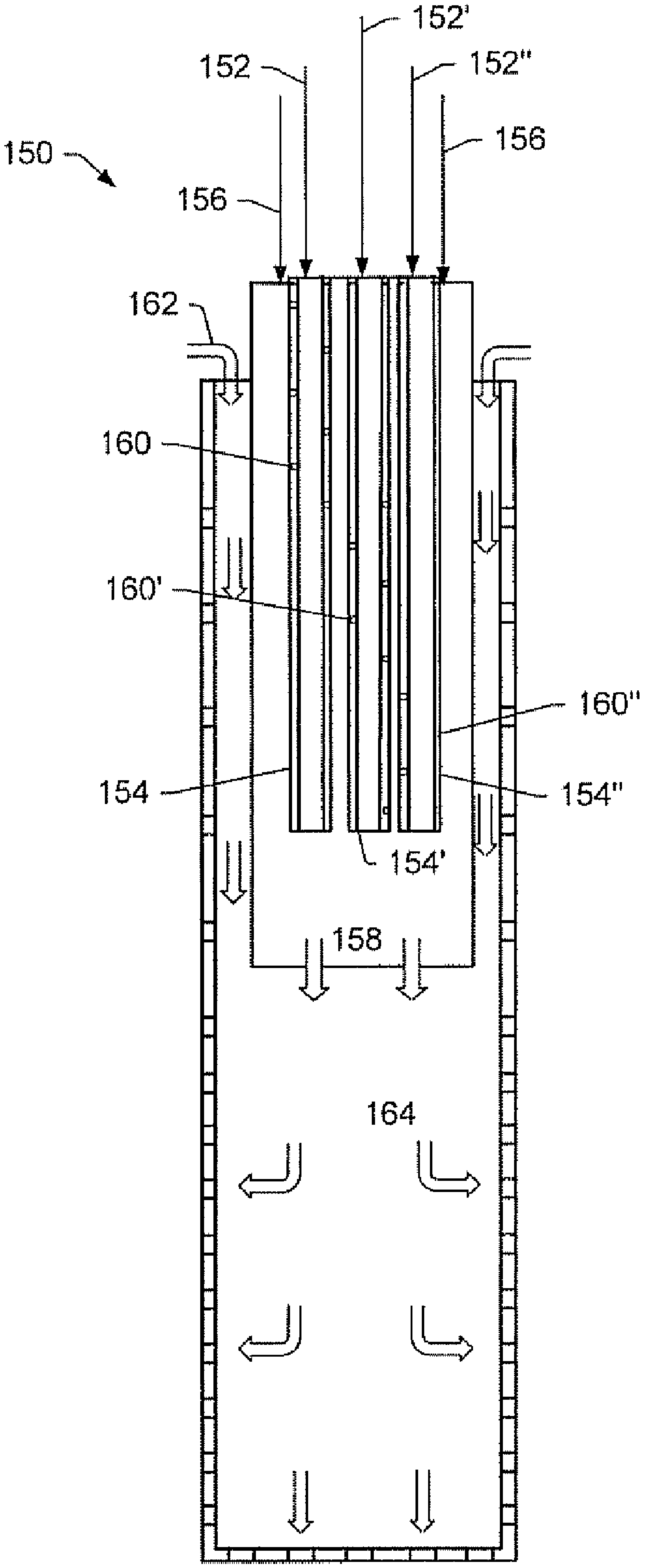

FIG. 5

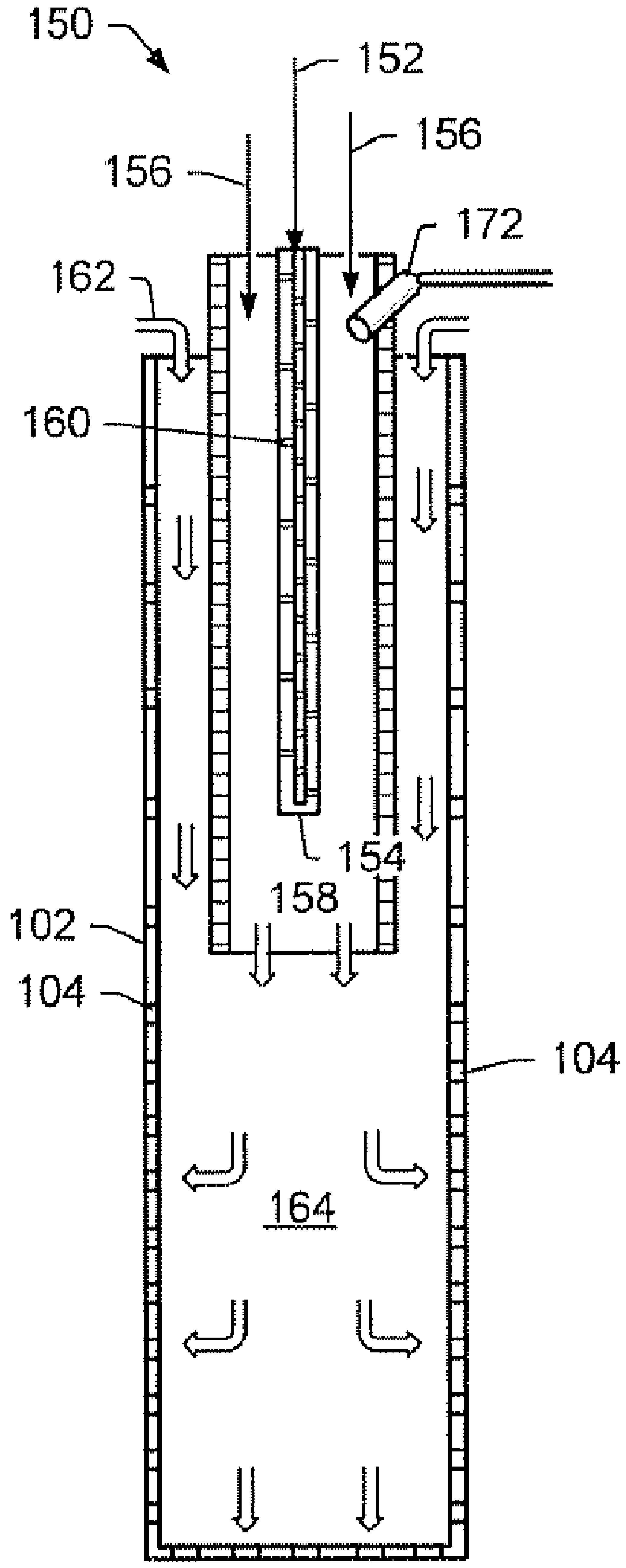
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FIG. 6

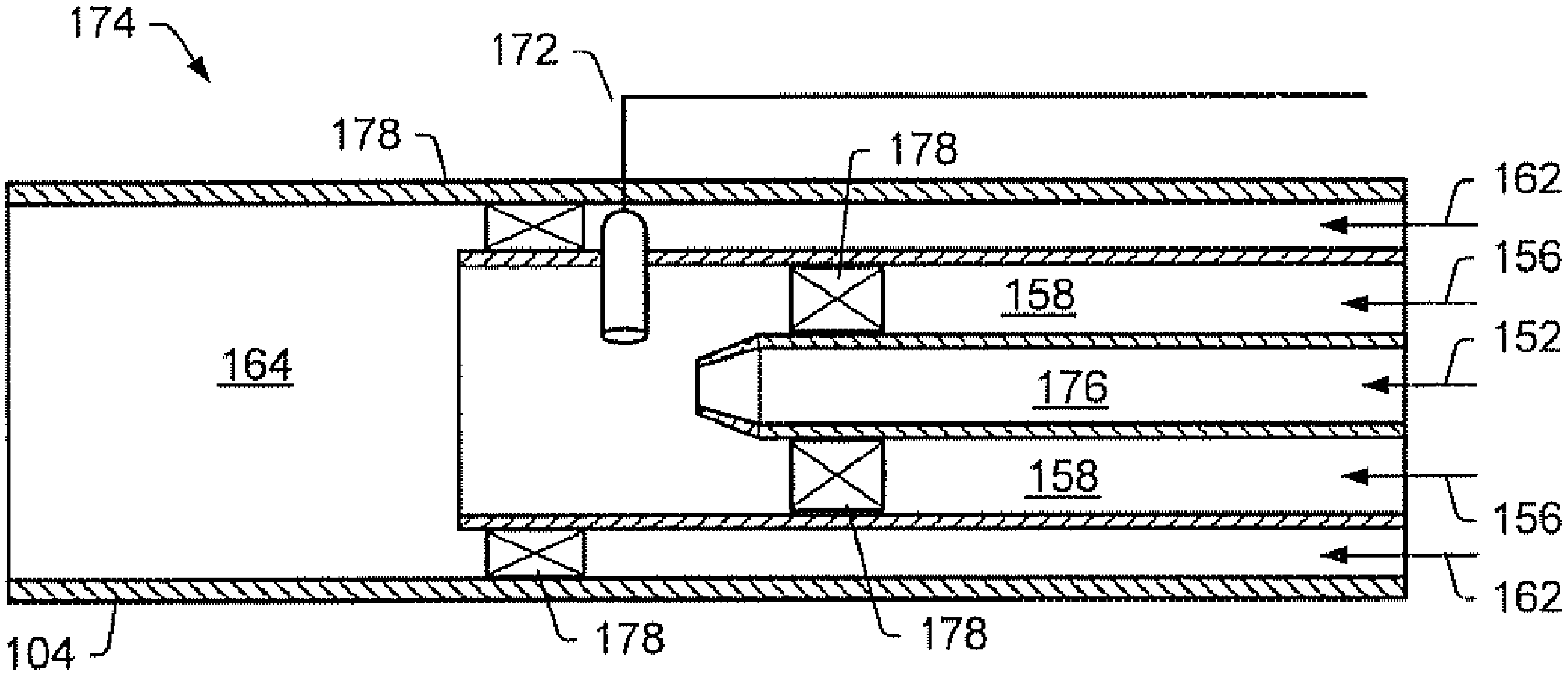
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FIG. 7

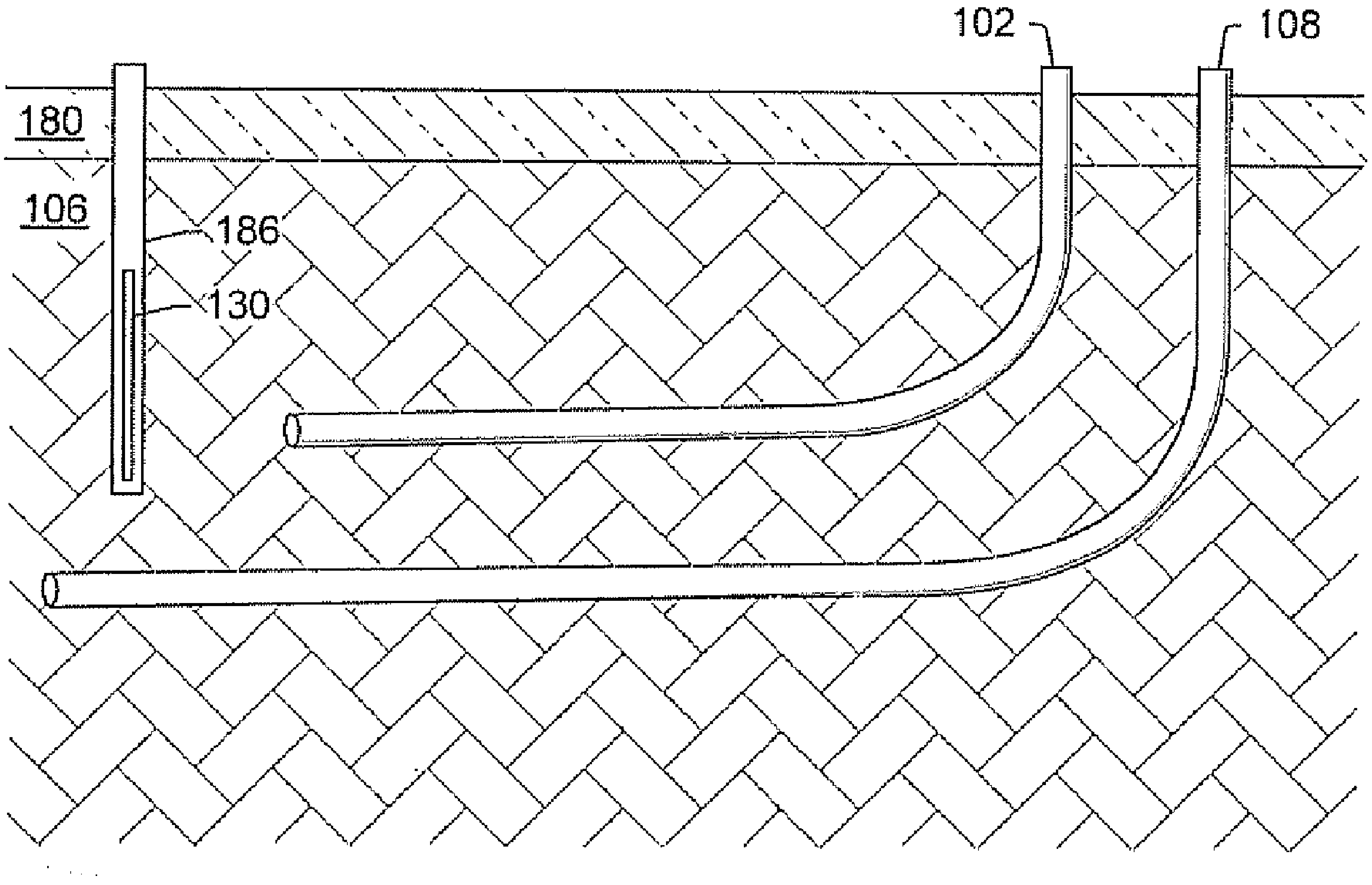

FIG. 8

METHODS FOR GENERATION OF SUBSURFACE HEAT FOR TREATMENT OF A HYDROCARBON CONTAINING FORMATION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Application Ser. No. 61/046,172 filed Apr. 18, 2008, which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to methods of treating of a hydrocarbon containing formation.

DESCRIPTION OF RELATED ART

[0003] Hydrocarbons obtained from subterranean formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources.

[0004] Hydrocarbon formations may be treated in various ways to produce formation fluids. For example, application of heat, gases, and/or liquids to hydrocarbon formations to mobilize and/or produce formation fluids has been used to more efficiently recover hydrocarbons from hydrocarbon formations. Hydrocarbon formations containing heavy hydrocarbons—for example, tar sands or oil shale formations—may be heated using heat treatment methods to more efficiently recover hydrocarbons from the heavy hydrocarbon containing formations. Such processes include in situ heat treatment systems, combustion fronts, and drive processes. Typically used hydrocarbon recovery drive processes include, but are not limited to, cyclic steam injection, steam assisted gravity drainage (SAGD), solvent injection, vapor solvent and SAGD, and carbon dioxide injection.

[0005] Heaters have been used in hydrocarbon recovery drive processes to create high permeability zones (or injection zones) in hydrocarbon formations. Heaters may be used to create a mobilization geometry or production network in the hydrocarbon formation to allow fluids to flow through the formation during the drive process. For example, heaters may be used: to create drainage paths between the injection wells and production wells for the drive process; to preheat the hydrocarbon formation to mobilize fluids in the formation so that fluids and/or gases may be injected into the formation; and to provide heat to the fluids and/or gases used in the drive process within the hydrocarbon formation. Often, the amount of heat provided by such heaters is small relative to the amount of heat input from the drive process.

[0006] Combustion of fossil fuel has been used to heat a formation, for example, by direct injection of hot fossil fuel combustion gases in the formation, by combustion of fossil fuels in the formation (e.g. in a combustion front), by heat transfer from the hot fossil fuel combustion gases to another heat transfer agent such as steam, or by use in heaters located in the hydrocarbon formation. Combustion of fossil fuels to heat a formation may take place in the formation, in a well, and/or near the surface. Combustion of fossil fuel generates carbon dioxide, an undesirable greenhouse gas, as a combustion by-product.

[0007] Combustion of sulfur compounds has also been used to heat a hydrocarbon formation, where the sulfur containing combustion products may act as a drive fluid for the more efficient production of hydrocarbons from the hydrocarbon formation. U.S. Pat. No. 4,379,489 to Rollmann describes a method for recovery of heavy oil from a subterranean reservoir that includes burning liquid sulfur in an oxygen-containing gas underground to form sulfur dioxide. The sulfur dioxide may act as a drive fluid for the recovery of oil or it may react with limestone in the formation to form carbon dioxide, an alternate drive fluid. The pressure of the oxygen-containing gas is maintained at a pressure sufficient to keep the sulfur dioxide in the liquid state.

[0008] An efficient, cost effective method for treating a hydrocarbon formation to more efficiently recover hydrocarbons from the hydrocarbon formation without the production of large quantities of carbon dioxide is desirable.

SUMMARY OF THE INVENTION

[0009] The present invention is directed to a method of treating a hydrocarbon formation comprising providing steam to at least a portion of a hydrocarbon containing formation from a plurality of substantially horizontal steam injection wells; combusting at least a portion of a mixture comprising hydrogen sulfide and an oxidant in one or more flameless distributed combustors positioned in one or more substantially vertical wellbores to generate heat, wherein at least one of the substantially vertical wellbores is within ten meters of an end of at least one of the substantially horizontal steam injection wells; transferring at least a portion of the generated heat to a portion of the hydrocarbon containing formation located between at least one of the substantially horizontal steam injection wells and at least one of the substantially vertical heater wells; and mobilizing at least a portion of formation fluids in the heated portion of the hydrocarbon containing formation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Further advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description of the preferred embodiments and upon reference to the accompanying drawings in which:

[0011] FIG. **1** depicts a representation of a steam drive process.

[0012] FIG. **2** depicts a schematic representation of an embodiment of treatment of formation fluids produced from a hydrocarbon formation.

[0013] FIG. **3** depicts a cross-sectional representation of a portion of an embodiment of a hydrogen sulfide fueled flameless distributed combustor positioned in a vertical wellbore.

[0014] FIG. **4** depicts a cross-sectional representation of a portion of an embodiment of a hydrogen sulfide fueled flameless distributed combustor with two fuel conduits.

[0015] FIG. **5** depicts a cross-sectional representation of a portion of an embodiment of a hydrogen sulfide fueled flameless distributed combustor with three fuel conduits.

[0016] FIG. **6** depicts a cross-sectional representation of a portion of an embodiment of a hydrogen sulfide fueled flameless distributed combustor with an ignition source positioned in a vertical wellbore.

[0017] FIG. **7** depicts a cross-sectional representation of a portion of an embodiment of a hydrogen sulfide fueled burner positioned in a horizontal wellbore.

[0018] FIG. **8** depicts a representation of an embodiment for producing hydrocarbons using a vertical hydrogen sulfide fueled heater in combination with a horizontal steam injection well.

[0019] While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings. The drawings may not be to scale. It should be understood, however, that the drawings are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE INVENTION

[0020] The present invention is directed to providing subsurface heat to a hydrocarbon formation where the heat is generated by 1) combusting at least a portion of a mixture comprising hydrogen sulfide and an oxidant in one or more flameless distributed combustors positioned in one or more substantially vertical wellbores; and 2) providing steam in one or more substantially horizontal steam injection wells. The heat provided to the hydrocarbon formation mobilizes at least a portion of formation fluids in the heated portion of the hydrocarbon containing formation. Since the fuel stream is sulfur based, production of carbon dioxide is avoided upon combustion of the sulfide components of the fuel stream, reducing the overall production of carbon dioxide of the heating process relative to processes that utilize a fuel stream comprised mostly of hydrocarbons.

[0021] The process of the present invention provides heat efficiently to the hydrocarbon formation since heat from combustion of a fuel stream comprising hydrogen sulfide and heat from steam are provided to the hydrocarbon formation. The heat provided to the hydrocarbon formation from the combustion of the fuel stream comprising hydrogen sulfide may enhance the mobilization of formation fluids by the steam injection due to the relative positioning of the vertical wellbores from which the heat of combustion is provided relative to the steam injection wellbores. The substantially horizontal steam injection wells and the substantially vertical wellbores are positioned to provide heat generated by the combustion of the mixture of hydrogen sulfide and oxidant to the hydrocarbon formation at a portion of the hydrocarbon containing formation located between at least one of the substantially horizontal steam injection wells and at least one of the substantially vertical wellbores. The heat provided to the heated portion of the hydrocarbon formation mobilizes the formation fluids in the heated portion of the hydrocarbon formation, and may increase the amount of formation fluids recovered and produced from the hydrocarbon formation from a production well.

[0022] The process of oxidizing hydrogen sulfide through a combustion process to a produce sulfuric acid may have a heat value similar to methane combustion. For example, using data from "The Chemical Thermodynamics of Organic Compounds" by Stull et al.; Kreiger Publishing Company, Malabar Fla., 1987, pp. 220, 229, 230, 233 and 234, the enthalpies of reaction for the combustion of methane and hydrogen sulfide can be calculated. Combustion of methane produces carbon dioxide as a by-product, as shown by the following reaction:

$$CH_4+2O_2\rightarrow CO_2+2H_2O\ (\Delta H_{rxn}=-191.2\text{ kcal/mol at }600^\circ\text{ K.}).$$

In contrast, oxidation (combustion) of hydrogen sulfide to form sulfuric acid has a calculated reaction enthalpy as shown in the following reaction:

$$H_2S+2O_2\rightarrow H_2SO_4\ (\Delta H_{rxn}=-185.4\text{ kcal/mol at }600^\circ\text{ K.}).$$

More heat may be generated upon mixing the sulfuric acid in water by the heat of solution of sulfuric acid in water as shown below:

$$H_2SO_4+H_2O\rightarrow 50\text{ wt \% }H_2SO_4\ (\Delta H_{dil}=-14.2\text{ kcal/mol at }298^\circ\text{ K.}).$$

[0023] The total amount of heat content produced from the combustion of hydrogen sulfide and the dissolution of the sulfuric acid may range from −185 kcal/mol to −206 kcal/mol depending on the amount of water used to produce the sulfuric acid. Combustion of hydrogen sulfide as a fuel instead of methane in accordance with the process of the present invention, therefore, provides heat to a hydrocarbon formation in an amount comparable to the combustion of methane while producing no carbon dioxide. Furthermore, the use of fuels containing hydrogen sulfide in the process of the present invention provides a method to dispose of waste hydrogen sulfide from other processes (for example, sour gas and/or hydrotreating effluent streams) without creating elemental sulfur.

[0024] Terms used herein are defined as follows.

[0025] "API gravity" refers to API gravity at 15.5° C. (60° F.). API gravity is as determined by ASTM Method D6822 or ASTM Method D1298.

[0026] "ASTM" refers to American Standard Testing and Materials.

[0027] A "formation" includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. "Hydrocarbon layers" refer to layers in the formation that contain hydrocarbons. The hydrocarbon layers may contain non-hydrocarbon material and hydrocarbon material. The "overburden" and/or the "underburden" include one or more different types of hydrocarbon impermeable materials. In some cases, the overburden and/or the underburden may be somewhat permeable to hydrocarbon materials.

[0028] "Formation fluids" refer to fluids present in a formation and may include pyrolysis fluid, synthesis gas, mobilized hydrocarbons, and water (steam). Formation fluids may include hydrocarbon fluids as well as non-hydrocarbon fluids. The term "mobilized fluid" refers to fluids in a hydrocarbon containing formation that are able to flow as a result of treatment of the formation. "Produced fluids" refer to fluids removed from the formation.

[0029] A "heater" is any system or heat source for generating heat in a well or a near wellbore region. Heaters may be, but are not limited to, electric heaters, burners, combustors that react with material in or produced from a formation, and/or combinations thereof. "Flameless distributed combustor" refers to a substantially flameless heater where an oxidant stream and a fuel stream are mixed together over at least a portion of the distributed length of the heater at or above an auto-ignition temperature of the mixture.

[0030] "Heavy hydrocarbons" are viscous hydrocarbon fluids. Heavy hydrocarbons may include highly viscous hydrocarbon fluids such as heavy oil, tar, and/or asphalt. Heavy hydrocarbons may include carbon and hydrogen, as well as smaller concentrations of compounds containing sulfur, oxygen, and nitrogen. Additional elements (for example, nickel, iron, vanadium, or mixtures thereof) may also be present in heavy hydrocarbons. Heavy hydrocarbons may be classified by API gravity. Heavy hydrocarbons generally have an API gravity below about 20. Heavy oil, for example, generally has an API gravity of about 10-20, whereas tar generally has an API gravity below about 10. The viscosity of heavy hydrocarbons is generally at least 100 centipoise at 15° C. Heavy hydrocarbons may include aromatics or other complex ring hydrocarbons.

[0031] "Hydrocarbons" are generally defined as molecules formed primarily by carbon and hydrogen atoms.

[0032] Hydrocarbons as used herein may also include metallic elements and/or other compounds that contain, but are not limited to, halogens, nitrogen, oxygen, and/or sulfur. Hydrocarbon compounds that contain sulfur are referred to as "organosulfur compounds." Hydrocarbons may be, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. "Hydrocarbon fluids" are fluids that include hydrocarbons. Hydrocarbon fluids may include, entrain, or be entrained in non-hydrocarbon fluids such as hydrogen, nitrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, sulfur oxides, carbonyl sulfide, nitrogen oxide, water, ammonia, or mixtures thereof.

[0033] "Oxidant" refers to compounds suitable to support combustion. Examples of oxidants include air, oxygen, and/or enriched air. "Enriched air" refers to air having a larger mole fraction of oxygen than air in the atmosphere. Air is typically enriched to increase combustion-supporting ability of the air.

[0034] "SAGD" is steam assisted gravity drainage.

[0035] "Tar" is a viscous hydrocarbon that generally has a viscosity greater than about 10,000 centipoise at 15° C. The specific gravity of tar generally is greater than 1.000. Tar may have an API gravity less than 10°.

[0036] "Tar sands formation" refers to a formation in which hydrocarbons are predominantly present in the form of heavy hydrocarbons and/or tar entrained in a mineral grain framework or other host lithology (for example, sand or carbonate). Examples of tar sands formations include formations such as the Athabasca formation, the Grosmont formation, and the Peace River formation, all three in Alberta, Canada; and the Faja formation in the Orinoco belt in Venezuela.

[0037] "Water" refers to the liquid and vapor phases of water. For example, water, steam, super-heated steam.

[0038] In the process of the present invention, steam is provided to at least a portion of a hydrocarbon formation. The hydrocarbon formation includes hydrocarbon material and may include non-hydrocarbon materials, where the hydrocarbon materials may be recovered from the hydrocarbon formation. The hydrocarbon formation may include an overburden and an underburden that are impermeable or only slightly permeable to hydrocarbons.

[0039] Steam is provided to the hydrocarbon formation to enable an increased amount of hydrocarbon materials to be recovered from the hydrocarbon formation. The steam provided to the hydrocarbon formation may heat the hydrocarbon formation and thereby mobilize formation fluids including hydrocarbon materials, where the mobilized formation fluids may be recovered and produced from the hydrocarbon formation by a production well. The steam may also displace formation fluids in the hydrocarbon formation and drive the formation fluids to a production well so the formation fluids may be recovered and produced from the production well.

[0040] In an embodiment of the process of the invention, the steam may be provided to the hydrocarbon formation in a drive process to treat a hydrocarbon formation. Such drive processes include, but are not limited to cyclic steam injection, SAGD, solvent injection, or a vapor solvent and SAGD process. The process of the invention may also be used to preheat a hydrocarbon formation for a drive process, or may be used to provide heat during or after a drive process.

[0041] FIG. **1** depicts a representation of a steam drive process in which the process of the present invention may be utilized. Steam **100** enters injection well **102**. Injection well **102** may include openings **104** to allow steam **100** to flow and/or be pressurized into hydrocarbon layer **106**. Steam **100** provides heat to formation fluids in the hydrocarbon layer **106**. Heating the formation fluids may mobilize the formation fluids to promote drainage of the formation fluids towards production well **108** positioned below injection well **102**. Formation fluid **110** is produced from production well **108** and transported to one or more processing facilities.

[0042] The steam is provided to the hydrocarbon formation from a plurality—at least two—of substantially horizontal steam injection wells. The steam injection wells are preferably located in a position relative to one or more production wells such that formation fluids mobilized and/or driven by injection of the steam in the steam injection wells are mobilized and/or driven towards the production well so that the formation fluids may be recovered and produced by the production well. Most preferably, the steam injection wells are located in a position relative to the one or more production wells and the one or more substantially vertical wellbores in which the mixture comprising hydrogen sulfide and an oxidant are combusted to optimize the amount of formation fluids recovered from the hydrocarbon formation. As used herein, a "substantially horizontal" well or wellbore refers to a well or wellbore that has an inclination of 30° or less, or 15° or less, or 10° or less in the hydrocarbon formation at or near, for example within 20 meters, of one or more of the substantially vertical wells or wellbores, and preferably at the terminus of the substantially horizontal well or wellbore. A substantially horizontal well or wellbore may have portions of the well or wellbore that have an inclination of greater than 30° C., and may approach or be vertical. For example, a substantially horizontal well or wellbore may have a substantially vertical portion at or near the surface of a hydrocarbon formation, but has a portion that is substantially horizontal within the hydrocarbon formation near a substantially vertical wellbore in which the mixture comprising hydrogen sulfide and an oxidant are combusted.

[0043] The steam provided to the hydrocarbon containing formation preferably has a temperature greater than the temperature of the hydrocarbon containing formation to which the steam is provided. The steam may be provided to the hydrocarbon containing formation through the substantially horizontal injection wells at a temperature of from 100° C. to 500° C., or from 110° C. to 290° C., and at pressures ranging from 1 MPa to 15 MPa.

[0044] Water or steam may be heated prior to being provided to the hydrocarbon formation through the steam injection wells. The water/steam may be heated at the surface of the hydrocarbon formation prior to provided to the steam injection wells for injection into the hydrocarbon formation, and/or it may be heated subsurface in one or more wellbores by one or more heaters provided in the one or more wellbores.

[0045] The water/steam may be heated at the surface of the hydrocarbon formation by transferring heat from combustion of a fuel stream and an oxidant with the water/steam. The fuel stream may be a hydrocarbon containing fuel, for example, natural gas, and/or the fuel stream may be a fuel stream comprising hydrogen sulfide. The oxidant may be air, compressed air, oxygen-enriched air, or oxygen gas. The fuel stream and the oxidant may be combusted in a conventional combustor reactor, and the heat of combustion may be transferred to the water/steam by heat exchange between the combustion by-product gases and the water/steam.

[0046] The water/steam may be heated in the one or more wellbores subsurface prior to being provided to the hydrocarbon formation. One or more heaters may be provided within the one or more wellbores for heating the water/steam in the one or more wellbores prior to providing the steam to the hydrocarbon formation. Subsurface heating of the water/steam permits efficient transmission of heat from the steam to the hydrocarbon formation by enabling the steam to be heated near the point at which the steam is provided to the hydrocarbon formation. In an embodiment, a fuel stream and an oxidant stream are combusted in the one or more heaters in the one or more steam injection wellbores and the heat of combustion is transferred to the water/steam in the wellbore prior to providing the steam to the hydrocarbon formation. The fuel stream may be a hydrocarbon containing fuel, for example, natural gas, and/or the fuel stream may comprise hydrogen sulfide. The oxidant may be air, compressed air, oxygen-enriched air, and/or oxygen gas. The heaters for providing heat to the water/steam in the wellbore(s) may be flameless distributed combustors or burners.

[0047] In some embodiments, one or more heaters may be positioned in an inner portion of a wellbore of one or more substantially horizontal steam injection wells, and the steam may flow through an outer portion of the wellbore in position so that heat may be transferred from the heater to the steam. The heater may be positioned in an inner conduit coupled to an outer conduit. The two conduits may be placed in the wellbore. The conduits may be side by side. It should be understood that any number and/or configuration contemplated configuration of conduits may be used as contemplated or desired.

[0048] Fuel may be provided to one or more fuel conduits in the one or more heaters in the one or more substantially horizontal steam injection wells. The fuel stream for the heaters and an oxidant may be provided to one or more fuel conduits in at least one of the heaters for combustion in the heaters. The fuel conduits may be arranged such that at least a portion of the fuel is introduced to an upstream portion of at least one of the heaters and at least a portion of the fuel stream is introduced to a downstream portion of at least one of the heaters. The fuel may be provided to one or more fuel conduits in at least one of the heaters, where at least one of the conduits is adjustable such that at least a portion of the fuel is delivered to a first portion of the heater and then to a second portion of the heater downstream of the first portion.

[0049] The steam is provided to the hydrocarbon formation from the plurality of substantially horizontal steam injection wells. The steam may be provided to the hydrocarbon formation under pressure so that the steam is injected into the hydrocarbon formation. The injected steam may mobilize formation fluids by driving the formation fluids. Preferably the steam provided to the hydrocarbon formation is provided to the hydrocarbon formation at a temperature higher than the temperature of the hydrocarbon formation so that heat may be transferred from the steam to the hydrocarbon formation. Heat provided from the steam to the hydrocarbon formation may mobilize formation fluids in the hydrocarbon formation.

[0050] Providing the steam to the hydrocarbon formation through the plurality of substantially horizontal steam injection wells into the hydrocarbon containing formation may move or drive the formation fluids to a production well. The steam may contact the formation fluids and mix with a portion of the formation fluids, solvate a portion of the formation fluids and/or dissolve a portion of the hydrocarbons. Contacting of the steam with the formation fluids may lower the viscosity the formation fluids and promote movement of the formation fluids towards one or more production wells.

[0051] In the process of the present invention, a mixture comprising hydrogen sulfide and an oxidant is combusted in one or more flameless distributed combustors positioned in one or more substantially vertical wellbores to generate heat. One or more of the substantially vertical wellbores is/are positioned within ten meters of an end of at least one of the substantially horizontal steam injection wells. Most preferably, the substantially vertical wellbores in which the mixture is combusted are located in position relative to the one or more production wells and the one or more substantially horizontal steam injection wells to optimize the amount of formation fluids recovered from the hydrocarbon formation. As used herein, a "substantially vertical" well or wellbore refers to a well or wellbore that has an inclination of 60° or more, or 75° or more, or 80° or more in the hydrocarbon formation at or near, for example within 20 meters or within 10 meters, of one or more of the end of one or more substantially horizontal steam injection wells or wellbores. A substantially vertical well or wellbore may have portions of the well or wellbore that have an inclination of less than 60° C., and may approach or be horizontal in some portions of the well or wellbore.

[0052] The hydrogen sulfide used in the process of the present invention may be provided in a fuel stream including from 1% to 100%, from 3% to 90%, from 10% to 80%, or from 20% to 50% of hydrogen sulfide by volume, or may include at least 10%, or at least 30%, or at least 40%, or at least 50%, or at least 60%, or at least 70% hydrogen sulfide by volume. Hydrogen sulfide content in a stream may be measured using ASTM Method D2420. The fuel stream comprising hydrogen sulfide may include hydrocarbons (for example, methane, and ethane), hydrogen, carbon dioxide, or mixtures thereof. In some embodiments, the fuel may include organosulfur compounds. Examples of organosulfur compounds include, but are not limited to, methyl thiol, thiophene, thiophene compounds, carbon disulfide, carbonyl sulfide, or mixtures thereof. The use of fuels containing hydrogen sulfide and/or organosulfur compounds may allow from 0.3 moles to 1 mole of methane to be conserved per mole of atomic sulfur in the fuel.

[0053] A fuel stream comprising hydrogen sulfide may produced from a hydrocarbon containing formation. FIG. **2** depicts a schematic representation of treatment of formation fluids produced from a hydrocarbon formation. Produced formation fluid **110** enters fluid separation unit **112** and is separated into liquid stream **114**, gas stream **116**, and aqueous stream **118**. Produced formation fluid **110** may obtained from a hydrocarbon formation that is primarily a gas reservoir or from a hydrocarbon formation that is primarily a liquid hydrocarbon reservoir. Liquid stream **114** may be transported to other processing units and/or storage units. Gas stream **116** may include, but is not limited to, hydrocarbons, carbonyl sulfide, hydrogen sulfide, sulfur oxides, organosulfur compounds, hydrogen, carbon dioxide, or mixtures thereof. Gas stream **116** may enter gas separation unit **120** to separate at least a portion of a gas hydrocarbon stream **122**, at least a portion of a hydrogen sulfide stream **124**, at least a portion of a carbon dioxide stream **126**, at least a portion of a sulfur dioxide stream **128**, and at least a portion of a hydrogen stream **130** from the gas stream **116**.

[0054] One or more streams containing hydrogen sulfide from a variety of sources, including the gas stream **116** from the hydrocarbon formation, may be combined and sent to a gas separation unit to produce the fuel stream comprising hydrogen sulfide utilized in the process of the present invention. For example, streams from gas reservoirs, liquid hydrocarbon reservoirs, and/or streams from surface facilities may be combined as a feedstream for the gas separation unit from which a hydrogen sulfide enriched gas may be separated. The resulting hydrogen sulfide stream **124** may be stored and/or combined with one or more hydrogen sulfide streams produced from other gas separation units and/or other processing facilities to form a fuel stream comprising hydrogen sulfide for use in the process of the present invention.

[0055] Gas separation units **120** useful for forming the fuel stream comprising hydrogen sulfide utilized in the process of the present invention may include physical treatment systems and/or chemical treatment systems. Physical treatment systems include, but are not limited to, a membrane unit, a pressure swing adsorption unit, a liquid absorption unit, and/or a cryogenic unit. Chemical treatment systems may include units that use amines (for example, diethanolamine or diisopropanolamine), zinc oxide, sulfolane, water, or mixtures thereof in the treatment process. In some embodiments, gas separation unit **120** uses a Sulfinol gas treatment process for removal of sulfur compounds. Carbon dioxide may be removed using Catacarb® (Catacarb, Overland Park, Kans., U.S.A.) and/or Benfield (UOP, Des Plaines, Ill., U.S.A.) gas treatment processes. The gas separation unit may be a rectified adsorption and high pressure fractionation unit.

[0056] The fuel stream comprising hydrogen sulfide may be dried to remove moisture to improve the combustibility of the fuel stream. For example, the fuel stream comprising hydrogen sulfide may be dried by contacting the hydrogen sulfide stream with ethylene glycol to remove water.

[0057] In the process of the present invention, the oxidant in the mixture comprising hydrogen sulfide and an oxidant is an oxygen-containing gas or liquid. The oxidant is preferably selected from compressed air, oxygen-enriched air, or oxygen gas. Compressed air may be provided as the oxidant in the process of the invention by compressing air by conventional air compressing processes, for example, air may be compressed by passing the air through a turbine compressor. Oxygen-enriched air, which may contain from 0.5 vol. % to 15 vol. % more oxygen than air, may be produced by compressing air and passing the compressed air through a membrane that reduces the amount of nitrogen in the air. Oxygen gas may be provided as the oxidant by conventional air separation technology.

[0058] In some embodiments, the ratio of hydrogen sulfide to oxidant in the mixture combusted in the substantially vertical wellbores is selected and controlled during the combustion process and the combustion by-product gases are injected from the substantially vertical wellbores into the hydrocarbon formation. By selecting the amount of hydrogen sulfide relative to the amount of oxidant present—on the basis of atomic sulfur to atomic oxygen ratio or on a stoichiometric basis—and adjusting the amount of hydrogen sulfide to the selected amount, the amount of hydrogen sulfide in the combustion and the composition of the combustion by-products produced (for example, sulfur dioxide and/or sulfur trioxide) may be controlled. The amount of the fuel stream comprising hydrogen sulfide may be controlled and/or the amount the oxidant stream may be controlled to produce a mixture containing selected ratio of hydrogen sulfide to oxidant for combustion such that a preferred combustion by-product stream composition is produced.

[0059] The amounts of a fuel stream comprising hydrogen sulfide and an oxidant stream provided to produce a mixture for combustion in the process of the present invention may be selected in a manner such that combustion of the mixture generates substantially sulfur trioxide in the combustion by-product stream. To produce a sulfur trioxide-rich combustion by-product stream, the ratio of hydrogen sulfide to oxidant may be selected so that excess oxidant is present in the mixture for combustion relative to the hydrogen sulfide content of the mixture. Combusting a hydrogen sulfide lean mixture produces more sulfur trioxide than sulfur dioxide as a combustion by-product. The sulfur trioxide may react with water in the hydrocarbon formation to form sulfuric acid. Sulfur trioxide is readily converted to sulfuric acid, thus heat of solution may be produced and delivered to the hydrocarbon formation more rapidly than when hydrogen sulfide is combusted at a stoichiometric amount or deficient amount relative to the amount of oxidant.

[0060] Alternatively, the amounts of the fuel stream comprising hydrogen sulfide and the oxidant in the mixture for combustion may be selected in a manner such that combustion of the mixture generates substantially sulfur dioxide in the combustion by-product stream. To produce a sulfur dioxide-rich combustion by-product stream, the ratio of hydrogen sulfide to oxidant in the mixture may be selected so that a deficient amount of oxidant is present in the mixture relative to the hydrogen sulfide content of the mixture. Using an excess of hydrogen sulfide relative to oxidant in the mixture for combustion produces a combustion by-products stream rich in sulfur dioxide that also contains hydrogen sulfide, and allows hydrogen sulfide and/or sulfur dioxide to be introduced into the hydrocarbon containing formation. A portion of the hydrogen sulfide and/or sulfur dioxide may contact at least a portion of the formation fluids and solvate and/or dissolve a portion of the heavy hydrocarbons in the formation fluids. Solvation and/or dissolution of at least a portion the heavy hydrocarbons may facilitate movement of the heavy hydrocarbons towards the production well. Furthermore, introduction of at least a portion of the combustion by-product stream comprising sulfur dioxide into the formation fluids may increase a shear rate applied to hydrocarbon fluids in the formation and decrease the viscosity of non-Newtonian hydrocarbon fluids within the formation. The introduction of the sulfur dioxide rich combustion by-products stream into the formation may thereby increase a portion of the formation available for production, and may increase a ratio of energy output of the formation (energy content of products produced from the formation) to energy input into the formation (energy costs for treating the formation).

[0061] In a further alternative, the amounts of hydrogen sulfide and the oxidant in the mixture provided for combustion may be selected to provide stoichometrically equivalent amounts of hydrogen sulfide and the oxidant. Combustion of a stoichiometric amount of hydrogen sulfide with oxygen may generate predominately sulfur dioxide and water as the combustion by-products as shown in the following reaction:

$$H_2S+1.5O_2 \rightarrow SO_2+H_2O \ (\Delta H_{rxn}=-124 \text{ kcal/mol at } 600^\circ \text{ K.}).$$

[0062] In addition to the heat value that is obtained from combustion of hydrogen sulfide, the introduction of heated sulfur dioxide/water combustion by-product stream into the hydrocarbon formation may facilitate recovery of hydrocarbons from the formation. The heat from the sulfur dioxide may transfer heat to fluids in the formation and the heated fluids may flow towards production wells. Furthermore, as discussed above, the sulfur dioxide in the combustion by-product stream may reduce the viscosity of hydrocarbon formation fluids in the hydrocarbon formation and thereby increase the amount of hydrocarbons available to be recovered from the formation. The heat of solution of sulfur dioxide, although less than the heat of solution of sulfuric acid, may also be transferred to the formation fluids of the hydrocarbon formation thereby mobilizing the formation fluids.

[0063] The combustion of the mixture comprising hydrogen sulfide and the oxidant is effected in one or more heaters positioned in one or more of the substantially vertical wellbores to generate heat. The heaters include at least one flameless distributed combustor, and may also include burners.

[0064] In a preferred embodiment, each heater is a flameless distributed combustor in which the mixture comprising hydrogen sulfide and the oxidant is flamelessly combusted. In a flameless distributed combustor, the oxidant is provided to the combustor as an oxidant stream at a velocity that is sufficiently elevated to prevent the formation of a fixed diffusion flame upon combustion of the mixture of the oxidant and the hydrogen sulfide in the heater, thereby ensuring a controlled heat release along the length of the flameless distributed combustor.

[0065] In operating a flameless distributed combustor heater to combust the mixture comprising hydrogen sulfide and the oxidant stream, the hydrogen sulfide, preferably provided in a gas stream, and the oxidant are mixed, where the mixture of the hydrogen sulfide and the oxidant is heated to a temperature at or above the auto-ignition temperature of the mixture, typically from 250° C. to 800° C., or from 300° C. to 750° C., or from 400° C. to 700° C. (where the auto-ignition temperature of a fuel stream of pure hydrogen sulfide is 260° C.)

[0066] Prior to mixing the oxidant stream and the fuel stream comprising hydrogen sulfide in the heater, the oxidant stream, the fuel stream, or both may be pre-heated to a temperature sufficient to bring the mixture to a temperature at or above the auto-ignition temperature of the mixture upon mixing. The oxidant stream and/or the fuel stream comprising hydrogen sulfide may be pre-heated by heat exchange with a heat source, for example, steam or superheated steam. Alternatively, the fuel stream comprising hydrogen sulfide and the oxidant stream may be mixed and ignited using an ignition device—such as a spark plug or a glow plug—that facilitates raising the temperature of the mixture to at or above the auto-ignition temperature of the mixture.

[0067] The heaters may also include one or more burners that produce a flame. In operating a burner, the fuel stream comprising hydrogen sulfide and the oxidant stream are provided to the burner for combustion. The fuel stream and the oxidant stream may be mixed in the burner or may be mixed prior to being provided to the burner. The mixture of the fuel stream comprising hydrogen sulfide and the oxidant stream is combusted by raising the temperature of the mixture to a temperature at or above the auto-ignition temperature of the mixture, for example, by igniting the mixture with an ignition device such as a spark plug or a glow plug. The oxidant stream and the fuel stream comprising hydrogen sulfide are provided to the burner at a velocity such that a stable flame may be produced by the burner. The burner may include flame stabilizing shields near the burner flame to assist in stabilizing the flame after ignition.

[0068] Combustion of the mixture of hydrogen sulfide and the oxidant generates heat. Heat from the combustion is transferred to a portion of the hydrocarbon containing formation located between at least one of the substantially horizontal steam injection wells and at least one of the substantially vertical heater wells. Heat from the combustion of the mixture of hydrogen sulfide and the oxidant may be directed from a substantially vertical heater well to a portion of the hydrocarbon containing formation located between the heater well and a substantially horizontal steam injection well by injecting a combustion by-product stream produced from the combustion from the heater well into the hydrocarbon formation, where the combustion by-product stream carries at least a portion of the heat of combustion from the heater well to the hydrocarbon containing formation. In an embodiment of the process of the present invention, the combustion by-product stream may be injected into the hydrocarbon containing formation from the end of the substantially vertical heater well located nearest the substantially horizontal steam injection well.

[0069] Heat may be transferred to fluids introduced into the formation, formation fluids and/or to a portion of the hydrocarbon containing formation through heat of reaction, heat of salvation, conductive heat, or convective heat. Fluids introduced into the formation and/or combustion by-products may transfer heat to at least a portion of the hydrocarbon containing formation and/or formation fluids.

[0070] Convective heat transfer may occur when non-condensable non-miscible gases such as nitrogen contact the formation fluids and/or hydrocarbon containing formation. When the oxidant stream is formed of compressed air or oxygen-enriched air, the combustion by-products may include nitrogen gas. Convective heat transfer may also occur when superheated miscible solvent vapors (for example, hydrogen sulfide, carbon dioxide, and/or sulfur dioxide vapors) contact the formation fluids and/or hydrocarbon containing formation. Convective heat transfer may also occur when superheated non-miscible solvent vapors such as water contact the formation fluids and/or hydrocarbon containing formation.

[0071] Conductive heat transfer may occur when hot liquid steam condensate contacts the formation fluids and/or hydrocarbon containing formation. Conductive heat transfer may occur when hot liquid miscible solvent (for example, hydrogen sulfide, carbon dioxide, and/or sulfur dioxide) contacts the formation fluids and/or hydrocarbon containing formation.

[0072] Heat of reaction heat transfer may occur when one compound reacts with another compound. For example, sulfur oxides form solutions with liquid water in the hydrocarbon containing formation and/or in the outer portion of the wellbore to generate a heat of reaction. Heat of reaction also occurs as oxygen reacts with hydrocarbons or sulfur compounds to form carbon oxides or sulfur oxides.

[0073] Heat of solution may occur when at least one component is dissolved in a solvent. For example, heat is generated when sulfuric acid is dissolved in water.

[0074] The heat transferred from the one or more substantially vertical heater wells to the hydrocarbon containing formation heats at least a portion of the portion of the hydrocarbon containing formation located between the substantially horizontal steam injection well and the substantially vertical heater well located within ten meters of the end of the substantially horizontal steam injection well. At least a portion of the formation fluids in the heated portion of the hydrocarbon containing formation are mobilized by the transfer of heat from the heater well(s) to the hydrocarbon formation. The mobilized formation fluids may be collected by a production well and a hydrocarbon material including formation fluids mobilized by the heat transfer or driven by the mobilized formation fluids may be produced from the hydrocarbon containing formation.

[0075] FIGS. **3** through **7** are embodiments of hydrogen sulfide fueled heaters **130** for subsurface heating. FIGS. **3** through **6** depict cross-sections of hydrogen sulfide fueled flameless distributed combustors. FIG. **7** depicts a cross-section of a hydrogen sulfide fueled burner.

[0076] FIG. **3** depicts a perspective of a portion of hydrogen sulfide fueled flameless distributed combustor **150** positioned in vertical wellbore **102**. Fuel stream **152** comprising hydrogen sulfide (for example, gas stream **116** and/or hydrogen sulfide stream **124** optionally including sulfur dioxide stream **128**, hydrogen stream **130**, and/or gas hydrocarbon stream **122** from FIG. **2**) enters central fuel conduit **154**. Oxidant stream **156** (for example, air, oxygen enriched air, oxygen gas, or mixtures thereof) enters combustion conduit **158**. In some embodiments, heat from water **162** heats fuel stream **152**, oxidant stream **156**, and/or the fuel/oxidant mixture to a temperature at or above the auto-ignition temperature necessary to cause combustion of the fuel stream mixture. In some embodiments, fuel stream **152** and/or oxidant stream **156** are heated prior to entering the fuel conduit and/or combustion conduit to a temperature at or above the auto-ignition temperature of the mixture. Oxidant stream **156** and fuel stream **152** mix, and the fuel/oxidant mixture reacts (combusts) at a temperature at or above the auto-ignition temperature of the mixture.

[0077] Central fuel conduit **154** is positioned inside of combustion conduit **158** and may extend the length of flameless distributed combustor **150**. Central fuel conduit **154** includes orifices **160** along the length of the central fuel conduit. Orifices **160** may be critical flow orifices. Orifices **160** allow heated fuel to mix with heated oxidant so that the mixture reacts (flamelessly combusts) to produces heat. In some embodiments, orifices **160** are shaped to allow a fuel to oxidant momentum ratio to range from 10 to 100, from 30 to 80, or from 50 to 70, where momentum is equal to the density of the fuel or oxidant times velocity of the fuel or oxidant squared. In some embodiments, a fuel to oxidant pressure ratio through orifices **160** ranges from 1.5 to 2.

[0078] Combustion in a downstream portion of combustion conduit **158** may transfer heat to water **162** in outer conduit **164**. In some embodiments, the water is heated to form steam and/or super heated steam. Outer conduit **164** may be the space formed between the inner wall of injection well **102** and outer wall of combustion conduit **158**. Outer conduit **164** may include openings **104** that allow the water and/or heat to enter the hydrocarbon layer adjacent to the injection well. In some embodiments, outer conduit **164** is a conduit that surrounds combustion conduit **158** and is coupled to or an integral part of flameless distributed combustor **150**. Coupling outer conduit **164** to flameless distributed combustor **150** may facilitate insertion of the flameless distributed combustor into an existing injection well.

[0079] In some embodiments, combustion of fuel in combustion conduit **158** produces a combustion by-products stream. Combustion by-products stream may heat water **162**. The combustion by-products stream may exit openings **104** and drive, heat, and/or reduce viscosity of formation fluids in the hydrocarbon containing formation. Contact of water with the combustion by-products stream in a portion of the formation at a distance from well **102** may generate heat, and heat at least a portion of the formation to allow fluids to be mobilized.

[0080] In some embodiments, a portion or portions of central fuel conduit **154** are adjustable. The ability to adjust central fuel conduit **154** allows fuel to be provided to selected portions of combustion conduit **158**. For example, positioning central fuel conduit **154** at an upstream portion of the flameless distributed combustor may facilitate the combustion process in the upstream portion of the well at a desired time. Once combustion is established, the fuel conduit may be advanced along the length of the injection well (or selected valves may be opened along the length of the injection well) to provide fuel to other combustors positioned in the well. In some embodiments, orifices **160** may be adjusted to allow flow of fuel into combustion conduit **158**. For example orifices, **160** may be connected to a computer system that opens and/or closes the orifices as required.

[0081] FIG. **4** depicts central fuel conduit **154** having inner fuel conduit **166** and outer fuel conduit **168**. Inner fuel conduit **166** may be coupled and/or removably coupled to outer fuel conduit **168**. Inner fuel conduit **166** may fit inside of outer fuel conduit **168** such that a space is formed between the two conduits. In some embodiments, the two conduits are co-axial. In some embodiments, the conduits are separate and parallel.

[0082] Hydrogen sulfide stream **124** enters inner fuel conduit **166** and flows into outer fuel conduit **168** through orifices **170**. In some embodiments, hydrogen sulfide is delivered to outer fuel conduit **168** through an opening in a downstream portion (for example, the end of fuel conduit is open) of inner fuel conduit **166**. Fuel stream **152** enters outer fuel conduit **168**. In some embodiments, a portion of inner fuel conduit **166** relative to outer fuel conduit **168** is adjustable to allow for removal of either of the conduits for maintenance purposes, and/or for selected delivery of hydrogen sulfide and/or fuel to selected portions of the flameless distributed combustor. Delivery of hydrogen sulfide as a separate stream may allow for control of the amount of hydrogen sulfide in the fuel stream provided to combustion conduit **158**. In some embodiments, outer conduit **168** is the hydrogen sulfide conduit and fuel is delivered to the formation through inner conduit **166**.

[0083] FIG. **5** depicts flameless distributed combustor **150** having more than one fuel conduit. As shown, the fuel conduits are separate and parallel to one another. In some embodiments, the conduits are co-axial. Fuel conduits **154**, **154'**, **154"** include orifices **160**, **160'**, **160"** positioned at different intervals along the fuel conduits. Positioning of the orifices **160**, **160'**, **160"** may allow for delivery of fuel to selected portions of flameless distributed combustor **150** at selected time periods. For example, fuel stream **152** may be delivered to an upstream portion of combustion conduit **158** through orifice **160**. Combustion of fuel **152** in the upstream portion of the combustion conduit **158** may provide heat to steam **162** in upstream portion of outer conduit **164**. Fuel stream **152'** enters a middle portion of combustion conduit **158** through orifices **160'**, mixes with oxidant, and then react to provide heat to steam in a middle portion of outer conduit **164**. Fuel stream **152"** delivered through orifices **160"** in fuel conduit **154"** and subsequent combustion in downstream portion of combustion conduit **158** provides heat to steam in a downstream portion of outer conduit **164**. In some embodiments, fuel streams **152**, **152'**, **152"** contain different amounts of hydrogen sulfide. In some embodiments, fuel streams **152**, **152'**, **152"** contain the same amounts of hydrogen sulfide. It should be understood that the number of fuel conduits and/or position of the orifices in the fuel conduit may be varied. In some embodiments, orifices **160**, **160'**, **160"** are adjusted (opened and/or closed) to control the flow of fuel and/or hydrogen sulfide into combustion conduit **158**.

[0084] FIG. **6** depicts a cross-section of flameless distributed combustor **150** with ignition device **172**. Ignition device **172** may raise the temperature of the fuel/oxidant mixture to combustion temperatures in combustion conduit **158**. For example, once the fuel/oxidant mixture is ignited near ignition device **172**, heat from the flame heats the fuel/oxidant mixture to an auto-ignition temperature of the fuel/oxidant mixture to facilitate the reaction of the fuel with the oxidant to produce flameless combustion and heat.

[0085] FIG. **7** depicts a perspective of hydrogen sulfide fueled burner **174**. Burner **174** may include fuel conduit **176**, combustion conduit **158**, and outer conduit **164**. Ignition device **172** may be positioned in a bottom portion of combustion conduit **158**. Fuel stream **152** (for example, gas stream **116**, hydrogen sulfide stream **124**, sulfur dioxide stream **128**, hydrogen stream **130**, and/or gas hydrocarbon stream **122** from FIG. **2**, (methane, natural gas, sour gas, or mixtures thereof) enters central fuel conduit **176**. Oxidant stream **156** (for example, air, oxygen enriched air, or mixtures thereof) enters combustion conduit **158**. In some embodiments, burner **174** may include more than one fuel conduit. For example, one conduit for hydrogen sulfide and one conduit or a fossil fuel. In some embodiments, fuel conduit **176** is combustion conduit **158** and combustion conduit is fuel conduit **176**.

[0086] In some embodiments, fuel stream **152** and/or oxidant stream **156** are heated prior to entering the fuel conduit and/or combustion conduit. In some embodiments, water **162** heats fuel stream **152** and/or oxidant stream **156**. Fuel stream **152** and oxidant stream **156** mix in combustion conduit **158**. Ignition device **172** provides a spark to combust the fuel/oxidant mixture to produce a flame.

[0087] In some embodiments, burner includes one or more nozzles **178**. The fuel and oxidant may be mixed by flowing at least a portion of the fuel and at least a portion of the oxidant through nozzles **178**. Nozzles **178** may enhance mixing in combustion conduit **158** and/or outer conduit **164**. Geometry of nozzles **178** (for example, converging-diverging section dimensions, length, diameter, and/or flare angle) may be adjusted based on firing rate, fuel stream composition, and/or oxidant stream composition. A nozzle flare angle may range from 1 degree to 10 degrees, from 2 degrees to 9 degrees, or from 3 degrees to 8 degrees in the flow direction. In some embodiments, nozzles **178** are shaped to allow concentric flow or counter-concentric flow (swirling of the mixture). The nozzle swirl angle may range from 10 degrees to 40 degrees, from 15 degrees to 35 degrees, or from 20 degrees to 30 degrees. In some embodiments, the nozzle swirl angle is 30 degrees. In some embodiments, burner **174** does not include nozzles **178**.

[0088] In some embodiments, a downstream portion of fuel conduit **176** may be tapered. The taper angle may range from 5 to 30 degrees, from 10 degrees to 25 degrees, or from 15 degrees to 20 degrees.

[0089] Combustion of the fuel/oxidant mixture in combustion conduit **158** of burner **174** may transfer heat to water **162** in outer conduit **164**. In some embodiments, the water is heated to form steam and/or super heated steam. Outer conduit **164** may be the space formed between the inner wall of injection well **102** and outer wall of combustion conduit **158**. Outer conduit **164** may include openings **104** that allow the water and/or heat to enter the hydrocarbon layer adjacent to the injection well. In some embodiments, outer conduit **164** is a conduit that surrounds combustion conduit **158** and is coupled to or an integral part of burner **174**. Coupling outer conduit **164** to burner **174** may facilitate insertion of the burner into an existing injection well. In some embodiments, the outer conduit is the fuel conduit and water is delivered through the inner conduit.

[0090] In some embodiments, combustion of the fuel/oxidant mixture in combustion conduit **158** of burner **174** produces the combustion by-products stream. Combustion by-products stream may heat water **162**. The combustion by-products stream may exit openings **104** and drive, heat, and/or reduce viscosity of formation fluids in the hydrocarbon containing formation. Contact of water with the combustion by-products stream in a portion of the formation at a distance from well **102** may generate heat and heat at least a portion of the formation to allow fluids to be mobilized.

[0091] Heaters **130** (for example, flameless distributed combustors and burners described in FIGS. **3**-**7**) may be manufactured from materials suitable for downhole combustion processes. In some embodiments, water present in the fuel and/or hydrogen sulfide streams interacts with hydrogen sulfide to form a sulfide layer on metal surfaces of the conduit walls. Formation of the sulfide layer may inhibit further corrosion of the metal surfaces of the conduit walls by carbonic acid and/or other acids. The formation of the sulfide layer may allow outer conduit **164**, central fuel conduit **154**, and combustion conduit **158** to be fabricated from carbon steel or other alloys. For example, alloy 230, alloy 800H, alloy 370H or Hastelloy C276 may be used to manufacture portions of heaters **130**. In some embodiments, inner fuel conduit **166** (shown in FIG. **4**) is manufactured from materials resistant to high temperature and/or high concentrations of hydrogen sulfide.

[0092] In some embodiments, a start-up mixture of hydrocarbon fuel containing a minimal amount of hydrogen sulfide or a less than a stoichiometric amount of hydrogen sulfide relative to the amount of oxidant is introduced into fuel conduit **154** of heaters **130** (for example, flameless distributed combustor **150** and/or burner **174**). In some embodiments, a start up fuel stream includes at most 1%, at most 0.5%, at most 0.01% by volume of hydrogen sulfide. In some embodiments, the start-up fuel includes hydrogen and/or oxygenated ethers such as dimethyl ether to lower the ignition temperature. Once combustion has been initiated, the hydrogen sulfide concentration in fuel stream **152** may be increased.

[0093] In some embodiments, a mixture containing a low amount of hydrogen sulfide relative to oxidant is not necessary for start-up and/or for sustaining combustion. For example, the fuel stream may include from 0.1% to 100%, from 3% to 90%, from 10% to 80%, or from 20% to 50% of hydrogen sulfide by volume. In some embodiments, the fuel has a sulfur content of at least 0.01 grams, at least 0.1 grams, at least 0.5 grams or at least 0.9 grams of atomic sulfur per gram of fuel as determined by ASTM Method D4294.

[0094] FIG. **8** depicts a representation of a system for producing hydrocarbons using a substantially vertical hydrogen sulfide fueled heater in combination with a substantially horizontal or inclined steam injection well. Vertical heater well **186** may be positioned proximate the downstream portion of horizontal steam injection well **102**. For example, vertical heater well **186** may be positioned from 1 to 10 meters from the end of horizontal injection well **102**. Production well **108** extends past injection well **102** and below heater well **186**. Vertical heater well **186** includes hydrogen sulfide fueled heaters **130** described herein. Heat generated from heater well **186** through oxidation of hydrogen sulfide in heaters **130** may mobilize hydrocarbons towards production well **108**. Heat transfer produced from hydrogen sulfide fueled heater well **186**, in combination with heat and stream drive from steam injection well **102**, may allow more hydrocarbons to be produced from production well **108** as compared to conventional drive processes using horizontal injection wells.

[0095] Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as examples of embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims.

What is claimed is:

1. A method of treating a hydrocarbon containing formation, comprising:

providing steam to at least a portion of a hydrocarbon containing formation from a plurality of substantially horizontal steam injection wells;

combusting at least a portion of a mixture comprising hydrogen sulfide and oxidant in one or more flameless distributed combustors positioned in one or more substantially vertical wellbores to generate heat, wherein at least one of the substantially vertical wellbores is within ten meters of an end of at least one of the substantially horizontal steam injection wells;

transferring at least a portion of the generated heat to a portion of the hydrocarbon containing formation located between at least one of the substantially horizontal steam injection wells and at least one of the substantially vertical heater wells; and

mobilizing at least a portion of formation fluids in the heated portion of the hydrocarbon containing formation.

2. The method of claim **1**, further comprising producing formation fluids from a volume between at least one of the substantially vertical heater wells and at least one of the substantially horizontal steam injection wells.

3. The method of claim **1**, wherein the steam transfers heat to at least a portion of the hydrocarbon containing formation.

4. The method of claim **1**, wherein at least a portion of the steam drives at least a portion of the formation fluids towards one or more production wells.

5. The method of claim **1**, wherein combustion produces combustion by-products, and further comprising the step of transferring at least a portion of the combustion by-products into the formation such that at least a portion of the combustion by-products provide a driving force for mobilization of at least a portion of the formation fluids.

6. The method of claim **5**, wherein at least a portion of the steam provides a driving force for mobilization of at least a portion of the formation fluids.

7. The method of claim **1**, wherein combustion produces combustion by-products comprising sulfur oxides, further comprising the step of mixing at least a portion of the combustion by-products with water in the hydrocarbon formation to generate a heat of solution generating a heat of solution.

8. The method of claim **1**, wherein combustion produces combustion by-products comprising sulfur dioxide, further comprising the step of mixing at least a portion of the combustion by-products with at least a portion of formation fluids to form a mixture, and mobilizing at least a portion of the mixture.

9. The method of claim **1**, wherein combustion produces a combustion by-products stream and the method further comprising the steps of transferring at least a portion of the generated heat to a least a portion formation fluids in the hydrocarbon containing formation; solvating at least a portion of the heated formation fluids with at least a portion of the combustion by-products stream; and mobilizing at least a portion of heated and solvated formation fluids.

10. The method of claim **1**, wherein combusting at least a portion of the mixture comprises selecting a ratio of hydrogen sulfide to the oxidant for combustion such that during combustion a selected amount of hydrogen sulfide, sulfur trioxide, sulfur dioxide, or mixtures thereof is formed.

11. The method of claim **10**, wherein combusting at least a portion of the mixture comprises selecting a ratio of hydrogen sulfide to the oxidant for combustion such that combustion generates substantially sulfur trioxide.

12. The method of claim **10** wherein combusting at least a portion of the mixture comprises selecting a ratio of hydrogen sulfide to the oxidant for combustion such that combustion generates substantially sulfur dioxide and hydrogen sulfide.

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