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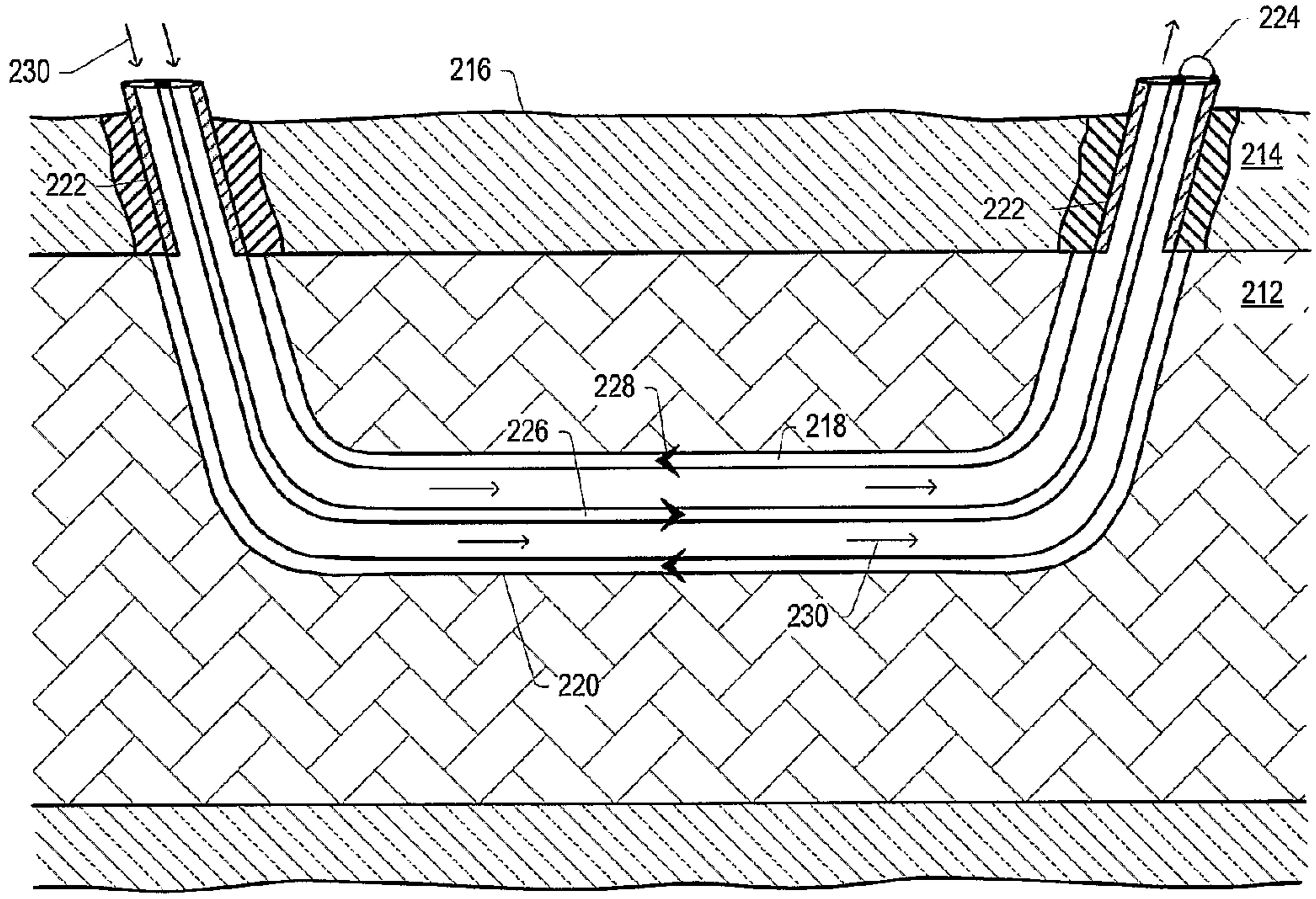

(57) Abrégé/Abstract:
A system for heating a hydrocarbon containing formation includes a conduit located in an opening in the formation. An electrical conductor is positioned inside the conduit. The electrical conductor forms a heater which is electrically isolated from the formation thereby reducing electrical losses to the formation and is electrically coupled to the conduit at or near an end portion of the conduit so that the electrical conductor and the conduit are electrically coupled in series. Electrical current flows in the electrical conductor in a substantially opposite direction to electrical current flow in the conduit during application of electrical current to the system. The flow of electrons is substantially confined to the inside of the conduit by the electromagnetic field generated from electrical current flow in the electrical conductor so that the outside surface of the conduit is at or near substantially zero potential at 25 0C. The conduit is configured to generate heat and heat the formation during application of electrical current to the system.

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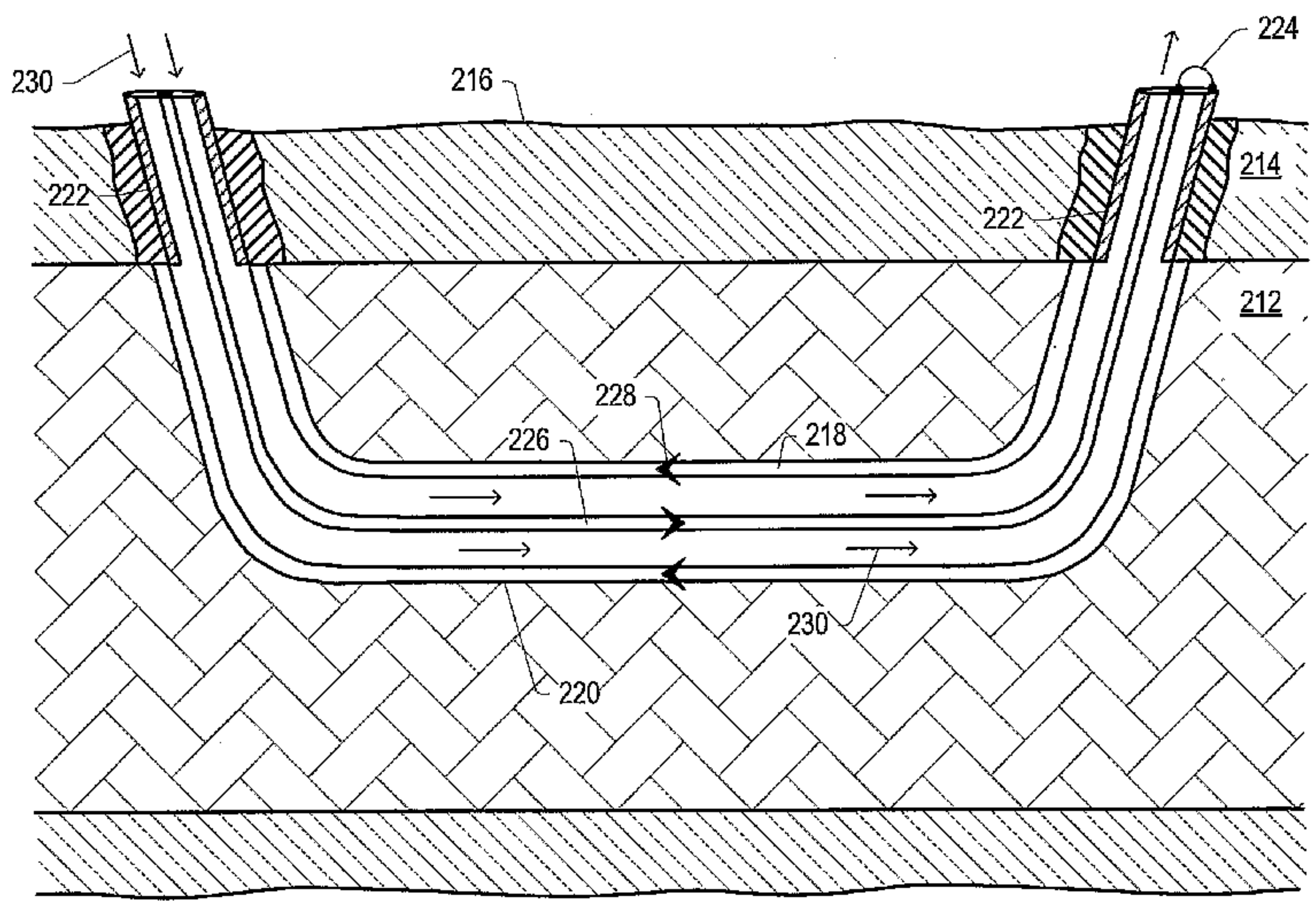
(54) **Title:** TEMPERATURE LIMITED HEATER WITH A CONDUIT SUBSTANTIALLY ELECTRICALLY ISOLATED FROM THE FORMATION



(57) **Abstract:** A system for heating a hydrocarbon containing formation includes a conduit located in an opening in the formation. An electrical conductor is positioned inside the conduit. The electrical conductor forms a heater which is electrically isolated from the formation thereby reducing electrical losses to the formation and is electrically coupled to the conduit at or near an end portion of the conduit so that the electrical conductor and the conduit are electrically coupled in series. Electrical current flows in the electrical conductor in a substantially opposite direction to electrical current flow in the conduit during application of electrical current to the system. The flow of electrons is substantially confined to the inside of the conduit by the electromagnetic field generated from electrical current flow in the electrical conductor so that the outside surface of the conduit is at or near substantially zero potential at 25 0C. The conduit is configured to generate heat and heat the formation during application of electrical current to the system.

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TEMPERATURE LIMITED HEATER WITH A CONDUIT SUBSTANTIALLY ELECTRICALLY ISOLATED FROM THE FORMATION

BACKGROUND

1. Field of the Invention

The present invention relates generally to methods and systems for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. In particular, certain embodiments relate to heating a selected portion or portions of the formation using temperature limited heaters with conduits that are electrically isolated from the formation.

2. Description of Related Art

Hydrocarbons obtained from subterranean formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources and concerns over declining overall quality of produced hydrocarbons have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources. In situ processes may be used to remove hydrocarbon materials from subterranean formations. Chemical and/or physical properties of hydrocarbon material in a subterranean formation may need to be changed to allow hydrocarbon material to be more easily removed from the subterranean formation. The chemical and physical changes may include in situ reactions that produce removable fluids, composition changes, solubility changes, density changes, phase changes, and/or viscosity changes of the hydrocarbon material in the formation. A fluid may be, but is not limited to, a gas, a liquid, an emulsion, a slurry, and/or a stream of solid particles that has flow characteristics similar to liquid flow.

Heaters may be placed in wellbores to heat a formation during an in situ process. Examples of in situ processes utilizing downhole heaters are illustrated in U.S. Patent Nos. 2,634,961 to Ljungstrom; 2,732,195 to Ljungstrom; 2,780,450 to Ljungstrom; 2,789,805 to Ljungstrom; 2,923,535 to Ljungstrom; and 4,886,118 to Van Meurs et al.

Application of heat to oil shale formations is described in U.S. Patent Nos. 2,923,535 to Ljungstrom and 4,886,118 to Van Meurs et al. Heat may be applied to the oil shale formation to pyrolyze kerogen in the oil shale formation. The heat may also fracture the formation to increase permeability of the formation. The increased permeability may allow formation fluid to travel to a production well where the fluid is removed from the oil shale formation. In some processes disclosed by Ljungstrom, for example, an oxygen containing gaseous medium is introduced to a permeable stratum, preferably while still hot from a preheating step, to initiate combustion.

A heat source may be used to heat a subterranean formation. Electric heaters may be used to heat the subterranean formation by radiation and/or conduction. An electric heater may resistively heat an element. U.S. Patent No. 2,548,360 to Germain describes an electric heating element placed in a viscous oil in a wellbore. The heater element heats and thins the oil to allow the oil to be pumped from the wellbore. U.S. Patent No. 4,716,960 to Eastlund et al. describes electrically heating tubing of a petroleum well by passing a relatively low voltage current through the tubing to prevent formation of solids. U.S. Patent No. 5,065,818 to Van Egmond describes an electric heating element that is cemented into a well borehole without a casing surrounding the heating element.

U.S. Patent No. 6,023,554 to Vinegar et al. describes an electric heating element that is positioned in a casing. The heating element generates radiant energy that heats the casing. A granular solid fill material may be placed between the casing and the formation. The casing may conductively heat the fill material, which in turn conductively heats the formation.

Some formations may have thin hydrocarbon layers or thin rich layers in a thick hydrocarbon layer. It may be advantageous to use heaters that are electrically isolated from the formation for heating and/or treating these types of formations. Electrically isolating the heater from the formation reduces electrical losses to the formation and increases heating efficiency in the heater. Electrically isolating the heater may also provide for safer operation of the heater. The heaters may be substantially u-shaped wellbores that reduce the number of openings on the surface of the formation. Reducing the number of openings may be desirable to reduce capital costs and/or reduce the impact of drilling openings in the formation (for example, the environmental impact and/or surface topography modifications).

SUMMARY

Embodiments described herein generally relate to systems, methods, and heaters for treating a subsurface formation. Embodiments described herein also generally relate to heaters that have novel components therein. Such heaters can be obtained by using the systems and methods described herein.

In certain embodiments, the invention provides one or more systems, methods, and/or heaters. In some embodiments, the systems, methods, and/or heaters are used for treating a subsurface formation.

In certain embodiments, the invention provides a system for heating a hydrocarbon containing formation, comprising: a conduit located in an opening in the formation, the conduit comprising ferromagnetic material; an electrical conductor positioned inside the conduit, and electrically coupled to the conduit at or near an end portion of the conduit so that the electrical conductor and the conduit are electrically coupled in series and electrical current flows in the electrical conductor in a substantially opposite direction to electrical current flow in the conduit during application of electrical current to the system; wherein, during application of electrical current to the system, the flow of electrons is substantially confined to the inside of the conduit by the electromagnetic field generated from electrical current flow in the electrical conductor so that the outside surface of the conduit is at or near substantially zero potential at 25 °C; and the conduit is configured to generate heat and heat the formation during application of electrical current to the system.

In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments.

In further embodiments, treating a subsurface formation is performed using any of the methods, systems, or heaters described herein.

In further embodiments, additional features may be added to the specific embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 depicts an illustration of stages of heating a hydrocarbon containing formation.

FIG. 2 shows a schematic view of an embodiment of a portion of an in situ heat treatment system for treating a hydrocarbon containing formation.

FIG. 3 depicts an embodiment of a substantially u-shaped heater that electrically isolates itself from the formation.

FIG. 4 depicts an embodiment of a single-ended, substantially horizontal heater that electrically isolates itself from the formation.

FIG. 5 depicts an embodiment of a single-ended, substantially horizontal heater that electrically isolates itself from the formation using an insulated conductor as the center conductor.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and may herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto 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

The following description generally relates to systems and methods for treating hydrocarbons in the formations. Such formations may be treated to yield hydrocarbon products, hydrogen, and other products.

"Hydrocarbons" are generally defined as molecules formed primarily by carbon and hydrogen atoms. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. 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, water, and ammonia.

A "formation" includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. The "overburden" and/or the "underburden" include one or more different types of impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ heat treatment processes, the overburden and/or the underburden may include a hydrocarbon containing layer or hydrocarbon containing layers that are relatively impermeable and are not subjected to temperatures during in situ heat treatment processing that result in significant characteristic changes of the hydrocarbon containing layers of the overburden and/or the underburden. For example, the underburden may contain shale or mudstone, but the underburden is not allowed to heat to pyrolysis temperatures during the in situ heat treatment process. In some cases, the overburden and/or the underburden may be somewhat permeable.

"Formation fluids" and refer to fluids present in a formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbon, 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 thermal treatment of the formation. "Produced fluids" refer to formation fluids removed from the formation.

A "heat source" is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and/or a conductor disposed in a conduit. A heat source may also include systems that generate heat by burning a fuel external to or in a formation. The systems may be surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In some embodiments, heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer medium that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. Thus, for example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (for example, chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (for example, an oxidation reaction). A heat source may also include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

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.

An "in situ heat treatment process" refers to a process of heating a hydrocarbon containing formation with heat sources to raise the temperature of at least a portion of the formation above a mobilization, or visbreaking, or pyrolysis temperature so that mobilized fluids, visbroken fluids, or pyrolyzation fluids are produced in the formation.

"Insulated conductor" refers to any elongated material that is able to conduct electricity and that is covered, in whole or in part, by an electrically insulating material.

An elongated member may be a bare metal heater or an exposed metal heater. "Bare metal" and "exposed metal" refer to metals that do not include a layer of electrical insulation, such as mineral insulation, that is designed to provide electrical insulation for the metal throughout an operating temperature range of the elongated member. Bare metal and exposed metal may encompass a metal that includes a corrosion inhibiter such as a naturally occurring oxidation layer, an applied oxidation layer, and/or a film. Bare metal and exposed metal include metals with polymeric or other types of electrical insulation that cannot retain electrical insulating properties at typical operating temperature of the elongated member. Such material may be placed on the metal and may be thermally degraded during use of the heater.

"Temperature limited heater" generally refers to a heater that regulates heat output (for example, reduces heat output) above a specified temperature without the use of external controls such as temperature controllers, power regulators, rectifiers, or other devices. Temperature limited heaters may be AC (alternating current) or modulated (for example, "chopped") DC (direct current) powered electrical resistance heaters.

"Curie temperature" is the temperature above which a ferromagnetic material loses all of its ferromagnetic properties. In addition to losing all of its ferromagnetic properties above the Curie temperature, the ferromagnetic material begins to lose its ferromagnetic properties when an increasing electrical current is passed through the ferromagnetic material.

"Time-varying current" refers to electrical current that produces skin effect electricity flow in a ferromagnetic conductor and has a magnitude that varies with time. Time-varying current includes both alternating current (AC) and modulated direct current (DC).

"Alternating current (AC)" refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

"Modulated direct current (DC)" refers to any substantially non-sinusoidal time-varying current that produces skin effect electricity flow in a ferromagnetic conductor.

"Turndown ratio" for the temperature limited heater is the ratio of the highest AC or modulated DC resistance below the Curie temperature to the lowest resistance above the Curie temperature for a given current.

In the context of reduced heat output heating systems, apparatus, and methods, the term "automatically" means such systems, apparatus, and methods function in a certain way without the use of external control (for example, external controllers such as a controller with a temperature sensor and a feedback loop, PID controller, or predictive controller).

The term "wellbore" refers to a hole in a formation made by drilling or insertion of a conduit into the formation. A wellbore may have a substantially circular cross section, or another cross-sectional shape. As used herein, the terms "well" and "opening," when referring to an opening in the formation may be used interchangeably with the term "wellbore."

A "u-shaped wellbore" refers to a wellbore that extends from a first opening in the formation, through at least a portion of the formation, and out through a second opening in the formation. In this context, the wellbore may be only roughly in the shape of a "v" or "u", with the understanding that the "legs" of the "u" do not need to be parallel to each other, or perpendicular to the "bottom" of the "u" for the wellbore to be considered "u-shaped".

"Pyrolysis" is the breaking of chemical bonds due to the application of heat. For example, pyrolysis may include transforming a compound into one or more other substances by heat alone. Heat may be transferred to a section of the formation to cause pyrolysis. In some formations, portions of the formation and/or other materials in the formation may promote pyrolysis through catalytic activity.

"Pyrolyzation fluids" or "pyrolysis products" refers to fluid produced substantially during pyrolysis of hydrocarbons. Fluid produced by pyrolysis reactions may mix with other fluids in a formation. The mixture would be considered pyrolyzation fluid or pyrolyzation product. As used herein, "pyrolysis zone" refers to a volume of a formation (for example, a relatively permeable formation such as a tar sands formation) that is reacted or reacting to form a pyrolyzation fluid.

Hydrocarbons in formations may be treated in various ways to produce many different products. In certain embodiments, hydrocarbons in formations are treated in stages. FIG. 1 depicts an illustration of stages of heating the hydrocarbon containing formation. FIG. 1 also depicts an example of yield ("Y") in barrels of oil equivalent per ton (y axis) of formation fluids from the formation versus temperature ("T") of the heated formation in degrees Celsius (x axis).

Desorption of methane and vaporization of water occurs during stage 1 heating. Heating of the formation through stage 1 may be performed as quickly as possible. For example, when the hydrocarbon containing formation is initially heated, hydrocarbons in the formation desorb adsorbed methane. The desorbed methane may be produced from the formation. If the hydrocarbon containing formation is heated further, water in the hydrocarbon containing formation is vaporized. Water may occupy, in some hydrocarbon containing formations, between 10% and 50% of the pore volume in the formation. In other formations, water occupies larger or smaller portions of the pore volume. Water typically is vaporized in a formation between 160 °C and 285 °C at pressures of 600 kPa absolute to 7000 kPa absolute. In some embodiments, the vaporized water produces wettability changes in the formation and/or increased formation pressure. The wettability changes and/or increased pressure may affect pyrolysis reactions or other reactions in the formation. In certain embodiments, the vaporized water is produced from the formation. In other embodiments, the vaporized water is used for steam extraction and/or distillation in the formation or outside the formation. Removing the water from and increasing the pore volume in the formation increases the storage space for hydrocarbons in the pore volume.

In certain embodiments, after stage 1 heating, the formation is heated further, such that a temperature in the formation reaches (at least) an initial pyrolyzation temperature (such as a temperature at the lower end of the temperature range shown as stage 2). Hydrocarbons in the formation may be pyrolyzed throughout stage 2. A pyrolysis temperature range varies depending on the types of hydrocarbons in the formation. The pyrolysis temperature range may include temperatures between 250 °C and 900 °C. The pyrolysis temperature range for producing desired products may extend through only a portion of the total pyrolysis temperature range. In some embodiments, the pyrolysis temperature range for producing desired products may include temperatures between 250 °C and 400 °C or temperatures between 270 °C and 350 °C. If a temperature of hydrocarbons in the formation is slowly raised through the temperature range from 250 °C to 400 °C, production of pyrolysis products may be substantially complete when the temperature approaches 400 °C. Average temperature of the hydrocarbons may be raised at a rate of less than 5 °C per day, less than 2 °C per day, less than 1 °C per day, or less than 0.5 °C per day through the pyrolysis temperature range for producing desired products. Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that slowly raise the temperature of hydrocarbons in the formation through the pyrolysis temperature range.

The rate of temperature increase through the pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may inhibit mobilization of large chain molecules in the formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may limit reactions between mobilized hydrocarbons that produce undesired products. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

In some in situ heat treatment embodiments, a portion of the formation is heated to a desired temperature instead of slowly heating the temperature through a temperature range. In some embodiments, the desired temperature is 300 °C, 325 °C, or 350 °C. Other temperatures may be selected as the desired temperature. Superposition of heat from heat sources allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heat sources may be adjusted to maintain the temperature in the formation substantially at the desired temperature. The heated portion of the formation is maintained substantially at the desired temperature until pyrolysis declines such that production of desired formation fluids from the formation becomes uneconomical. Parts of the formation that are subjected to pyrolysis may include regions brought into a pyrolysis temperature range by heat transfer from only one heat source.

In certain embodiments, formation fluids including pyrolyzation fluids are produced from the formation. As the temperature of the formation increases, the amount of condensable hydrocarbons in the produced formation fluid may decrease. At high temperatures, the formation may produce mostly methane and/or hydrogen. If the hydrocarbon containing formation is heated throughout an entire pyrolysis range, the formation may produce only small amounts of hydrogen towards an upper limit of the pyrolysis range. After all of the available hydrogen is depleted, a minimal amount of fluid production from the formation will typically occur.

After pyrolysis of hydrocarbons, a large amount of carbon and some hydrogen may still be present in the formation. A significant portion of carbon remaining in the formation can be produced from the formation in the form of synthesis gas. Synthesis gas generation may take place during stage 3 heating depicted in FIG. 1. Stage 3 may include heating a hydrocarbon containing formation to a temperature sufficient to allow synthesis gas generation. For example, synthesis gas may be produced in a temperature range from about 400 °C to about 1200 °C, about 500 °C to about 1100 °C, or about 550 °C to about 1000 °C. The temperature of the heated portion of the formation when the synthesis gas generating fluid is introduced to the formation determines the composition of synthesis gas produced in the formation. The generated synthesis gas may be removed from the formation through a production well or production wells.

Total energy content of fluids produced from the hydrocarbon containing formation may stay relatively constant throughout pyrolysis and synthesis gas generation. During pyrolysis at relatively low formation temperatures, a significant portion of the produced fluid may be condensable hydrocarbons that have a high energy content. At higher pyrolysis temperatures, however, less of the formation fluid may include condensable hydrocarbons. More non-condensable formation fluids may be produced from the formation. Energy content per unit volume of the produced fluid may decline slightly during generation of predominantly non-condensable formation fluids. During synthesis gas generation, energy content per unit volume of produced synthesis gas declines significantly compared to energy content of pyrolyzation fluid. The volume of the produced synthesis gas, however, will in many instances increase substantially, thereby compensating for the decreased energy content.

FIG. 2 depicts a schematic view of an embodiment of a portion of the in situ heat treatment system for treating the hydrocarbon containing formation. The in situ heat treatment system may include barrier wells 200. Barrier wells are used to form a barrier around a treatment area. The barrier inhibits fluid flow into and/or out of the treatment area. Barrier wells include, but are not limited to, dewatering wells, vacuum wells, capture wells, injection wells, grout wells, freeze wells, or combinations thereof. In some embodiments, barrier wells 200 are dewatering wells. Dewatering wells may remove liquid water and/or inhibit liquid water from entering a portion of the formation to be heated, or to the formation being heated. In the embodiment depicted in FIG. 2, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells typically encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

Heat sources 202 are placed in at least a portion of the formation. Heat sources 202 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 202 may also include other types of heaters. Heat sources 202 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 202 through supply lines 204. Supply lines 204 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 204 for heat sources may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated in the formation.

Production wells 206 are used to remove formation fluid from the formation. In some embodiments, production well 206 includes a heat source. The heat source in the production well may heat one or more portions of the formation at or near the production well. In some in situ heat treatment process embodiments, the amount of heat supplied to the formation from the production well per meter of the production well is less than the amount of heat applied to the formation from a heat source that heats the formation per meter of the heat source. Heat applied to the formation from the production well may increase formation permeability adjacent to the production well by vaporizing and removing liquid phase fluid adjacent to the production well and/or by increasing the permeability of the formation adjacent to the production well by formation of macro and/or micro fractures.

Formation fluid produced from production wells 206 may be transported through collection piping 208 to treatment facilities 210. Formation fluids may also be produced from heat sources 202. For example, fluid may be produced from heat sources 202 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 202 may be transported through tubing or piping to collection piping 208 or the produced fluid may be transported through tubing or piping directly to treatment facilities 210. Treatment facilities 210 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids. The treatment facilities may form transportation fuel from at least a portion of the hydrocarbons produced from the formation. In some embodiments, the transportation fuel may be jet fuel, such as JP-8.

Temperature limited heaters may be in configurations and/or may include materials that provide automatic temperature limiting properties for the heater at certain temperatures. In certain embodiments, ferromagnetic materials are used in temperature limited heaters. Ferromagnetic material may self-limit temperature at or near the Curie temperature of the material to provide a reduced amount of heat at or near the Curie temperature when a time-varying current is applied to the material. In certain embodiments, the ferromagnetic material self-limits temperature of the temperature limited heater at a selected temperature that is approximately the Curie temperature. In certain embodiments, the selected temperature is within 35 °C, within 25 °C, within 20 °C, or within 10 °C of the Curie temperature. In certain embodiments, ferromagnetic materials are coupled with other materials (for example, highly conductive materials, high strength materials, corrosion resistant materials, or combinations thereof) to provide various electrical and/or mechanical properties. Some parts of the temperature limited heater may have a lower resistance (caused by different geometries and/or by using different ferromagnetic and/or non-ferromagnetic materials) than other parts of the temperature limited heater. Having parts of the temperature limited heater with various materials and/or dimensions allows for tailoring the desired heat output from each part of the heater.

Temperature limited heaters may be more reliable than other heaters. Temperature limited heaters may be less apt to break down or fail due to hot spots in the formation. In some embodiments, temperature limited heaters allow for substantially uniform heating of the formation. In some embodiments, temperature limited heaters are able to heat the formation more efficiently by operating at a higher average heat output along the entire length of the heater. The temperature limited heater operates at the higher average heat output along the entire length of the heater because power to the heater does not have to be reduced to the entire heater, as is the case with typical constant wattage heaters, if a temperature along any point of the heater exceeds, or is to exceed, a maximum operating temperature of the heater. Heat output from portions of a temperature limited heater approaching a Curie temperature of the heater automatically reduces without controlled adjustment of the time-varying current applied to the heater. The heat output automatically reduces due to changes in electrical properties (for example, electrical resistance) of portions of the temperature limited heater. Thus, more power is supplied by the temperature limited heater during a greater portion of a heating process.

In certain embodiments, the system including temperature limited heaters initially provides a first heat output and then provides a reduced (second heat output) heat output, near, at, or above the Curie temperature of an electrically resistive portion of the heater when the temperature limited heater is energized by a time-varying current. The first heat output is the heat output at temperatures below which the temperature limited heater begins to self-limit. In some embodiments, the first heat output is the heat output at a temperature 50 °C, 75 °C, 100 °C, or 125 °C below the Curie temperature of the ferromagnetic material in the temperature limited heater.

The temperature limited heater may be energized by time-varying current (alternating current or modulated direct current) supplied at the wellhead. The wellhead may include a power source and other components (for example, modulation components, transformers, and/or capacitors) used in supplying power to the temperature limited heater. The temperature limited heater may be one of many heaters used to heat a portion of the formation.

In certain embodiments, the temperature limited heater includes a conductor that operates as a skin effect or proximity effect heater when time-varying current is applied to the conductor. The skin effect limits the depth of current penetration into the interior of the conductor. For ferromagnetic materials, the skin effect is dominated by the magnetic permeability of the conductor. The relative magnetic permeability of ferromagnetic materials is typically between 10 and 1000 (for example, the relative magnetic permeability of ferromagnetic materials is typically at least 10 and may be at least 50, 100, 500, 1000 or greater). As the temperature of the ferromagnetic material is raised above the Curie temperature and/or as the applied electrical current is increased, the magnetic permeability of the ferromagnetic material decreases substantially and the skin depth expands rapidly (for example, the skin depth expands as the inverse square root of the magnetic permeability). The reduction in magnetic permeability results in a decrease in the AC or modulated DC resistance of the conductor near, at, or above the Curie temperature and/or as the applied electrical current is increased. When the temperature limited heater is powered by a substantially constant current source, portions of the heater that approach, reach, or are above the Curie temperature may have reduced heat dissipation. Sections of the temperature limited heater that are not at or near the Curie temperature may be dominated by skin effect heating that allows the heater to have high heat dissipation due to a higher resistive load.

An advantage of using the temperature limited heater to heat hydrocarbons in the formation is that the conductor is chosen to have a Curie temperature in a desired range of temperature operation. Operation within the desired operating temperature range allows substantial heat injection into the formation while maintaining the temperature of the temperature limited heater, and other equipment, below design limit temperatures. Design limit temperatures are temperatures at which properties such as corrosion, creep, and/or deformation are adversely affected. The temperature limiting properties of the temperature limited heater inhibits overheating or burnout of the heater adjacent to low thermal conductivity "hot spots" in the formation. In some embodiments, the temperature limited heater is able to lower or control heat output and/or withstand heat at temperatures above 25 °C, 37 °C, 100 °C, 250 °C, 500 °C, 700 °C, 800 °C, 900 °C, or higher up to 1131 °C, depending on the materials used in the heater.

The temperature limited heater allows for more heat injection into the formation than constant wattage heaters because the energy input into the temperature limited heater does not have to be limited to accommodate low thermal conductivity regions adjacent to the heater. For example, in Green River oil shale there is a difference of at least a factor of 3 in the thermal conductivity of the lowest richness oil shale layers and the highest richness oil shale layers. When heating such a formation, substantially more heat is transferred to the formation with the temperature limited heater than with the conventional heater that is limited by the temperature at low thermal conductivity layers. The heat output along the entire length of the conventional heater needs to accommodate the low thermal conductivity layers so that the heater does not overheat at the low thermal conductivity layers and burn out. The heat output adjacent to the low thermal conductivity layers that are at high temperature will reduce for the temperature limited heater, but the remaining portions of the temperature limited heater that are not at high temperature will still provide high heat output. Because heaters for heating hydrocarbon formations typically have long lengths (for example, at least 10 m, 100 m, 300 m, at least 500 m, 1 km or more up to 10 km), the majority of the length of the temperature limited heater may be operating below the Curie temperature while only a few portions are at or near the Curie temperature of the temperature limited heater.

The use of temperature limited heaters allows for efficient transfer of heat to the formation. Efficient transfer of heat allows for reduction in time needed to heat the formation to a desired temperature. For example, in Green River oil shale, pyrolysis typically requires 9.5 years to 10 years of heating when using a 12 m heater well spacing with conventional constant wattage heaters. For the same heater spacing, temperature limited heaters may allow a larger average heat output while maintaining heater equipment temperatures below equipment design limit temperatures. Pyrolysis in the formation may occur at an earlier time with the larger average heat output provided by temperature limited heaters than the lower average heat output provided by constant wattage heaters. For example, in Green River oil shale, pyrolysis may occur in

5 years using temperature limited heaters with a 12 m heater well spacing. Temperature limited heaters counteract hot spots due to inaccurate well spacing or drilling where heater wells come too close together. In certain embodiments, temperature limited heaters allow for increased power output over time for heater wells that have been spaced too far apart, or limit power output for heater wells that are spaced too close together. Temperature limited heaters also supply more power in regions adjacent the overburden and underburden to compensate for temperature losses in these regions.

Temperature limited heaters may be advantageously used in many types of formations. For example, in tar sands formations or relatively permeable formations containing heavy hydrocarbons, temperature limited heaters may be used to provide a controllable low temperature output for reducing the viscosity of fluids, mobilizing fluids, and/or enhancing the radial flow of fluids at or near the wellbore or in the formation. Temperature limited heaters may be used to inhibit excess coke formation due to overheating of the near wellbore region of the formation.

The use of temperature limited heaters, in some embodiments, eliminates or reduces the need for expensive temperature control circuitry. For example, the use of temperature limited heaters eliminates or reduces the need to perform temperature logging and/or the need to use fixed thermocouples on the heaters to monitor potential overheating at hot spots.

In certain embodiments, the temperature limited heater is deformation tolerant. Localized movement of material in the wellbore may result in lateral stresses on the heater that could deform its shape. Locations along a length of the heater at which the wellbore approaches or closes on the heater may be hot spots where a standard heater overheats and has the potential to burn out. These hot spots may lower the yield strength and creep strength of the metal, allowing crushing or deformation of the heater. The temperature limited heater may be formed with S curves (or other non-linear shapes) that accommodate deformation of the temperature limited heater without causing failure of the heater.

In some embodiments, temperature limited heaters are more economical to manufacture or make than standard heaters. Typical ferromagnetic materials include iron, carbon steel, or ferritic stainless steel. Such materials are inexpensive as compared to nickel-based heating alloys (such as nichrome, Kanthal™ (Bulten-Kanthal AB, Sweden), and/or LOHM™ (Driver-Harris Company, Harrison, New Jersey, U.S.A.)) typically used in insulated conductor (mineral insulated cable) heaters. In one embodiment of the temperature limited heater, the temperature limited heater is manufactured in continuous lengths as an insulated conductor heater to lower costs and improve reliability.

The ferromagnetic alloy or ferromagnetic alloys used in the temperature limited heater determine the Curie temperature of the heater. Curie temperature data for various metals is listed in "American Institute of Physics Handbook," Second Edition, McGraw-Hill, pages 5-170 through 5-176. Ferromagnetic conductors may include one or more of the ferromagnetic elements (iron, cobalt, and nickel) and/or alloys of these elements. In some embodiments, ferromagnetic conductors include iron-chromium (Fe-Cr) alloys that contain tungsten (W) (for example, HCM12A and SAVE12 (Sumitomo Metals Co., Japan) and/or iron alloys that contain chromium (for example, Fe-Cr alloys, Fe-Cr-W alloys, Fe-Cr-V (vanadium) alloys, Fe-Cr-Nb (Niobium) alloys). Of the three main ferromagnetic elements, iron has a Curie temperature of 770 °C; cobalt (Co) has a Curie temperature of 1131 °C; and nickel has a Curie temperature of approximately 358 °C. An iron-cobalt alloy has a Curie temperature higher than the Curie temperature of iron. For example, iron-cobalt alloy with 2% by weight cobalt has a Curie temperature of 800 °C; iron-cobalt alloy with 12% by weight cobalt has a Curie temperature of 900 °C; and iron-cobalt alloy with 20% by weight cobalt has a Curie temperature of 950 °C. Iron-nickel alloy has a Curie temperature lower than the Curie temperature of iron. For example, iron-nickel alloy with 20% by weight nickel has a Curie temperature of 720 °C, and iron-nickel alloy with 60% by weight nickel has a Curie temperature of 560 °C.

Some non-ferromagnetic elements used as alloys raise the Curie temperature of iron. For example, an iron-vanadium alloy with 5.9% by weight vanadium has a Curie temperature of approximately 815 °C. Other non-ferromagnetic elements (for example, carbon, aluminum, copper, silicon, and/or chromium) may be alloyed with iron or other ferromagnetic materials to lower the Curie temperature. Non-ferromagnetic materials that raise the Curie temperature may be combined with non-ferromagnetic materials that lower the Curie temperature and alloyed with iron or other ferromagnetic materials to produce a material with a desired Curie temperature and other desired physical and/or chemical properties. In some embodiments, the Curie temperature material is a ferrite such as $NiFe_2O_4$. In other embodiments, the Curie temperature material is a binary compound such as $FeNi_3$ or Fe_3Al.

Certain embodiments of temperature limited heaters may include more than one ferromagnetic material. Such embodiments are within the scope of embodiments described herein if any conditions described herein apply to at least one of the ferromagnetic materials in the temperature limited heater.

Ferromagnetic properties generally decay as the Curie temperature is approached. Thus, the self-limiting temperature may be somewhat below the actual Curie temperature of the ferromagnetic conductor. Skin depth generally defines an effective penetration depth of time-varying current into the conductive material. In general, current density decreases exponentially with distance from an outer surface to the center along the radius of the conductor. The depth at which the current density is approximately $1/e$ of the surface current density is called the skin depth. The skin depth for current flow in 1% carbon steel is 0.132 cm at room temperature and increases to 0.445 cm at 720 °C. From 720 °C to 730 °C, the skin depth sharply increases to over 2.5 cm. Thus, a temperature limited heater embodiment using 1% carbon steel begins to self-limit between 650 °C and 730 °C.

For most metals, resistivity (ρ) increases with temperature. The relative magnetic permeability generally varies with temperature and with current. Additional equations may be used to assess the variance of magnetic permeability and/or skin depth on both temperature and/or current. The dependence of μ on current arises from the dependence of μ on the electromagnetic field.

Materials used in the temperature limited heater may be selected to provide a desired turndown ratio. Turndown ratios of at least 1.1:1, 2:1, 3:1, 4:1, 5:1, 10:1, 30:1, or 50:1 may be selected for temperature limited heaters. Larger turndown ratios may also be used. A selected turndown ratio may depend on a number of factors including, but not limited to, the type of formation in which the temperature limited heater is located (for example, a higher turndown ratio may be used for an oil shale formation with large variations in thermal conductivity between rich and lean oil shale layers) and/or a temperature limit of materials used in the wellbore (for example, temperature limits of heater materials). In some embodiments, the turndown ratio is increased by coupling additional copper or another good electrical conductor to the ferromagnetic material (for example, adding copper to lower the resistance above the Curie temperature).

The temperature limited heater may provide a minimum heat output (power output) below the Curie temperature of the heater. In certain embodiments, the minimum heat output is at least 400 W/m (Watts per meter), 600 W/m, 700 W/m, 800 W/m, or higher up to 2000 W/m. The temperature limited heater reduces the amount of heat output by a section of the heater when the temperature of the section of the heater approaches or is above the Curie temperature. The reduced amount of heat may be substantially less than the heat output below the Curie temperature. In some embodiments, the reduced amount of heat is at most 400 W/m, 200 W/m, 100 W/m or may approach 0 W/m.

In some embodiments, AC frequency is adjusted to change the skin depth of the ferromagnetic material. For example, the skin depth of 1% carbon steel at room temperature is 0.132 cm at 60 Hz, 0.0762 cm at 180 Hz, and 0.046 cm at 440 Hz. Since heater diameter is typically larger than twice the skin depth, using a higher frequency (and thus a heater with a smaller diameter) reduces heater costs. For a fixed geometry, the higher frequency results in a higher turndown ratio. The turndown ratio at a higher frequency is calculated by multiplying the turndown ratio at a lower frequency by the square root of the higher frequency divided by the lower frequency. In some embodiments, a frequency between 100 Hz and 1000 Hz, between 140 Hz and 200 Hz, or between 400 Hz and 600 Hz is used (for example, 180 Hz, 540 Hz, or 720 Hz). In some embodiments, high frequencies may be used. The frequencies may be greater than 1000 Hz.

In certain embodiments, modulated DC (for example, chopped DC, waveform modulated DC, or cycled DC) may be used for providing electrical power to the temperature limited heater. A DC modulator or DC chopper may be coupled to a DC power supply to provide an output of modulated direct current. In some embodiments, the DC power supply may include means for modulating DC. One example of a DC modulator is a DC-to-DC converter system. DC-to-DC converter systems are generally known in the art. DC is typically modulated or chopped into a desired waveform. Waveforms for DC modulation include, but are not limited to, square-wave, sinusoidal, deformed sinusoidal, deformed square-wave, triangular, and other regular or irregular waveforms.

The modulated DC waveform generally defines the frequency of the modulated DC. Thus, the modulated DC waveform may be selected to provide a desired modulated DC frequency. The shape and/or the rate of modulation (such as the rate of chopping) of the modulated DC waveform may be varied to vary the modulated DC frequency. DC may be modulated at frequencies that are higher than generally available AC frequencies. For example, modulated DC may be provided at frequencies of at least 1000 Hz. Increasing the frequency of supplied current to higher values advantageously increases the turndown ratio of the temperature limited heater.

In certain embodiments, the modulated DC waveform is adjusted or altered to vary the modulated DC frequency. The DC modulator may be able to adjust or alter the modulated DC waveform at any time during use of the temperature limited heater and at high currents or voltages. Thus, modulated DC provided to the temperature limited heater is not limited to a single frequency or even a small set of frequency values. Waveform selection using the DC modulator typically allows for a wide range of modulated DC frequencies and for discrete control of the modulated DC frequency. Thus, the modulated DC frequency is more easily set at a distinct value whereas AC frequency is generally limited to multiples of the line frequency. Discrete control of the modulated DC frequency allows for more selective control over the turndown ratio of the temperature limited heater. Being able to selectively control the turndown ratio of the temperature limited heater allows for a broader range of materials to be used in designing and constructing the temperature limited heater.

In some embodiments, the modulated DC frequency or the AC frequency is adjusted to compensate for changes in properties (for example, subsurface conditions such as temperature or pressure) of the temperature limited heater during use. The modulated DC frequency or the AC frequency provided to the temperature limited heater is varied based on assessed downhole conditions. For example, as the temperature of the temperature limited heater in the wellbore increases, it may be advantageous to increase the frequency of the current provided to the heater, thus increasing the turndown ratio of the heater. In an embodiment, the downhole temperature of the temperature limited heater in the wellbore is assessed.

In certain embodiments, the modulated DC frequency, or the AC frequency, is varied to adjust the turndown ratio of the temperature limited heater. The turndown ratio may be adjusted to compensate for hot spots occurring along a length of the temperature limited heater. For example, the turndown ratio is increased because the temperature limited heater is getting too hot in certain locations. In some embodiments, the modulated DC frequency, or the AC frequency, are varied to adjust a turndown ratio without assessing a subsurface condition.

The Metals Handbook, vol. 8, page 291 (American Society of Materials (ASM)) includes a graph of Curie temperature of iron-chromium alloys versus the amount of chromium in the alloys. In some temperature limited heater embodiments, a separate support rod or tubular (made from 347H stainless steel) is coupled to the temperature limited heater made from an iron-chromium alloy to provide yield strength and/or creep resistance. In certain embodiments, the support material and/or the ferromagnetic material is selected to provide a 100,000 hour creep-rupture strength of at least 20.7 MPa at 650 °C. In some embodiments, the 100,000 hour creep-rupture strength is at least 13.8 MPa at 650 °C or at least 6.9 MPa at 650 °C. For example, 347H steel has a favorable creep-rupture strength at or above 650°C. In some embodiments, the 100,000 hour creep-rupture strength ranges from 6.9 MPa to 41.3 MPa or more for longer heaters and/or higher earth or fluid stresses.

In certain embodiments, temperature limited heating elements are used in substantially horizontal sections of u-shaped wellbores. Substantially u-shaped wellbores may be used in tar sands formations, oil shale formation, or other formations with relatively thin hydrocarbon layers. Tar sands or thin oil shale formations may have thin shallow layers that are more easily and uniformly heated using heaters placed in substantially u-shaped wellbores. Substantially u-shaped wellbores may also be used to process formations with thick hydrocarbon layers in formations. In some embodiments, substantially u-shaped wellbores are used to access rich layers in a thick hydrocarbon formation.

Heaters in substantially u-shaped wellbores may have long lengths compared to heaters in vertical wellbores because horizontal heating sections do not have problems with creep or hanging stress encountered with vertical heating elements. Substantially u-shaped wellbores may make use of natural seals in the formation and/or the limited thickness of the hydrocarbon layer. For example, the wellbores may be placed above or below natural seals in the formation without punching large numbers of holes in the natural seals, as would be needed with vertically oriented wellbores. Using substantially u-shaped wellbores instead of vertical wellbores may also reduce the number of wells needed to treat a surface footprint of the formation. Using less wells reduces capital costs for equipment and reduces the environmental impact of treating the formation by reducing the amount of wellbores on the surface and the amount of equipment on the surface. Substantially u-shaped wellbores may also utilize a lower ratio of overburden section to heated section than vertical wellbores.

Substantially u-shaped wellbores may allow for flexible placement of opening of the wellbores on the surface. Openings to the wellbores may be placed according to the surface topology of the formation. In certain embodiments, the openings of wellbores are placed at geographically accessible locations such as topological highs (for examples, hills). For example, the wellbore may have a first opening on a first topologic high and a second opening on a second topologic high and the wellbore crosses beneath a topologic low (for example, a valley with alluvial fill) between the first and second topologic highs. This placement of the openings may avoid placing openings or equipment in topologic lows or other inaccessible locations. In addition, the water level may not be artesian in topologically high areas. Wellbores may be drilled so that the openings are not located near environmentally sensitive areas such as, but not limited to, streams, nesting areas, or animal refuges.

In certain embodiments, a heater is electrically isolated from the formation because the heater has little or no voltage potential on the outside of the heater. FIG. 3 depicts an embodiment of a substantially u-shaped heater that electrically isolates itself from the formation. Heater 220 has a first end portion at a first opening on surface 216 and a second end portion at a second opening on the surface. In some embodiments, heater 220 has only the first end portion at the surface with the second end of the heater located in hydrocarbon layer 212 (the heater is a single-ended heater). FIGS. 4 and 5 depict embodiments of single-ended heaters that electrically isolate themselves from the formation. In certain embodiments, single-ended heater 220 has an elongated portion that is substantially horizontal in hydrocarbon layer 212, as shown in FIGS. 4 and 5. In some embodiments, single-ended heater 220 has an elongated portion with an orientation other than substantially horizontal in hydrocarbon layer 212. For example, the single-ended heater may have an elongated portion that is oriented 15° off horizontal in the hydrocarbon layer.

As shown in FIGS. 3-5, heater 220 includes heating element 218 located in hydrocarbon layer 212. Heating element 218 may be a ferromagnetic conduit heating element or ferromagnetic tubular heating element. In certain embodiments, heating element 218 is a temperature limited heater tubular heating element. In certain embodiments, heating element 218 is a 9% by weight to 13% by weight chromium stainless steel tubular such as a 410 stainless steel tubular, a T/P91 stainless steel tubular, or a T/P92 stainless steel tubular. In certain embodiments, heating element 218 includes ferromagnetic material with a wall thickness of at least about one skin depth of the ferromagnetic material at 25 °C. In some embodiments, heating element 218 includes ferromagnetic material with a wall thickness of at least about two times the skin depth of the ferromagnetic material at 25 °C, at least about three times the skin depth of the ferromagnetic material at 25 °C, or at least about four times the skin depth of the ferromagnetic material at 25 °C.

Heating element 218 is coupled to one or more sections 222. Sections 222 are located in overburden 214. Sections 222 include higher electrical conductivity materials such as copper or aluminum. In certain embodiments, sections 222 are copper clad inside carbon steel.

Center conductor 226 is positioned inside heating element 218. In some embodiments, heating element 218 and center conductor 226 are placed or installed in the formation by unspooling the heating element and the center conductor from one or more spools while they are placed into the formation. In some embodiments, heating element 218 and center conductor 226 are coupled together on a single spool and unspooled as a single system with the center conductor inside the heating element. In some embodiments, heating element 218 and center conductor 226 are located on separate spools and the center conductor is positioned inside the heating element after the heating element is placed in the formation.

In certain embodiments, center conductor 226 is located at or near a center of heating element 218. Center conductor 226 may be substantially electrically isolated from heating element 218 along a length of the center conductor (for example, the length of the center conductor in hydrocarbon layer 212). In certain embodiments, center conductor 226 is separated from heating element 218 by one or more electrically-insulating centralizers. The centralizers may include silicon nitride or another electrically insulating material. The centralizers may inhibit electrical contact between center conductor 226 and heating element 218 so that, for example, arcing or shorting between the center conductor and the heating element is inhibited. In some embodiments, center conductor 226 is a conductor (for example, a solid conductor or a tubular conductor) so that the heater is in a conductor-in-conduit configuration.

In certain embodiments, center conductor 226 is a copper rod or copper tubular. In some embodiments, center conductor 226 and/or heating element 218 has a thin electrically insulating layer to inhibit current leakage from the heating elements. In some embodiments, the thin electrically insulating layer is aluminum oxide or thermal spray coated aluminum oxide. In some embodiments, the thin electrically insulating layer is an enamel coating of a ceramic composition. The thin electrically insulating layer may inhibit heating elements of a three-phase heater from leaking current between the elements, from leaking current into the formation, and from leaking current to other heaters in the formation. Thus, the three-phase heater may have a longer heater length.

In certain embodiments, center conductor 226 is an insulated conductor. The insulated conductor may include an electrically conductive core inside an electrically conductive sheath with electrical insulation between the core and the sheath. In certain embodiments, the insulated conductor includes a copper core inside a non-ferromagnetic stainless steel (for example, 347 stainless steel) sheath with magnesium oxide insulation between the core and the sheath. The core may be used to conduct electrical current through the insulated conductor. In some embodiments, the insulated conductor is placed inside heating element 218 without centralizers or spacers between the insulated conductor and the heating element. The sheath and the electrical insulation of the insulated conductor may electrically insulate the core from heating element 218 if the center conductor and the heating element touch. Thus, the core and heating element 218 are inhibit from electrically shorting to each other. The insulated conductor or another solid center conductor 226 may be inhibited from being crushed or deformed by heating element 218.In certain embodiments, one end portion of center conductor 226 is electrically coupled to one end portion of heating element 218 at surface 216 using electrical coupling 224, as shown in FIG. 3. In some embodiments, the end of center conductor 226 is electrically coupled to the end of heating element 218 in hydrocarbon layer 212 using electrical coupling 224, as shown in FIGS. 4 and 5. Thus, center conductor 226 is electrically coupled to heating element 218 in a series configuration in the embodiments depicted in FIGS. 3-5. In certain embodiments, center conductor 226 is the insulated conductor and the core of the insulated conductor is electrically coupled to heating element 218 in the series configuration. Center conductor 226 is a return electrical conductor for heating element 218 so that current in the center conductor flows in an opposite direction from current in the heating element (as represented by arrows 228). The electromagnetic field generated by current flow in center conductor 226 substantially confines the flow of electrons and heat generation to the inside of heating element 218 (for example, the inside wall of the heating element) below the Curie temperature of the ferromagnetic material in the heating element. Thus, the outside of heating element 218 is at substantially zero potential and the heating element is electrically isolated from the formation and any adjacent heater or heating element at temperatures below the Curie temperature of the ferromagnetic material (for example, at 25 °C). Having the outside of heating element 218 at substantially zero potential and the heating element electrically isolated from the formation and any adjacent heater or heating element allows for long length heaters to be used in hydrocarbon layer 212 without significant electrical (current) losses to the hydrocarbon layer. For example, heaters with lengths of at least about 100 m, at least about 500 m, or at least about 1000 m may be used in hydrocarbon layer 212.

During application of electrical current to heating element 218 and center conductor 226, heat is generated by the heater. In certain embodiments, heating element 218 generates a majority or all of the heat output of the heater. For example, when electrical current flows through ferromagnetic material in heating element 218 and copper or another low resistivity material in center conductor 226, the heating element generates a majority or all of the heat output of the heater. Generating a majority of the heat in the outer conductor (heating element 218) instead of center conductor 226 may increase the efficiency of heat transfer to the formation by allowing direct heat transfer from the heat generating element (heating element 218) to the formation and may reduce heat losses across heater 220 (for example, heat losses between the center conductor and the outer conductor if the center conductor is the heat generating element). Generating heat in heating element 218 instead of center conductor 226 also increases the heat generating surface area of heater 220. Thus, for the same operating temperature of heater 220, more heat can be provided to the formation using the outer conductor (heating element 218) as the heat generating element rather than center conductor 226.

In some embodiments, a fluid flows through heater 220 (represented by arrows 230 in FIGS. 3 and 4) to preheat the formation and/or to recover heat from the heating element. In the embodiment depicted in FIG. 3, fluid flows from one end of heater 220 to the other end of the heater inside and through heating element 218 and outside center conductor 226, as shown by arrows 230. In the embodiment depicted in FIG. 4, fluid flows into heater 220 through center conductor 226, which is a tubular conductor, as shown by arrows 230. Center conductor 226 includes openings 232 at the end of the center conductor to allow fluid to exit the center conductor. Openings 232 may be perforations or other orifices that allow fluid to flow into and/or out of center conductor 226. Fluid then returns to the surface inside heating element 218 and outside center conductor 226, as shown by arrows 230.

Fluid flowing inside heater 220 (represented by arrows 230 in FIGS. 3 and 4) may be used to preheat the heater, to initially heat the formation, and/or to recover heat from the formation after heating is completed for the in situ heat treatment process. Fluids that may flow through the heater include, but are not limited to, air, water, steam, helium, carbon dioxide or other high heat capacity fluids. In some embodiments, a hot fluid, such as carbon dioxide, helium, or DOWTHERM® (The Dow Chemical Company, Midland, Michigan, U.S.A.), flows through the tubular heating elements to provide heat to the formation. The hot fluid may be used to provide heat to the formation before electrical heating is used to provide heat to the formation. In some embodiments, the hot fluid is used to provide heat in addition to electrical heating. Using the hot fluid to provide heat to or preheat the formation in addition to providing electrical heating may be less expensive than using electrical heating alone to provide heat to the formation. In some embodiments, water and/or steam flows through the tubular heating element to recover heat from the formation after in situ heat treatment of the formation. The heated water and/or steam may be used for solution mining and/or other processes.

Further modifications and alternative embodiments of various aspects of the invention may 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 the presently preferred 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. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS

1. A system for heating a hydrocarbon containing formation, comprising:

a conduit located in an opening in the formation, the conduit comprising ferromagnetic material;

an electrical conductor positioned inside the conduit, and electrically coupled to the conduit at or near an end portion of the conduit so that the electrical conductor and the conduit are electrically coupled in series and electrical current flows in the electrical conductor in a substantially opposite direction to electrical current flow in the conduit during application of electrical current to the system;

wherein, during application of electrical current to the system, the flow of electrons is substantially confined to the inside of the conduit by the electromagnetic field generated from electrical current flow in the electrical conductor so that the outside surface of the conduit is at or near substantially zero potential at 25 °C; and

the conduit is configured to generate heat and heat the formation during application of electrical current to the system.

2. The system as claimed in claim 1, wherein the outside of the conduit is substantially electrically isolated from the formation.

3. The system as claimed in any of claims 1 or 2, wherein the conduit is proximate the formation.

4. The system as claimed in any of claims 1-3, wherein the conduit is proximate the formation such that heat generated in the conduit wall transfers to the formation.

5. The system as claimed in any of claims 1-4, wherein the conduit is configured to generate a majority of the heat output of the system.

6. The system as claimed in any of claims 1-5, wherein the conduit has an outer circumference that is greater than an outer circumference of the electrical conductor, and heat generated in the conduit wall transfers from the outer circumference of the conduit to the formation.

7. The system as claimed in any of claims 1-6, wherein the conduit has a wall thickness of at least one skin depth of the ferromagnetic material at 25 °C.

8. The system as claimed in any of claims 1-7, wherein the conduit is electrically isolated from at least one adjacent conduit located in the formation.

9. The system as claimed in any of claims 1-8, wherein the opening has a first end portion at a first location on the surface of the formation and a second end portion at a second location on the surface of the formation.

10. The system as claimed in any of claims 1-9, wherein a majority of the conduit is oriented substantially horizontally in a hydrocarbon layer of the formation.

11. The system as claimed in any of claims 1-10, wherein the electrical conductor is substantially electrically isolated from the conduit along a length of the conduit, and the electrical conductor is electrically coupled to the conduit near an end portion of the conduit.

12. The system as claimed in any of claims 1-11, wherein the system further comprises one or more centralizers to electrically separate the conduit from the electrical conductor.

13. The system as claimed in any of claims 1-12, wherein the system further comprises a thin electrically insulating layer on a surface of the conduit and/or on the outside surface of the electrical conductor.

14. The system as claimed in any of claims 1-13, wherein the conduit is configured to provide a first heat output below the Curie temperature of the ferromagnetic member, the conduit being configured to automatically provide a second heat output approximately at and above the Curie temperature of the ferromagnetic member, and the second heat output is reduced compared to the first heat output.

15. The system as claimed in any of claims 1-14, wherein the electrical conductor is an insulated conductor, the insulated conductor including an electrically conductive core inside an electrically conductive sheath with electrical insulation between the core and the sheath.

16. The system of claim 15, wherein the core is copper and the sheath is non-ferromagnetic stainless steel.

17. The system as claimed in any of claims 1-16, wherein the system has a turndown ratio of at least 2 to 1.

18. The system as claimed in any of claims 1-17, wherein the conduit has a length of at least 100 m, at least 500 m, or at least 1000 m and is in a hydrocarbon layer of the formation.

19. The system as claimed in any of claims 1-18, wherein the conduit is configured to allow a fluid to flow through the conduit to (a) preheat the conduit and the system and/or (b) recover heat from the system.

20. The system as claimed in any of claims 1-19, wherein the electrical conductor is a tubular conductor with openings at or near an end portion of the electrical conductor, the openings being configured to allow a fluid to flow between the inside of the electrical conductor and the conduit.

21. A method of heating a subsurface formation using the system in any of claims 1-20, the method comprising providing electrical current to the conduit to provide heat to at least a portion of the subsurface formation.

22. The method as claimed in claim 21, wherein the subsurface formation comprises hydrocarbons, the method further comprising allowing the heat to transfer to the formation such that at least some hydrocarbons are pyrolyzed in the formation.

23. The method as claimed in any of claims 21-22, further comprising providing a hot heat transfer fluid to the conduit to provide heat to the formation.

24. The method as claimed in 23, wherein the hot heat transfer fluid is heated water, steam, and/or heated carbon dioxide.

25. The method as claimed in any of claims 21-24, further comprising producing a fluid from the formation.

26. The method as claimed in any of claims 21-25, further comprising providing a fluid to the conduit to recover heat from the system.

27. A method of installing the system in any of claims 1-20 in the opening, the method comprising unspooling the conduit and the electrical conductor from one or more spools, and placing the conduit and the electrical conductor in the opening in the formation.

28. A composition comprising hydrocarbons produced from a subsurface formation using the system as claimed in any of claims 1-20, or using the methods as claimed in any of claims 21-27.

29. A transportation fuel comprising hydrocarbons made from the composition as claimed in claim 28.

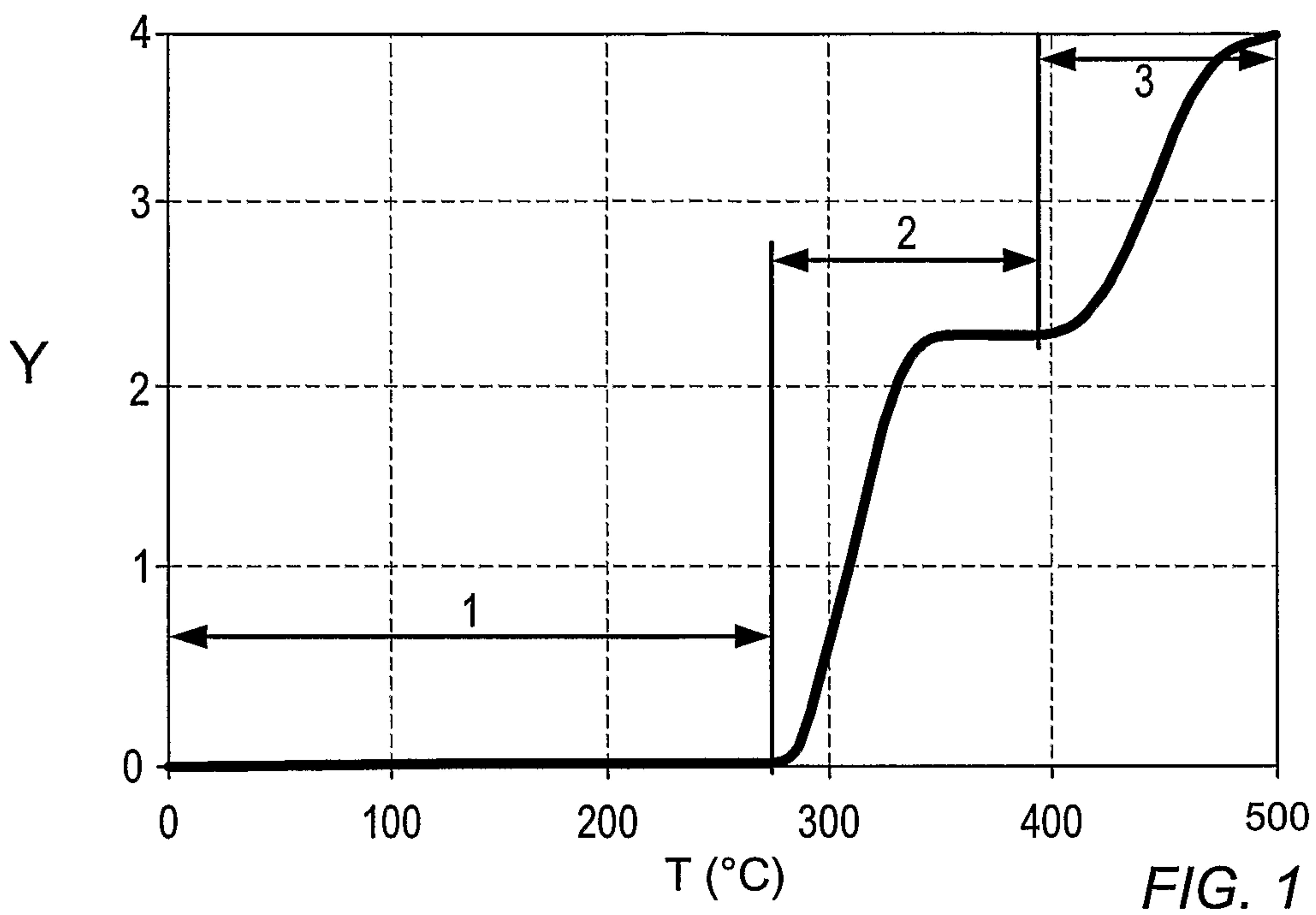
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FIG. 1

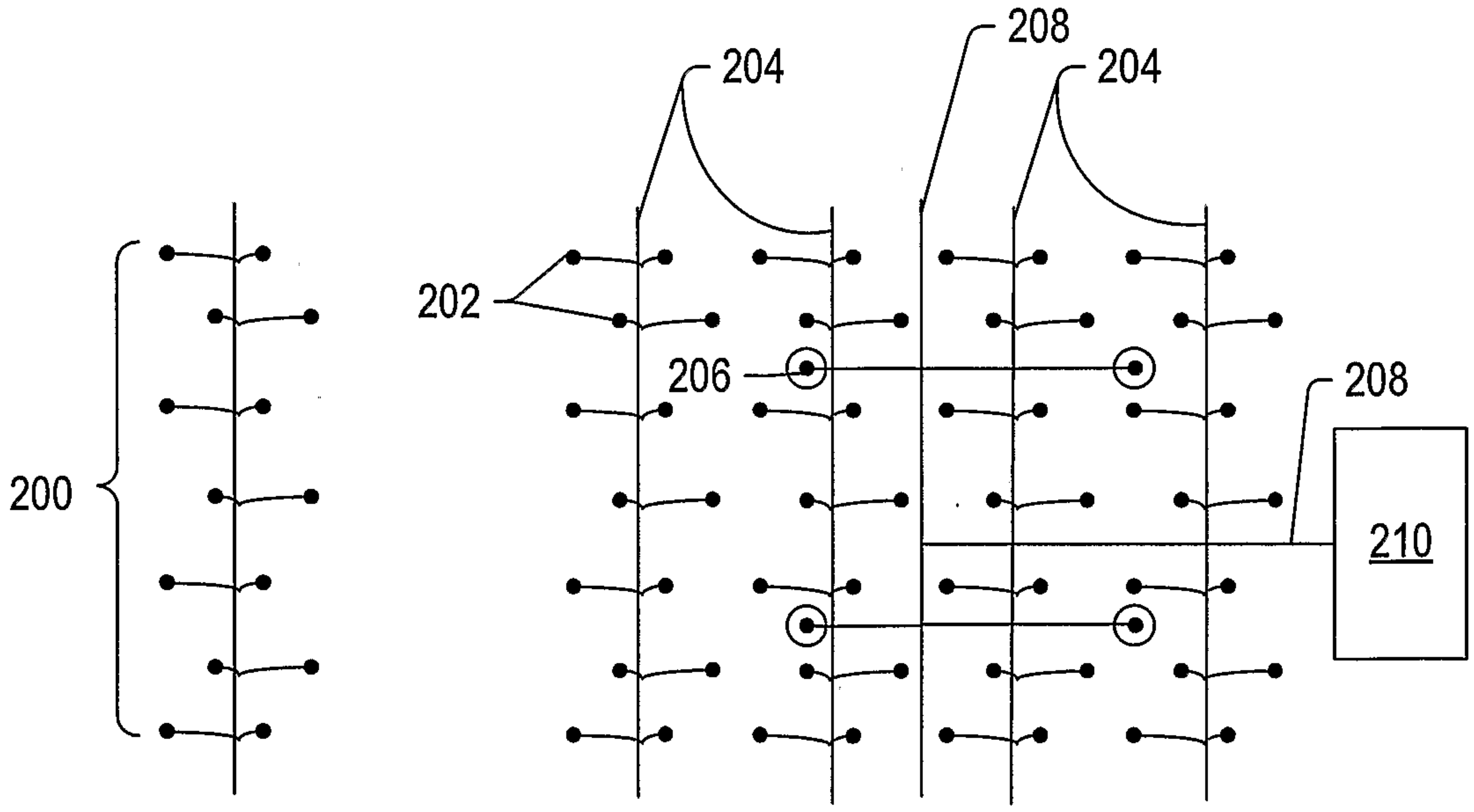
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FIG. 2

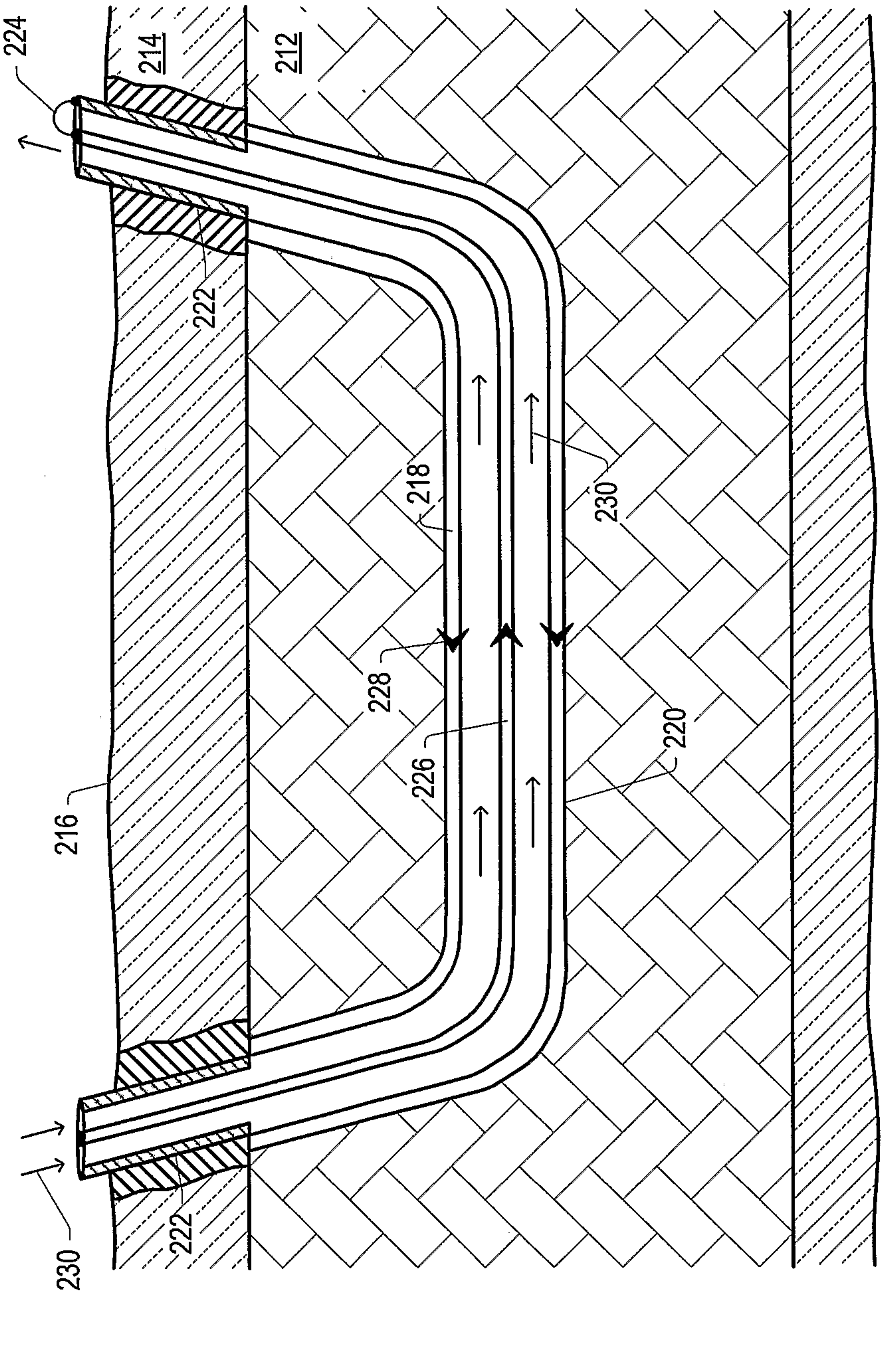


FIG. 3

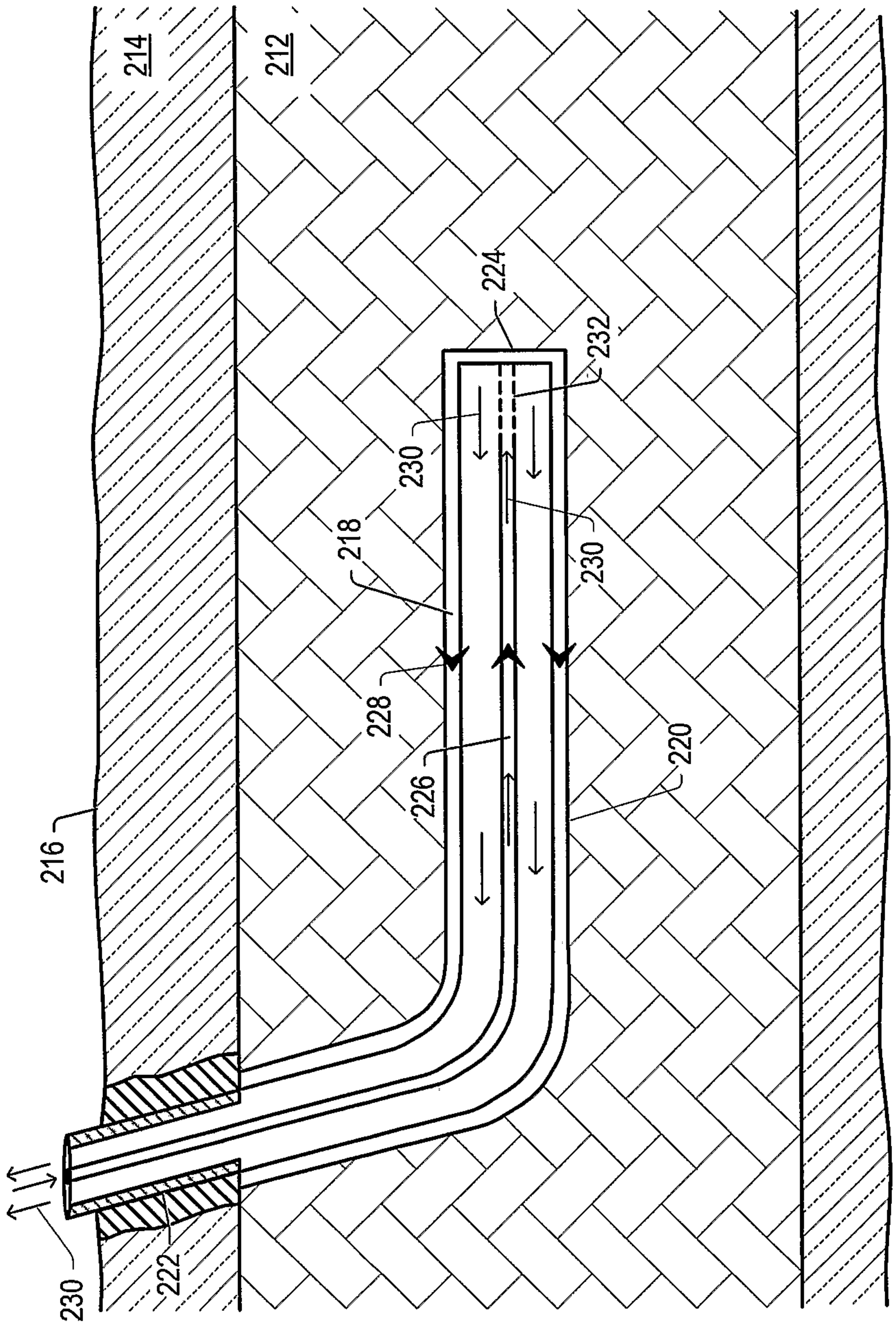


FIG. 4

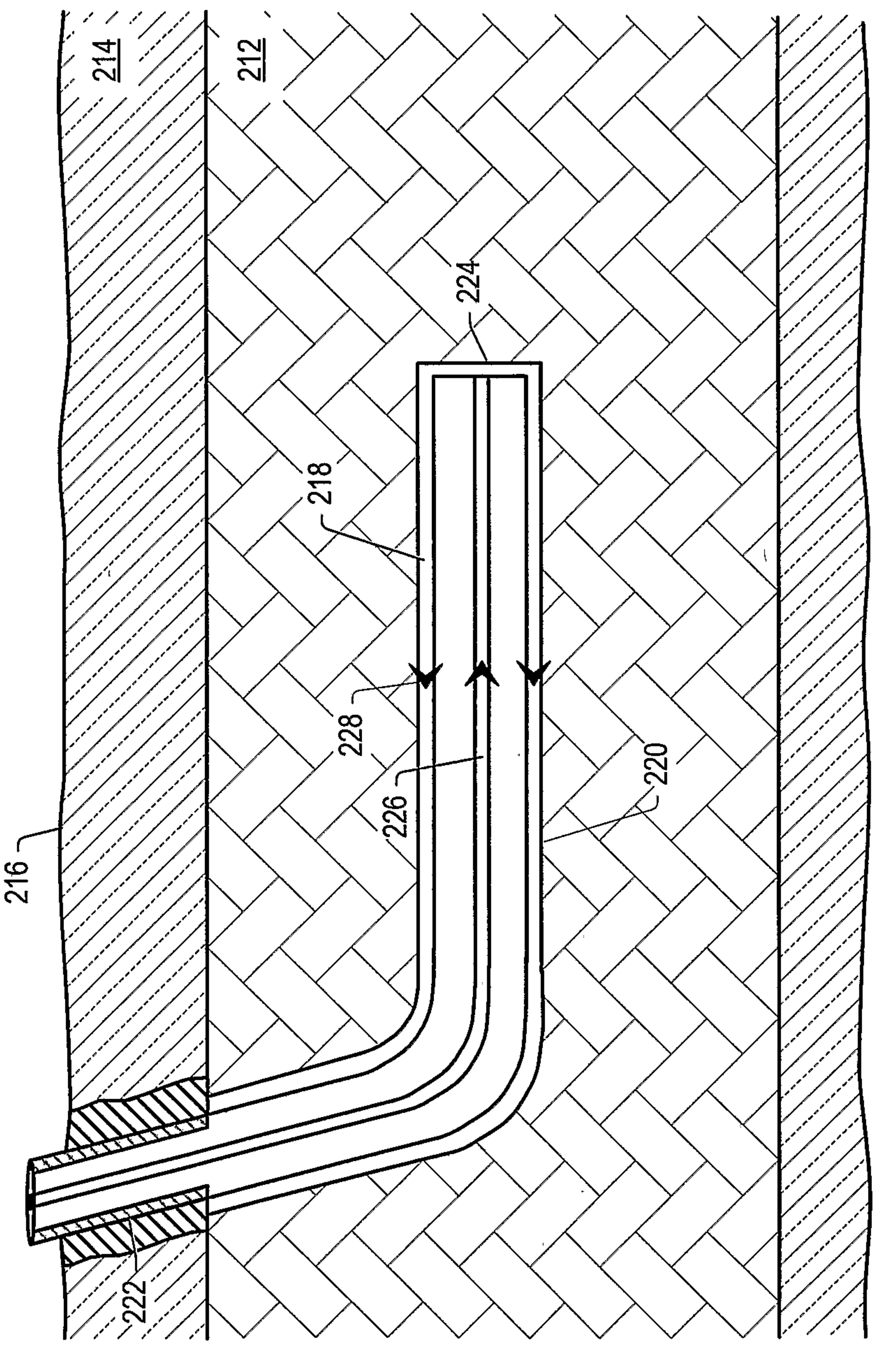
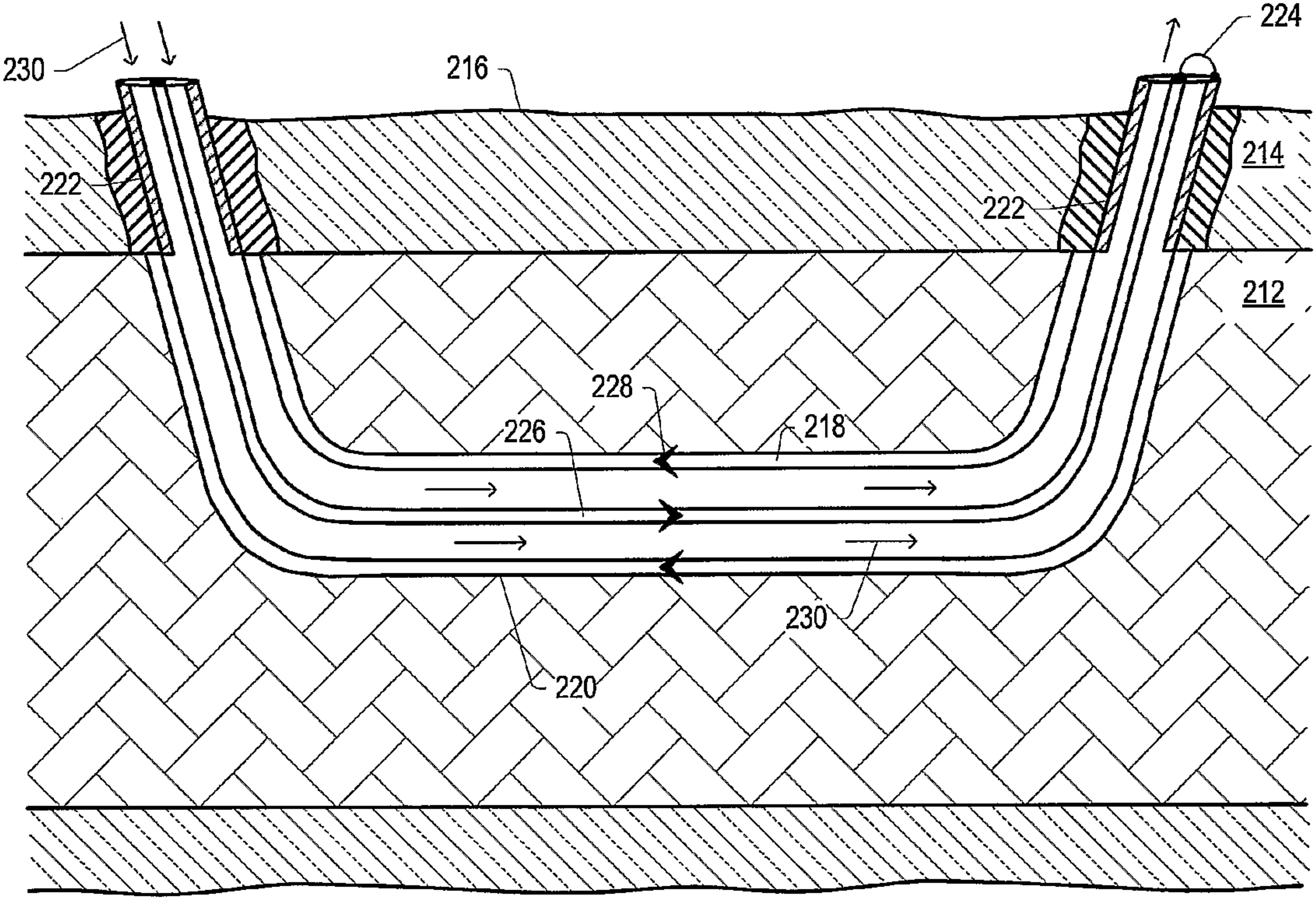


FIG. 5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