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(54) Title: INDUCTION HEATERS USED TO HEAT SUBSURFACE FORMATIONS

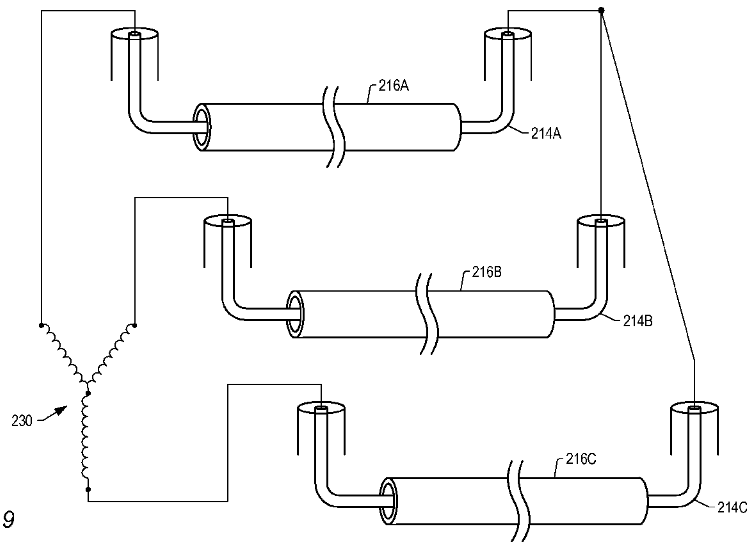

FIG. 9

(57) **Abstract:** A heating system for a subsurface formation includes an elongated electrical conductor located in the subsurface formation. The electrical conductor extends between at least a first electrical contact and a second electrical contact. A ferromagnetic conductor at least partially surrounds and at least partially extends lengthwise around the electrical conductor. The electrical conductor, when energized with time-varying electrical current, induces sufficient electrical current flow in the ferromagnetic conductor such that the ferromagnetic conductor resistively heats to a temperature of at least about 300°C.

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INDUCTION HEATERS USED TO HEAT SUBSURFACE FORMATIONS

BACKGROUND

1. Field of the Invention

[0001] The present invention relates generally to heating methods and heating systems for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Certain embodiments relate to heater systems for heating subsurface formations that induce current in ferromagnetic materials.

2. Description of Related Art

[0002] 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.

[0003] A wellbore may be formed in a formation. In some embodiments, a casing or other pipe system may be placed or formed in a wellbore. In some embodiments, an expandable tubular may be used in a wellbore. Heaters may be placed in wellbores to heat a formation during an in situ process.

[0004] 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.

[0005] 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 Nos. 2,548,360 to Germain; 4,716,960 to Eastlund et al.; 4,716,960 to Eastlund et al.; and 5,065,818 to Van Egmond describes electric heating elements placed in wellbores. 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.

[0006] U.S. Patent No. 4,570,715 to Van Meurs et al. describes an electric heating element. The heating element has an electrically conductive core, a surrounding layer of insulating material, and a surrounding metallic sheath. The conductive core may have a relatively low resistance at high temperatures. The insulating material may have electrical resistance, compressive strength, and heat conductivity properties that are relatively high at high temperatures. The insulating layer may inhibit arcing from the core to the metallic sheath. The metallic sheath may have tensile strength and creep resistance properties that are relatively high at high temperatures. U.S. Patent No. 5,060,287 to Van Egmond describes an electrical heating element having a copper-nickel alloy core.

[0007] Heaters may be manufactured from wrought stainless steels. U.S. Patent No. 7,153,373 to Maziasz et al. and U.S. Patent Application Publication No. US 2004/0191109 to Maziasz et al. described modified 237 stainless steels as cast microstructures or fined grained sheets and foils.

[0008] As outlined above, there has been a significant amount of effort to develop heaters, methods and systems to economically produce hydrocarbons, hydrogen, and/or other products from hydrocarbon containing formations. At present, however, there are still many hydrocarbon containing formations from which hydrocarbons, hydrogen, and/or other products cannot be economically produced. Thus, there is still a need for improved heating methods and systems for production of hydrocarbons, hydrogen, and/or other products from various hydrocarbon containing formations.

SUMMARY

[0009] 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.

[0010] 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.

[0011] In certain embodiments, the invention provides a heating system for a subsurface formation, comprising: an elongated electrical conductor located in the subsurface formation, wherein the electrical conductor extends between at least a first electrical contact and a second electrical contact; and a ferromagnetic conductor, wherein the ferromagnetic conductor at least partially surrounds and at least partially extends lengthwise around the electrical conductor; wherein the electrical conductor, when energized with time-varying electrical current, induces sufficient electrical current flow in the ferromagnetic conductor such that the ferromagnetic conductor resistively heats to a temperature of at least about 300 °C.

[0012] 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.

[0013] In further embodiments, treating a subsurface formation is performed using any of the methods, systems, or heaters described herein.

[0014] In further embodiments, additional features may be added to the specific embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] 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:

[0016] FIG. 1 shows a schematic view of an embodiment of a portion of an in situ heat treatment system for treating a hydrocarbon containing formation.

[0017] FIG. 2 depicts an embodiment of a u-shaped heater that has an inductively energized tubular.

[0018] FIG. 3 depicts an embodiment of an electrical conductor centralized inside a tubular.

[0019] FIG. 4 depicts an embodiment of an induction heater with a sheath of an insulated conductor in electrical contact with a tubular.

[0020] FIG. 5 depicts an embodiment of a resistive heater with a tubular having radial grooved surfaces.

[0021] FIG. 6 depicts an embodiment of an induction heater with a tubular having radial grooved surfaces.

[0022] FIG. 7 depicts an embodiment of a heater divided into tubular sections to provide varying heat outputs along the length of the heater.

[0023] FIG. 8 depicts an embodiment of three electrical conductors entering the formation through a first common wellbore and exiting the formation through a second common wellbore with three tubulars surrounding the electrical conductors in the hydrocarbon layer.

[0024] FIG. 9 depicts a representation of an embodiment of three electrical conductors and three tubulars in separate wellbores in the formation coupled to a transformer.

[0025] FIG. 10 depicts an embodiment of a multilayer induction tubular.

[0026] FIG. 11 depicts a cross-sectional end view of an embodiment of an insulated conductor that is used as an induction heater.

[0027] FIG. 12 depicts a cross-sectional side view of the embodiment depicted in FIG. 11.

[0028] FIG. 13 depicts a cross-sectional end view of an embodiment of a two-leg insulated conductor that is used as an induction heater.

[0029] FIG. 14 depicts a cross-sectional side view of the embodiment depicted in FIG. 13.

[0030] FIG. 15 depicts a cross-sectional end view of an embodiment of a multilayered insulated conductor that is used as an induction heater.

[0031] FIG. 16 depicts an end view representation of an embodiment of three insulated conductors located in a coiled tubing conduit and used as induction heaters.

[0032] FIG. 17 depicts a representation of cores of insulated conductors coupled together at their ends.

[0033] FIG. 18 depicts an end view representation of an embodiment of three insulated conductors strapped to a support member and used as induction heaters.

[0034] FIG. 19 depicts a representation of an embodiment of an induction heater with a core and an electrical insulator surrounded by a ferromagnetic layer.

[0035] FIG. 20 depicts a representation of an embodiment of an insulated conductor surrounded by a ferromagnetic layer.

[0036] FIG. 21 depicts a representation of an embodiment of an induction heater with two ferromagnetic layers spirally wound onto a core and an electrical insulator.

[0037] FIG. 22 depicts an embodiment for assembling a ferromagnetic layer onto an insulated conductor.

[0038] FIG. 23 depicts an embodiment of a casing having an axial grooved or corrugated surface.

[0039] 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

[0040] 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.

[0041] "Alternating current (AC)" refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

[0100] Bare metal" and "exposed metal" refer to metals of elongated members 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.

[0101] "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.

[0042] "Fluid pressure" is a pressure generated by a fluid in a formation. "Lithostatic pressure" (sometimes referred to as "lithostatic stress") is a pressure in a formation equal to a weight per unit area of an overlying rock mass. "Hydrostatic pressure" is a pressure in a formation exerted by a column of water.

[0043] 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 impermeable materials. For example, the 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.

[0044] "Formation fluids" refer to fluids present in a formation and may include pyrolyzation 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 thermal treatment of the formation. "Produced fluids" refer to fluids removed from the formation.

[0045] 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.

[0046] 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.

[0047] “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.

[0048] An “in situ conversion process” refers to a process of heating a hydrocarbon containing formation from heat sources to raise the temperature of at least a portion of the formation above a pyrolysis temperature so that pyrolyzation fluid is produced in the formation.

[0049] 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 temperature that results in mobilized fluid, visbreaking, and/or pyrolysis of hydrocarbon containing material so that mobilized fluids, visbroken fluids, and/or pyrolyzation fluids are produced in the formation.

[0050] "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.

[0051] "Phase transformation temperature" of a ferromagnetic material refers to a temperature or a temperature range during which the material undergoes a phase change (for example, from ferrite to austenite) that decreases the magnetic permeability of the ferromagnetic material. The reduction in magnetic permeability is similar to reduction in magnetic permeability due to the magnetic transition of the ferromagnetic material at the Curie temperature.

[0052] "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.

[0053] "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.

[0054] "Superposition of heat" refers to providing heat from two or more heat sources to a selected section of a formation such that the temperature of the formation at least at one location between the heat sources is influenced by the heat sources.

[0055] "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.

[0056] "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).

[0057] Turndown ratio" for the temperature limited heater in which current is applied directly to the 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. Turndown ratio for an inductive heater is the ratio of the highest heat output below the Curie temperature to the lowest heat output above the Curie temperature for a given current applied to the heater.

[0058] 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".

[0059] "Upgrade" refers to increasing the quality of hydrocarbons. For example, upgrading heavy hydrocarbons may result in an increase in the API gravity of the heavy hydrocarbons.

[0060] 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."

[0061] A formation may be treated in various ways to produce many different products. Different stages or processes may be used to treat the formation during an in situ heat treatment process. In some embodiments, one or more sections of the formation are solution mined to remove soluble minerals from the sections. Solution mining minerals may be performed before, during, and/or after the in situ heat treatment process. In some embodiments, the average temperature of one or more sections being solution mined may be maintained below about 120 °C.

[0062] In some embodiments, one or more sections of the formation are heated to remove water from the sections and/or to remove methane and other volatile hydrocarbons from the sections. In some embodiments, the average temperature may be raised from ambient temperature to temperatures below about 220 °C during removal of water and volatile hydrocarbons.

[0063] In some embodiments, one or more sections of the formation are heated to temperatures that allow for movement and/or visbreaking of hydrocarbons in the formation. In some embodiments, the average temperature of one or more sections of the formation are raised to mobilization temperatures of hydrocarbons in the sections (for example, to temperatures ranging from 100 °C to 250 °C, from 120 °C to 240 °C, or from 150 °C to 230 °C).

[0064] In some embodiments, one or more sections are heated to temperatures that allow for pyrolysis reactions in the formation. In some embodiments, the average temperature of one or more sections of the formation may be raised to pyrolysis temperatures of hydrocarbons in the sections (for example, temperatures ranging from 230 °C to 900 °C, from 240 °C to 400 °C or from 250 °C to 350 °C).

[0065] Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that raise the temperature of hydrocarbons in the formation to desired temperatures at desired heating rates. The rate of temperature increase through mobilization temperature range and/or pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Slowly raising the temperature of the formation through the mobilization temperature range and/or pyrolysis temperature range may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the mobilization temperature range and/or pyrolysis temperature range may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

[0066] 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.

[0067] 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 a desired temperature.

[0068] Mobilization and/or pyrolysis products may be produced from the formation through production wells. In some embodiments, the average temperature of one or more sections is raised to mobilization temperatures and hydrocarbons are produced from the production wells. The average temperature of one or more of the sections may be raised to pyrolysis temperatures after production due to mobilization decreases below a selected value. In some embodiments, the average temperature of one or more sections may be raised to pyrolysis temperatures without significant production before reaching pyrolysis temperatures. Formation fluids including pyrolysis products may be produced through the production wells.

[0069] In some embodiments, the average temperature of one or more sections may be raised to temperatures sufficient to allow synthesis gas production after mobilization and/or pyrolysis. In some embodiments, hydrocarbons may be raised to temperatures sufficient to allow synthesis gas production without significant production before reaching the temperatures sufficient to allow synthesis gas production. 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. A synthesis gas generating fluid (for example, steam and/or water) may be introduced into the sections to generate synthesis gas. Synthesis gas may be produced from production wells.

[0070] Solution mining, removal of volatile hydrocarbons and water, mobilizing hydrocarbons, pyrolyzing hydrocarbons, generating synthesis gas, and/or other processes may be performed during the in situ heat treatment process. In some embodiments, some processes may be performed after the in situ heat treatment process. Such processes may include, but are not limited to, recovering heat from treated sections, storing fluids (for example, water and/or hydrocarbons) in previously treated sections, and/or sequestering carbon dioxide in previously treated sections.

[0071] FIG. 1 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. 1, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells may encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

[0072] 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. In some embodiments, electricity for an in situ heat treatment process may be provided by a nuclear power plant or nuclear power plants. The use of nuclear power may allow for reduction or elimination of carbon dioxide emissions from the in situ heat treatment process.

[0073] 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.

[0074] In some embodiments, the heat source in production well 206 allows for vapor phase removal of formation fluids from the formation. Providing heating at or through the production well may: (1) inhibit condensation and/or refluxing of production fluid when such production fluid is moving in the production well proximate the overburden, (2) increase heat input into the formation, (3) increase production rate from the production well as compared to a production well without a heat source, (4) inhibit condensation of high carbon number compounds (C_6 and above) in the production well, and/or (5) increase formation permeability at or proximate the production well.

[0075] Subsurface pressure in the formation may correspond to the fluid pressure generated in the formation. As temperatures in the heated portion of the formation increase, the pressure in the heated portion may increase as a result of thermal expansion of fluids, increased fluid generation, and vaporization of water. Controlling rate of fluid removal from the formation may allow for control of pressure in the formation. Pressure in the formation may be determined at a number of different locations, such as near or at production wells, near or at heat sources, or at monitor wells.

[0076] In some hydrocarbon containing formations, production of hydrocarbons from the formation is inhibited until at least some hydrocarbons in the formation have been mobilized and/or pyrolyzed. Formation fluid may be produced from the formation when the formation fluid is of a selected quality. In some embodiments, the selected quality includes an API gravity of at least about 15°, 20°, 25°, 30°, or 40°. Inhibiting production until at least some hydrocarbons are mobilized and/or pyrolyzed may increase conversion of heavy hydrocarbons to light hydrocarbons. Inhibiting initial production may minimize the production of heavy hydrocarbons from the formation. Production of substantial amounts of heavy hydrocarbons may require expensive equipment and/or reduce the life of production equipment.

[0077] After mobilization or pyrolysis temperatures are reached and production from the formation is allowed, pressure in the formation may be varied to alter and/or control a composition of formation fluid produced, to control a percentage of condensable fluid as compared to non-condensable fluid in the formation fluid, and/or to control an API gravity of formation fluid being produced. For example, decreasing pressure may result in production of a larger condensable fluid component. The condensable fluid component may contain a larger percentage of olefins.

[0078] In some in situ heat treatment process embodiments, pressure in the formation may be maintained high enough to promote production of formation fluid with an API gravity of greater than 20°. Maintaining increased pressure in the formation may inhibit formation subsidence during in situ heat treatment. Maintaining increased pressure may reduce or eliminate the need to compress formation fluids at the surface to transport the fluids in collection conduits to treatment facilities.

[0079] Maintaining increased pressure in a heated portion of the formation may surprisingly allow for production of large quantities of hydrocarbons of increased quality and of relatively low molecular weight. Pressure may be maintained so that formation fluid produced has a minimal amount of compounds above a selected carbon number. The selected carbon number may be at most 25, at most 20, at most 12, or at most 8. Some high carbon number compounds may be entrained in vapor in the formation and may be removed from the formation with the vapor. Maintaining increased pressure in the formation may inhibit entrainment of high carbon number compounds and/or multi-ring hydrocarbon compounds in the vapor. High carbon number compounds and/or multi-ring hydrocarbon compounds may remain in a liquid phase in the formation for significant time periods. The significant time periods may provide sufficient time for the compounds to pyrolyze to form lower carbon number compounds.

[0080] 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.

[0081] FIG. 2 depicts a schematic of an embodiment of a u-shaped heater that has an inductively energized tubular. Heater 212 includes electrical conductor 214 and tubular 216 in an opening that spans between wellbore 218A and wellbore 218B. In certain embodiments, electrical conductor 214 and/or the current carrying portion of the electrical conductor is electrically insulated from tubular 216. Electrical conductor 214 and/or the current carrying portion of the electrical conductor is electrically insulated from tubular 216 such that electrical current does not flow from the electrical conductor to the tubular, or vice versa (for example, the tubular is not directly connected electrically to the electrical conductor).

[0082] In some embodiments, electrical conductor 214 is centralized inside tubular 216 (for example, using centralizers 220 or other support structures, as shown in FIG. 3). Centralizers 220 may electrically insulate electrical conductor 214 from tubular 216. In some embodiments, tubular 216 contacts electrical conductor 214. For example, tubular 216 may hang, drape, or otherwise touch electrical conductor 214. In some embodiments, electrical conductor 214 includes electrical insulation (for example, magnesium oxide or porcelain enamel) that insulates the current carrying portion of the electrical conductor from tubular 216. The electrical insulation inhibits current from flowing between the current carrying portion of electrical conductor 214 and tubular 216 if the electrical conductor and the tubular are in physical contact with each other.

[0083] In some embodiments, electrical conductor 214 is an exposed metal conductor heater or a conductor-in-conduit heater. In certain embodiments, electrical conductor 214 is an insulated conductor such as a mineral insulated conductor. The insulated conductor may have a copper core, copper alloy core, or a similar electrically conductive, low resistance core that has low electrical losses. In some embodiments, the core is a copper core with a diameter between about 0.5” (1.27 cm) and about 1” (2.54 cm). The sheath or jacket of the insulated conductor may be a non-ferromagnetic, corrosion resistant steel such as 347 stainless steel, 625 stainless steel, 825 stainless steel, 304 stainless steel, or copper with a protective layer (for example, a protective cladding). The sheath may have an outer diameter of between about 1” (2.54 cm) and about 1.25” (3.18 cm).

[0084] In some embodiments, the sheath or jacket of the insulated conductor is in physical contact with the tubular 216 (for example, the tubular is in physical contact with the sheath along the length of the tubular) or the sheath is electrically connected to the tubular. In such embodiments, the electrical insulation of the insulated conductor electrically insulates the core of the insulated conductor from the jacket and the tubular. FIG. 4 depicts an embodiment of an induction heater with the sheath of an insulated conductor in electrical contact with tubular 216. Electrical conductor 214 is the insulated conductor. The sheath of the insulated conductor is electrically connected to tubular 216 using electrical contactors 222. In some embodiments, electrical contactors 222 are sliding contactors. In certain embodiments, electrical contactors 222 electrically connect the sheath of the insulated conductor to tubular 216 at or near the ends of the tubular. Electrically connecting at or near the ends of tubular 216 substantially equalizes the voltage along the tubular with the voltage along the sheath of the insulated conductor. Equalizing the voltages along tubular 216 and along the sheath may inhibit arcing between the tubular and the sheath.

[0085] Tubular 216, such as the tubular shown in FIGS. 2, 3, and 4, may be ferromagnetic or include ferromagnetic materials. Tubular 216 may have a thickness such that when electrical conductor 214 induces electrical current flow on the surfaces of tubular 216 when the electrical conductor is energized with time-varying current. The electrical conductor induces electrical current flow due to the ferromagnetic properties of the tubular. Current flow is induced on both the inside surface of the tubular and the outside surface of tubular 216. Tubular 216 may operate as a skin effect heater when current flow is induced in the skin depth of one or more of the tubular surfaces. In certain embodiments, the induced current circulates axially (longitudinally) on the inside and/or outside surfaces of tubular 216. Longitudinal flow of current through electrical conductor 214 induces primarily longitudinal current flow in tubular 216 (the majority of the induced current flow is in the longitudinal direction in the tubular). Having primarily longitudinal induced current flow in tubular 216 may provide a higher resistance per foot than if the induced current flow is primarily angular current flow.

[0086] In certain embodiments, current flow in tubular 216 is induced with low frequency current in electrical conductor 214 (for example, from 50 Hz or 60 Hz up to about 1000 Hz). In some embodiments, induced currents on the inside and outside surfaces of tubular 216 are substantially equal.

[0087] In certain embodiments, tubular 216 has a thickness that is greater than the skin depth of the ferromagnetic material in the tubular at or near the Curie temperature of the ferromagnetic material or at or near the phase transformation temperature of the ferromagnetic material. For example, tubular 216 may have a thickness of at least 2.1, at least 2.5 times, at least 3 times, or at least 4 times the skin depth of the ferromagnetic material in the tubular near the Curie temperature or the phase transformation temperature of the ferromagnetic material. In certain embodiments, tubular 216 has a thickness of at least 2.1 times, at least 2.5 times, at least 3 times, or at least 4 times the skin depth of the ferromagnetic material in the tubular at about 50 °C below the Curie temperature or the phase transformation temperature of the ferromagnetic material.

[0088] In certain embodiments, tubular 216 is carbon steel. In some embodiments, tubular 216 is coated with a corrosion resistant coating (for example, porcelain or ceramic coating) and/or an electrically insulating coating. In some embodiments, electrical conductor 214 has an electrically insulating coating. Examples of the electrically insulating coating on tubular 216 and/or electrical conductor 214 include, but are not limited to, a porcelain enamel coating, an alumina coating, or an alumina-titania coating.

[0089] In some embodiments, tubular 216 and/or electrical conductor 214 are coated with a coating such as polyethylene or another suitable low friction coefficient coating that may melt or decompose when the heater is energized. The coating may facilitate placement of the tubular and/or the electrical conductor in the formation.

[0090] In some embodiments, tubular 216 includes corrosion resistant ferromagnetic material such as, but not limited to, 410 stainless steel, 446 stainless steel, T/P91 stainless steel, T/P92 stainless steel, alloy 52, alloy 42, and Invar 36. In some embodiments, tubular 216 is a stainless steel tubular with cobalt added (for example, between about 3% by weight and about 10% by weight cobalt added) and/or molybdenum (for example, about 0.5 % molybdenum by weight).

[0091] At or near the Curie temperature or the phase transformation temperature of the ferromagnetic material in tubular 216, the magnetic permeability of the ferromagnetic material decreases rapidly. When the magnetic permeability of tubular 216 decreases at or near the Curie temperature or the phase transformation temperature, there is little or no current flow in the tubular because, at these temperatures, the tubular is essentially non-ferromagnetic and electrical conductor 214 is unable to induce current flow in the tubular. With little or no current flow in tubular 216, the temperature of the tubular will drop to lower temperatures until the magnetic permeability increases and the tubular becomes ferromagnetic. Thus, tubular 216 self-limits at or near the Curie temperature or the phase transformation temperature and operates as a temperature limited heater due to the ferromagnetic properties of the ferromagnetic material in the tubular. Because current is induced in tubular 216, the turndown ratio may be higher and the drop in current sharper for the tubular than for temperature limited heaters that apply current directly to the ferromagnetic material. For example, heaters with current induced in tubular 216 may have turndown ratios of at least about 5, at least about 10, or at least about 20 while temperature limited heaters that apply current directly to the ferromagnetic material may have turndown ratios that are at most about 5.

[0092] When current is induced in tubular 216, the tubular provides heat to hydrocarbon layer 224 and defines the heating zone in the hydrocarbon layer. In certain embodiments, tubular 216 heats to temperatures of at least about 300 °C, at least about 500 °C, or at least about 700 °C. Because current is induced on both the inside and outside surfaces of tubular 216, the heat generation of the tubular is increased as compared to temperature limited heaters that have current directly applied to the ferromagnetic material and current flow is limited to one surface. Thus, less current may be provided to electrical conductor 214 to generate the same heat as heaters that apply current directly to the ferromagnetic material. Using less current in electrical conductor 214 decreases power consumption and reduces power losses in the overburden of the formation.

[0093] In certain embodiments, tubulars 216 have large diameters. The large diameters may be used to equalize or substantially equalize high pressures on the tubular from either the inside or the outside of the tubular. In some embodiments, tubular 216 has a diameter in a range between about 1.5" (about 3.8 cm) and about 6" (about 15.2 cm). In some embodiments, tubular 216 has a diameter in a range between about 3 cm and about 13 cm, between about 4 cm and about 12 cm, or between about 5 cm and about 11 cm. Increasing the diameter of tubular 216 may provide more heat output to the formation by increasing the heat transfer surface area of the tubular.

[0094] In certain embodiments, tubular 216 has surfaces that are shaped to increase the resistance of the tubular. FIG. 5 depicts an embodiment of a heater with tubular 216 having radial grooved surfaces. Heater 212 may include electrical conductors 214A,B coupled to tubular 216. Electrical conductors 214A,B may be insulated conductors. Electrical contactors may electrically and physically couple electrical conductors 214A,B to tubular 216. In certain embodiments, the electrical contactors are attached to ends of electrical conductors 214A,B. The electrical contactors have a shape such that when the ends of electrical conductors 214A,B are pushed into the ends of tubular 216, the electrical contactors physically and electrically couple the electrical conductors to the tubular. For example, the electrical contactors may be cone shaped. Heater 212 generates heat when current is applied directly to tubular 216. Current is provided to tubular 216 using electrical conductors 214A,B. Grooves 226 may increase the heat transfer surface area of tubular 216.

[0095] In some embodiments, one or more surfaces of the tubular of an induction heater may be textured to increase the resistance of the heater and increase the heat transfer surface area of the tubular. FIG. 6 depicts heater 212 that is an induction heater. Electrical conductor 214 extends through tubular 216.

[0096] Tubular 216 may include grooves 226. In some embodiments, grooves 226 are cut in tubular 216. In some embodiments, fins are coupled to tubular to form ridges and grooves 226. The fins may be welded or otherwise attached to the tubular. In an embodiment, the fins are coupled to a tubular sheath that is placed over the tubular. The sheath is physically and electrically coupled to the tubular to form tubular 216.

[0097] In certain embodiments, grooves 226 are on the outer surface of tubular 216. In some embodiments, the grooves are on the inner surface of the tubular. In some embodiments, the grooves are on both the inner and outer surfaces of the tubular.

[0098] In certain embodiments, grooves 226 are radial grooves (grooves that wrap around the circumference of tubular 216). In certain embodiments, grooves 226 are straight, angled, or spiral grooves or protrusions. In some embodiments, grooves 226 are evenly spaced grooves along the surface of tubular 216. In some embodiments, grooves 226 are part of a threaded surface on tubular 216 (the grooves are formed as a winding thread on the surface). Grooves 226 may have a variety of shapes as desired. For example, grooves 226 may have square edges, rectangular edges, v-shaped edges, u-shaped edges, or have rounded edges.

[0099] Grooves 226 increase the effective resistance of tubular 216 by increasing the path length of induced current on the surface of the tubular. Grooves 226 increase the effective resistance of tubular 216 as compared to a tubular with the same inside and outside diameters with smooth surfaces. Because induced current travels axially, the induced current has to travel up and down the grooves along the surface of the tubular. Thus, the depth of grooves 226 may be varied to provide a selected resistance in tubular 216. For example, increasing the grooves depth increases the path length and the resistance.

[0100] Increasing the resistance of tubular 216 with grooves 226 increases the heat generation of the tubular as compared to a tubular with smooth surfaces. Thus, the same electrical current in electrical conductor 214 will provide more heat output in the radial grooved surface tubular than the smooth surface tubular. Therefore, to provide the same heat output with the radial grooved surface tubular as the smooth surface tubular, less current is needed in electrical conductor 214 with the radial grooved surface tubular.

[0101] In some embodiments, grooves 226 are filled with materials that decompose at lower temperatures to protect the grooves during installation of tubular 216. For example, grooves 226 may be filled with polyethylene or asphalt. The polyethylene or asphalt may melt and/or desorb when heater 212 reaches normal operating temperatures of the heater.

[0102] It is to be understood that grooves 226 may be used in other embodiments of tubulars 216 described herein to increase the resistance of such tubulars. For example, grooves 226 may be used in embodiments of tubulars 216 depicted in FIGS. 2, 3, and 4.

[0103] FIG. 7 depicts an embodiment of heater 212 divided into tubular sections to provide varying heat outputs along the length of the heater. Heater 212 may include tubular sections 216A, 216B, 216C, 216D that have different properties to provide different heat outputs in each tubular section. Heat output from tubular sections 216D may be less than the heat output from grooved sections 216A, 216B, 216C. Examples of properties that may be varied include, but are not limited to, thicknesses, diameters, cross-sectional areas, resistances, materials, number of grooves, depth of grooves. The different properties in tubular sections 216A, 216B, and 216C may provide different maximum operating temperatures (for example, different Curie temperatures or phase transformation temperatures) along the length of heater 212. The different maximum temperatures of the tubular sections provides different heat outputs from the tubular sections. Sections such as grooved section 216A may be separate sections that are placed down the wellbore in separation installation procedures. Some sections, such as grooved section 216B and 216C may be connected together by non-grooved section 216D, and may be placed down the wellbore together.

[0104] Providing different heat outputs along heater 212 may provide different heating in one or more hydrocarbon layers. For example, heater 212 may be divided into two or more sections of heating to provide different heat outputs to different sections of a hydrocarbon layer and/or different hydrocarbon layers.

[0105] In one embodiment, a first portion of heater 212 may provide heat to a first section of the hydrocarbon layer and a second portion of the heater may provide heat to a second section of the hydrocarbon layer. Hydrocarbons in the first section may be mobilized by the heat provided by the first portion of the heater. Hydrocarbons in the second section may be heated by the second portion of the heater to a higher temperature than the first section. The higher temperature in the second section may upgrade hydrocarbons in the second section relative to the first section. For example, the hydrocarbons may be mobilized, visbroken, and/or pyrolyzed in the second section. Hydrocarbons from the first section may be moved into the second section by, for example, a drive fluid provided to the first section. As another example, heater 212 may have end sections that provide higher heat outputs to counteract heat losses at the ends of the heater to maintain a more constant temperature in the heated portion of the formation.

[0106] In certain embodiments, three, or multiples of three, electrical conductors enter and exit the formation through common wellbores with tubulars surrounding the electrical conductors in the portion of the formation to be heated. FIG. 8 depicts an embodiment of three electrical conductors 214A,B,C entering the formation through first common wellbore 218A and exiting the formation through second common wellbore 218C with three tubulars 216A,B,C surrounding the electrical conductors in hydrocarbon layer 224. In some embodiments, electrical conductors 214A,B,C are powered by a single, three-phase wye transformer. Tubulars 216A,B,C and portions of electrical conductors 214A,B,C may be in three separate wellbores in hydrocarbon layer 224. The three separate wellbores may be formed by drilling the wellbores from first common wellbore 218A to second common wellbore 218B, vice versa, or drilling from both common wellbores and connecting the drilled openings in the hydrocarbon layer.

[0107] Having multiple induction heaters extending from only two wellbores in hydrocarbon layer 224 reduces the footprint of wells on the surface needed for heating the formation. The number of overburden wellbores drilled in the formation is reduced, which reduces capital costs per heater in the formation. Power losses in the overburden may be a smaller fraction of total power supplied to the formation because of the reduced number of wells through the overburden used to treat the formation. In addition, power losses in the overburden may be smaller because the three phases in the common wellbores substantially cancel each other and inhibit induced currents in the casings or other structures of the wellbores.

[0108] In some embodiments, three, or multiples of three, electrical conductors and tubulars are located in separate wellbores in the formation. FIG. 9 depicts an embodiment of three electrical conductors 214A,B,C and three tubulars 216A,B,C in separate wellbores in the formation. Electrical conductors 214A,B,C may be powered by single, three-phase wye transformer 230 with each electrical conductor coupled to one phase of the transformer. In some embodiments, the single, three-phase wye transformer is used to power 6, 9, 12, or other multiples of three electrical conductors. Connecting multiples of three electrical conductors to the single, three-phase wye transformer may reduce equipment costs for providing power to the induction heaters.

[0109] In some embodiments, two, or multiples of two, electrical conductors enter the formation from a first common wellbore and exit the formation from a second common wellbore with tubulars surrounding each electrical conductor in the hydrocarbon layer. The multiples of two electrical conductors may be powered by a single, two-phase transformer. In such embodiments, the electrical conductors may be homogenous electrical conductors (for example, insulated conductors using the same materials throughout) in the overburden sections and heating sections of the insulated conductor. The reverse flow of current in the overburden sections may reduce power losses in the overburden sections of the wellbores because the currents reduce or cancel inductive effects in the overburden sections.

[0110] In certain embodiments, tubulars 216 depicted in FIGS. 2-8 include multiple layers of ferromagnetic materials separated by electrical insulators. FIG. 10 depicts an embodiment of a multilayered induction tubular. Tubular 216 includes ferromagnetic layers 232A,B,C separated by electrical insulators 236A,B. Three ferromagnetic layers and two layers of electrical insulators are shown in FIG. 10. Tubular 216 may include additional ferromagnetic layers and/or electrical insulators as desired. For example, the number of layers may be chosen to provide a desired heat output from the tubular.

[0111] Ferromagnetic layers 232A,B,C are electrically insulated from electrical conductor 214 by, for example, an air gap. Ferromagnetic layers 232A,B,C are electrically insulated from each other by electrical insulator 236A and electrical insulator 236B. Thus, direct flow of current is inhibited between ferromagnetic layers 232A,B,C and electrical conductor 214. When current is applied to electrical conductor 214, electrical current flow is induced in ferromagnetic layers 232A,B,C because of the ferromagnetic properties of the layers. Having two or more electrically insulated ferromagnetic layers provides multiple current induction loops for the induced current. The multiple current induction loops may effectively appear as electrical loads in series to a power source for electrical conductor 214. The multiple current induction loops may increase the heat generation per unit length of tubular 216 as compared to a tubular with only one current induction loop. For the same heat output, the tubular with multiple layers may have a higher voltage and lower current as compared to the single layer tubular.

[0112] In certain embodiments, ferromagnetic layers 232A,B,C include the same ferromagnetic material. In some embodiments, ferromagnetic layers 232A,B,C include different ferromagnetic materials. Properties of ferromagnetic layers 232A,B,C may be varied to provide different heat outputs from the different layers. Examples of properties of ferromagnetic layers 232A,B,C that may be varied include, but are not limited to, ferromagnetic material and thicknesses of the layers.

[0113] Electrical insulators 236A and 236B may be magnesium oxide, porcelain enamel, and/or another suitable electrical insulator. The thicknesses and/or materials of electrical insulators 236A and 236B may be varied to provide different operating parameters for tubular 216.

[0114] In some embodiments, fluids are circulated through tubulars 216 depicted in FIGS. 2-8. In some embodiments, fluids are circulated through the tubulars to add heat to the formation. For example, fluids may be circulated through the tubulars to preheat the formation prior to energizing the tubulars (providing current to the heating system). In some embodiments, fluids are circulated through the tubulars to recover heat from the formation. The recovered heat may be used to provide heat to other portions of the formation and/or surface processes used to treat fluids produced from the formation. In some embodiments, the fluids are used to cool down the heater.

[0115] In certain embodiments, insulated conductors are operated as induction heaters. FIG. 11 depicts a cross-sectional end view of an embodiment of insulated conductor 240 that is used as an induction heater. FIG. 12 depicts a cross-sectional side view of the embodiment depicted in FIG. 11. Insulated conductor 240 includes core 234, electrical insulator 236, and jacket 238. Core 234 may be copper or another non-ferromagnetic electrical conductor with low resistance that provides little or no heat output. In some embodiments, core may be clad with a thin layer of material such as nickel to inhibit migration of portions of the core into electrical insulator 236. Electrical insulator 236 may be magnesium oxide or another suitable electrical insulator that inhibits arcing at high voltages.

[0116] Jacket 238 includes at least one ferromagnetic material. In certain embodiments, jacket 238 includes carbon steel or another ferromagnetic steel (for example, 410 stainless steel, 446 stainless steel, T/P91 stainless steel, T/P92 stainless steel, alloy 52, alloy 42, and Invar 36). In some embodiments, jacket 238 includes an outer layer of corrosion resistant material (for example, stainless steel such as 347H stainless steel or 304 stainless steel). The outer layer may be clad to the ferromagnetic material or otherwise coupled to the ferromagnetic material using methods known in the art.

[0117] In certain embodiments, jacket 238 has a thickness of at least about 2 skin depths of the ferromagnetic material in the jacket. In some embodiments, jacket 238 has a thickness of at least about 3 skin depths, at least about 4 skin depths, or at least about 5 skin depths. Increasing the thickness of jacket 238 may increase the heat output from insulated conductor 240.

[0118] In one embodiment, core 234 is copper with a diameter of about 0.5” (1.27 cm), electrical insulator 236 is magnesium oxide with a thickness of about 0.20” (0.5 cm) (the outside diameter is about 0.9” (2.3 cm)), and jacket 238 is carbon steel with an outside diameter of about 1.6” (4.1 cm) (the thickness is about 0.35” (0.88 cm)). A thin layer (about 0.1” (0.25 cm) thickness (outside diameter of about 1.7” (4.3 cm)) of corrosion resistant material 347H stainless steel may be clad on the outside of jacket 238.

[0119] In another embodiment, core 234 is copper with a diameter of about 0.338” (0.86 cm), electrical insulator 236 is magnesium oxide with a thickness of about 0.096” (0.24 cm) (the outside diameter is about 0.53” (1.3 cm)), and jacket 238 is carbon steel with an outside diameter of about 1.13” (2.9 cm) (the thickness is about 0.30” (0.76 cm)). A thin layer (about 0.065” (0.17 cm) thickness (outside diameter of about 1.26” (3.2 cm)) of corrosion resistant material 347H stainless steel may be clad on the outside of jacket 238.

[0120] In another embodiment, core 234 is copper, electrical insulator 236 is magnesium oxide, and jacket 238 is a thin layer of copper surrounded by carbon steel. Core 234, electrical insulator 236, and the thin copper layer of jacket 238 may be obtained as a single piece of insulated conductor. Such insulated conductors may be obtained as long pieces of insulated conductors (for example, lengths of about 500’ (about 150 m) or more). The carbon steel layer of jacket 238 may be added by drawing down the carbon steel over the long insulated conductor. Such an insulated conductor may only generate heat on the outside of jacket 238 as the thin copper layer in the jacket shorts to the inside surface of the jacket.

[0121] In some embodiments, jacket 238 is made of multiple layers of ferromagnetic material. The multiple layers may be the same ferromagnetic material or different ferromagnetic materials. For example, in one embodiment, jacket 238 is a 0.35” (0.88 cm) thick carbon steel jacket made from three layers of carbon steel. The first and second layers are 0.10” (0.25 cm) thick and the third layer is 0.15” (0.38 cm) thick. In another embodiment, jacket 238 is a 0.3” (0.76 cm) thick carbon steel jacket made from three 0.10” (0.25 cm) thick layers of carbon steel.

[0122] In certain embodiments, jacket 238 and core 234 are electrically insulated such that there is no direct electrical connection between the jacket and the core. Core 234 may be electrically coupled to a single power source with each end of the core being coupled to one pole of the power source. For example, insulated conductor 240 may be a u-shaped heater located in a u-shaped wellbore with each end of core 234 being coupled to one pole of the power source.

[0123] When core 234 is energized with time-varying current, the core induces electrical current flow on the surfaces of jacket 238 (as shown by the arrows in FIG. 12) due to the ferromagnetic properties of the ferromagnetic material in the jacket. In certain embodiments, current flow is induced on both the inside and outside surfaces of jacket 238.

In these induction heater embodiments, jacket 238 operates as the heating element of insulated conductor 240.

[0124] At or near the Curie temperature or the phase transformation temperature of the ferromagnetic material in jacket 238, the magnetic permeability of the ferromagnetic material decreases rapidly. When the magnetic permeability of jacket 238 decreases at or near the Curie temperature or the phase transformation temperature, there is little or no current flow in the jacket because, at these temperatures, the jacket is essentially non-ferromagnetic and core 234 is unable to induce current flow in the jacket. With little or no current flow in jacket 238, the temperature of the jacket will drop to lower temperatures until the magnetic permeability increases and the jacket becomes ferromagnetic. Thus, jacket 238 self-limits at or near the Curie temperature or the phase transformation temperature and insulated conductor 240 operates as a temperature limited heater due to the ferromagnetic properties of the jacket. Because current is induced in jacket 238, the turndown ratio may be higher and the drop in current sharper for the jacket than if current is directly applied to the jacket.

[0125] In certain embodiments, portions of jacket 238 in the overburden of the formation do not include ferromagnetic material (for example, are non-ferromagnetic). Having the overburden portions of jacket 238 made of non-ferromagnetic material inhibits current induction in the overburden portions of the jackets. Power losses in the overburden are inhibited or reduced by inhibiting current induction in the overburden portions.

[0126] FIG. 13 depicts a cross-sectional view of an embodiment of two-leg insulated conductor 240 that is used as an induction heater. FIG. 14 depicts a longitudinal cross-sectional view of the embodiment depicted in FIG. 13. Insulated conductor 240 is a two-leg insulated conductor that includes two cores 234A,B; two electrical insulators 236A,B; and two jackets 238A,B. The two legs of insulated conductor 240 may be in physical contact with each other such that jacket 238A contacts jacket 238B along their lengths. Cores 234A,B; electrical insulators 236A,B; and jackets 238A,B may include materials such as those used in the embodiment of insulated conductor 240 depicted in FIGS. 11 and 12.

[0127] As shown in FIG. 14, core 234A and core 234B are coupled to transformer 230 and terminal block 242. Thus, core 234A and core 234B are electrically coupled in series such that current in core 234A flows in an opposite direction from current in core 234B, as shown by the arrows in FIG. 14. Current flow in cores 234A,B induces current flow in jackets 238A,B, respectively, as shown by the arrows in FIG. 14.

[0128] I n certain embodiments, portions of jacket 238A and/or jacket 238B are coated with an electrically insulating coating (for example, a porcelain enamel coating, alumina coating, and/or alumina-titania coating). The electrically insulating coating may inhibit the currents in one jacket from affecting current in the other jacket or vice versa (for example, current in one jacket cancelling out current in the other jacket). Electrically insulating the jackets from each other may inhibit the turndown ratio of the heater from being reduced by the interaction of induced currents in the jackets.

[0129] Because core 234A and core 234B are electrically coupled in series to a single transformer (transformer 230), insulated conductor 240 may be located in a wellbore that terminates in the formation (for example, a wellbore with a single surface opening such as an L-shaped or J-shaped wellbore). Insulated conductor 240, as depicted in FIG. 14, may be operated as a subsurface termination induction heater with electrical connections between the heater and the power source (the transformer) being made through one surface opening.

[0130] Portions of jackets 238A,B in the overburden and/or adjacent to portions of the formation that are not to be significantly heated (for example, thick shale breaks between two hydrocarbon layers) may be non-ferromagnetic to inhibit induction currents in such portions. The jacket may include one or more sections that are electrically insulating to restrict induced current flow to heater portions of the insulated conductor. Inhibiting induction currents in the overburden portion of the jackets inhibits inductive heating and/or power losses in the overburden. Induction effects in other structures in the overburden that surround insulated conductor 240 (for example, overburden casings) may be inhibited because the current in core 234A flows in an opposite direction from the current in core 234B.

[0131] FIG. 15 depicts a cross-sectional view of an embodiment of a multilayered insulated conductor that is used as an induction heater. Insulated conductor 240 includes core 234 surrounded by electrical insulator 236A and jacket 238A. Electrical insulator 236A and jacket 238A comprise a first layer of insulated conductor 240. The first layer is surrounded by a second layer that includes electrical insulator 236B and jacket 238B. Two layers of electrical insulators and jackets are shown in FIG. 15. The insulated conductor may include additional layers as desired. For example, the number of layers may be chosen to provide a desired heat output from the insulated conductor.

[0132] Jacket 238A and jacket 238B are electrically insulated from core 234 and each other by electrical insulator 236A and electrical insulator 236B. Thus, direct flow of current is inhibited between jacket 238A and jacket 238B and core 234. When current is applied to core 234, electrical current flow is induced in both jacket 238A and jacket 238B because of the ferromagnetic properties of the jackets. Having two or more layers of electrical insulators and jackets provides multiple current induction loops. The multiple current induction loops may effectively appear as electrical loads in series to a power source for insulated conductor 240. The multiple current induction loops may increase the heat generation per unit length of insulated conductor 240 as compared to an insulated conductor with only one current induction loop. For the same heat output, the insulated conductor with multiple layers may have a higher voltage and lower current as compared to the single layer insulated conductor.

[0133] In certain embodiments, jacket 238A and jacket 238B include the same ferromagnetic material. In some embodiments, jacket 238A and jacket 238B include different ferromagnetic materials. Properties of jacket 238A and jacket 238B may be varied to provide different heat outputs from the different layers. Examples of properties of jacket 238A and jacket 238B that may be varied include, but are not limited to, ferromagnetic material and thicknesses of the layers.

[0134] Electrical insulators 236A and 236B may be magnesium oxide, porcelain enamel, and/or another suitable electrical insulator. The thicknesses and/or materials of electrical insulators 236A and 236B may be varied to provide different operating parameters for insulated conductor 240.

[0135] FIG. 16 depicts an end view of an embodiment of three insulated conductors 240 located in a coiled tubing conduit and used as induction heaters. Insulated conductors 240 may each be, for example, the insulated conductor depicted in FIGS. 11, 12, and 15. The cores of insulated conductors 240 may be coupled to each other such that the insulated conductors are electrically coupled in a three-phase wye configuration. FIG. 17 depicts a representation of cores 234 of insulated conductors 240 coupled together at their ends.

[0136] As shown in FIG. 16, insulated conductors 240 are located in tubular 216. Tubular 216 may be a coiled tubing conduit or other coiled tubing tubular or casing. Insulated conductors 240 may be in a spiral or helix formation inside tubular 216 to reduce stresses on the insulated conductors when the insulated conductors are coiled, for example, on a coiled tubing reel. Tubular 216 allows the insulated conductors to be installed in the formation using a coiled tubing rig and protects the insulated conductors during installation into the formation.

[0137] FIG. 18 depicts an end view of an embodiment of three insulated conductors 240 located on a support member and used as induction heaters. Insulated conductors 240 may each be, for example, the insulated conductor depicted in FIGS. 11, 12, and 15. The cores of insulated conductors 240 may be coupled to each other such that the insulated conductors are electrically coupled in a three-phase wye configuration. For example, the cores may be coupled together as shown in FIG. 17.

[0138] As shown in FIG. 18, insulated conductors 240 are coupled to support member 244. Support member 244 provides support for insulated conductors 240. Insulated conductors 240 may be wrapped around support member 244 in a spiral or helix formation. In some embodiments, support member 244 includes ferromagnetic material. Current flow may be induced in the ferromagnetic material of support member 244. Thus, support member 244 may generate some heat in addition to the heat generated in the jackets of insulated conductors 240.

[0139] In certain embodiments, insulated conductors 240 are held together on support member 244 with band 246. Band 246 may be stainless steel or another non-corrosive material. In some embodiments, band 246 includes a plurality of bands that hold together insulated conductors 240. The bands may be periodically placed around insulated conductors 240 to hold the conductors together.

[0140] In some embodiments, jacket 238, depicted in FIGS. 11 and 12, or jackets 238A,B, depicted in FIG. 14, include grooves or other structures on the outer surface and/or the inner surface of the jacket to increase the effective resistance of the jacket. Increasing the resistance of jacket 238 and/or jackets 238A,B with grooves increases the heat generation of the jackets as compared to jackets with smooth surfaces. Thus, the same electrical current in core 234 and/or cores 234A,B will provide more heat output in the grooved surface jackets than the smooth surface jackets.

[0141] In some embodiments, jacket 238 (such as the jackets depicted in FIGS. 11 and 12, or jackets 238A,B depicted in FIG. 14) are divided into sections to provide varying heat outputs along the length of the heaters. For example, jacket 238 and/or jackets 238A,B may be divided into sections such as tubular sections 216A, 216B, and 216C, depicted in

FIG. 7. The sections of the jackets 238 depicted in FIGS. 11, 12, and 14 may have different properties to provide different heat outputs in each section. Examples of properties that may be varied include, but are not limited to, thicknesses, diameters, resistances, materials, number of grooves, depth of grooves. The different properties in the sections may provide different maximum operating temperatures (for example, different Curie temperatures or phase transformation temperatures) along the length of insulated conductor 240. The different maximum temperatures of the sections provides different heat outputs from the sections.

[0142] In certain embodiments, induction heaters include insulated electrical conductors surrounded by spiral wound ferromagnetic materials. For example, the spiral wound ferromagnetic materials may operate as inductive heating elements similarly to tubulars 216, depicted in FIGS. 2-8. FIG. 19 depicts a representation of an embodiment of an induction heater with core 234 and electrical insulator 236 surrounded by ferromagnetic layer 232. Core 234 may be copper or another non-ferromagnetic electrical conductor with low resistance that provides little or no heat output. Electrical insulator 236 may be a polymeric electrical insulator such as Teflon®, XPLE (cross-linked polyethylene), or EPDM (ethylene-propylene diene monomer). In some embodiments, core 234 and electrical insulator 236 are obtained together as a polymer (insulator) coated cable. In some embodiments, electrical insulator 236 is magnesium oxide or another suitable electrical insulator that inhibits arcing at high voltages and/or at high temperatures.

[0143] In certain embodiments, ferromagnetic layer 232 is spirally wound onto core 234 and electrical insulator 236. Ferromagnetic layer 232 may include carbon steel or another ferromagnetic steel (for example, 410 stainless steel, 446 stainless steel, T/P91 stainless steel, T/P92 stainless steel, alloy 52, alloy 42, and Invar 36).

[0144] In some embodiments, ferromagnetic layer 232 is spirally wound onto an insulated conductor. In some embodiments, ferromagnetic layer 232 includes an outer layer of corrosion resistant material. In some embodiments, ferromagnetic layer is bar stock. FIG. 20 depicts a representation of an embodiment of insulated conductor 240 surrounded by ferromagnetic layer 232. Insulated conductor 240 includes core 234, electrical insulator 236, and jacket 238. Core 234 is copper or another non-ferromagnetic electrical conductor with low resistance that provides little or no heat output. Electrical insulator 236 is magnesium oxide or another suitable electrical insulator. Ferromagnetic layer 232 is spirally wound onto insulated conductor 240.

[0145] Spirally winding ferromagnetic layer 232 onto the heater may increase control over the thickness of the ferromagnetic layer as compared to other construction methods for induction heaters. For example, more than one ferromagnetic layer 232 may be wound onto the heater to vary the output of the heater. The number of ferromagnetic layers 232 may be chosen to provide desired output from the heater. FIG. 21 depicts a representation of an embodiment of an induction heater with two ferromagnetic layers 232A,B spirally wound onto core 234 and electrical insulator 236. In some embodiments, ferromagnetic layer 232A is counter-wound relative to ferromagnetic layer 232B to provide neutral torque on the heater. Neutral torque may be useful when the heater is suspended or allowed to hang freely in an opening in the formation.

[0146] The number of spiral windings (for example, the number of ferromagnetic layers) may be varied to alter the heat output of the induction heater. In addition, other parameters may be varied to alter the heat output of the induction heater. Examples of other varied parameters include, but are not limited to, applied current, applied frequency, geometry, ferromagnetic materials, and thickness and/or number of spiral windings.

[0147] Use of spiral wound ferromagnetic layers may allow induction heaters to be manufactured in continuous long lengths by spiral winding the ferromagnetic material onto long lengths of conventional or easily manufactured insulated cable. Thus, spiral wound induction heaters may have reduced manufacturing costs as compared to other induction heaters. The spiral wound ferromagnetic layers may increase the mechanical flexibility of the induction heater as compared to solid ferromagnetic tubular induction heaters. The increased flexibility may allow spiral wound induction heaters to be bent over surface protrusions such as hanger joints.

[0148] FIG. 22 depicts an embodiment for assembling ferromagnetic layer 232 onto insulated conductor 240. Insulated conductor 240 may be an insulated conductor cable (for example, mineral insulated conductor cable or polymer insulated conductor cable) or other suitable electrical conductor core covered by insulation.

[0149] In certain embodiments, ferromagnetic layer 232 is made of ferromagnetic material 254 fed from reel 252 and wound onto insulated conductor 240. Reel 252 may be a coiled tubing rig or other rotatable feed rig. Reel 252 may rotate around insulated conductor 240 as ferromagnetic material 254 is wound onto the insulated conductor to form ferromagnetic layer 232. Insulated conductor 240 may be fed from a reel or from a mill as reel 252 rotates around the insulated conductor.

[0150] In some embodiments, ferromagnetic material 254 is heated prior to winding the material onto insulated conductor 240. For example, ferromagnetic material 254 may be heated using inductive heater 256. Pre-heating ferromagnetic material 254 prior to winding the ferromagnetic material may allow the ferromagnetic material to contract and grip onto insulated conductor 240 when the ferromagnetic material cools.

[0151] In some embodiments, portions of casings in the overburden sections of heater wellbores have surfaces that are shaped to increase the effective diameter of the casing. Casings in the overburden sections of heater wellbores may include, but are not limited to, overburden casings, heater casings, heater tubulars, and/or jackets of insulated conductors. Increasing the effective diameter of the casing may reduce inductive effects in the casing when current used to power a heater or heaters below the overburden is transmitted through the casing (for example, when one phase of power is being transmitted through the overburden section). When current is transmitted in only one direction through the overburden, the current may induce other currents in ferromagnetic or other electrically conductive materials such as those found in overburden casings. These induced currents may provide undesired power losses and/or undesired heating in the overburden of the formation.

[0152] FIG. 23 depicts an embodiment of casing 248 having a grooved or corrugated surface. In certain embodiments, casing 248 includes grooves 250. In some embodiments, grooves 250 are corrugations or include corrugations. Grooves 250 may be formed as a part of the surface of casing 248 (for example, the casing is formed with grooved surfaces) or the grooves may be formed by adding or removing (for example, milling) material on the surface of the casing. For example, grooves 250 may be located on a long piece of tubular that is welded to casing 248.

[0153] In certain embodiments, grooves 250 are on the outer surface of casing 248. In some embodiments, grooves 250 are on the inner surface of casing 248. In some embodiments, grooves 250 are on both the inner and outer surfaces of casing 248.

[0154] In certain embodiments, grooves 250 are axial grooves (grooves that go longitudinally along the length of casing 248). In certain embodiments, grooves 250 are straight, angled, or longitudinally spiral. In some embodiments, grooves 250 are substantially axial grooves or spiral grooves with a significant longitudinal component (i.e., the spiral angle is less than 10°, less than 5°, or less than 1°). In some embodiments, grooves 250 extend substantially axially along the length of casing 248. In some embodiments, grooves 250 are evenly spaced grooves along the surface of casing 248. Grooves 250 may have a variety of shapes as desired. For example, grooves 250 may have square edges, v-shaped edges, u-shaped edges, rectangular edges, or have rounded edges.

[0155] Grooves 250 increase the effective circumference of casing 248. Grooves 250 increase the effective circumference of casing 248 as compared to the circumference of a casing with the same inside and outside diameters and smooth surfaces. The depth of grooves 250 may be varied to provide a selected effective circumference of casing 248. For example, axial grooves that are ¼" (0.63 cm) wide and ¼" (0.63 cm) deep, and spaced ¼" (0.63 cm) apart may increase the effective circumference of a 6" (15.24 cm) diameter pipe from 18.84" (47.85 cm) to 37.68" (95.71 cm) (or the circumference of a 12" (30.48 cm) diameter pipe).

[0156] In certain embodiments, grooves 250 increase the effective circumference of casing 248 by a factor of at least about 2 as compared to a casing with the same inside and outside diameters and smooth surfaces. In some embodiments, grooves 250 increase the effective circumference of casing 248 by a factor of at least about 3, at least about 4, or at least about 6 as compared to a casing with the same inside and outside diameters and smooth surfaces.

[0157] Increasing the effective circumference of casing 248 with grooves 250 increases the surface area of the casing. Increasing the surface area of casing 248 reduces the induced current in the casing for a given current flux. Power losses associated with inductive heating in casing 248 are reduced as compared to a casing with smooth surfaces because of the reduced induced current. Thus, the same electrical current will provide less heat output from inductive heating in the axial grooved surface casing than the smooth surface casing. Reducing the heat output in the overburden section of the heater will increase the efficiency of, and reduce the costs associated with, operating the heater. Increasing the effective circumference of casing 248 and reducing inductive effects in the casing allows the casing to be made with less expensive materials such as carbon steel.

[0158] In some embodiments, an electrically insulating coating (for example, a porcelain enamel coating) is placed on one or more surfaces of casing 248 to inhibit current and/or power losses from the casing. In some embodiments, casing 248 is formed from two or more longitudinal sections of casing (for example, longitudinal sections welded or threaded together end to end). The longitudinal sections may be aligned so that the grooves on the sections are aligned. Aligning the sections may allow for cement or other material to flow along the grooves.

[0159] 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 heating system for a subsurface formation, comprising:

an elongated electrical conductor located in the subsurface formation, wherein the electrical conductor extends between at least a first electrical contact and a second electrical contact; and

a ferromagnetic conductor, wherein the ferromagnetic conductor at least partially surrounds and at least partially extends lengthwise around the electrical conductor;

wherein the electrical conductor, when energized with time-varying electrical current, induces sufficient electrical current flow in the ferromagnetic conductor such that the ferromagnetic conductor resistively heats to a temperature of at least about 300 °C.

2. The system of claim 1, wherein the electrical conductor comprises a substantially u-shaped electrical conductor.

3. The system of claim 1, wherein the ferromagnetic conductor is configured to provide heat to at least a portion of the subsurface formation.

4. The system of claim 1, wherein the ferromagnetic conductor is configured to resistively heat to a temperature of at least about 500 °C.

5. The system of claim 1, wherein the ferromagnetic conductor is configured to resistively heat to a temperature of at least about 700 °C.

6. The system of claim 1, wherein at least about 10 m of length of the ferromagnetic conductor is configured to resistively heat to the temperature of at least about 300 °C.

7. The system of claim 1, wherein the ferromagnetic conductor comprises carbon steel.

8. The system of claim 1, wherein the electrical conductor is the core of an insulated conductor.

9. The system of claim 1, wherein the ferromagnetic conductor has a thickness of at least 2.1 times the skin depth of the ferromagnetic material in the ferromagnetic conductor at 50 °C below the Curie temperature of the ferromagnetic material.

10. The system of claim 1, wherein the ferromagnetic conductor and the electrical conductor are configured in relation to each other such that electrical current does not flow from the electrical conductor to the ferromagnetic conductor, or vice versa.

11. The system of claim 1, wherein the ferromagnetic conductor is configured to provide different heat outputs along at least a portion of the length of the ferromagnetic conductor.

12. The system of claim 1, wherein the ferromagnetic conductor has different materials along at least a portion of the length of the ferromagnetic conductor that are configured to provide different heat outputs along at least a portion of the length of the ferromagnetic conductor.

13. The system of claim 1, wherein the ferromagnetic conductor has different dimensions along at least a portion of the length of the ferromagnetic conductor that are configured to provide different heat outputs along at least a portion of the length of the ferromagnetic conductor.

14. The system of claim 1, further comprising a corrosion resistant material coating on at least a portion of the ferromagnetic conductor.

15. The system of claim 1, wherein the ferromagnetic conductor is substantially cylindrical, and between about 3 cm and about 13 cm in diameter.

16. The system of claim 1, wherein at least about 10 m of length of the ferromagnetic conductor is positioned in a hydrocarbon containing layer in the subsurface formation.

17. The system of claim 1, wherein the electrical conductor is configured to flow electrical current in one direction from the first electrical contact to the second electrical contact.

18. The system of claim 1, wherein the ferromagnetic conductor comprises a ferromagnetic tubular.

19. The system of claim 1, wherein the ferromagnetic conductor comprises two or more ferromagnetic layers, the ferromagnetic layers being separated by one or more insulation layers, wherein the electrical conductor, when energized with time-varying electrical current, induces sufficient electrical current flow in at least two of the ferromagnetic layers such that at least two of the ferromagnetic layers resistively heat.

20. The system of claim 1, wherein the electrical conductor is a substantially u-shaped electrical conductor located in a u-shaped wellbore in the formation.

21. A method for heating a subsurface formation, comprising:

providing time-varying electrical current to the system of any of claims 1-20;

inducing electrical current flow in the ferromagnetic conductor with the time-varying electrical current in the electrical conductor; and resistively heating the ferromagnetic conductor with the induced electrical current flow such that the ferromagnetic conductor resistively heats to a temperature of at least about 300 °C.

22. The method of claim 21, further comprising allowing heat to transfer from the ferromagnetic conductor to at least a portion of the subsurface formation.

23. The method of claim 21, further comprising applying the electrical current to the electrical conductor in one direction from the first electrical contact to the second electrical contact.

24. The method of claim 21, further comprising allowing heat to transfer from the ferromagnetic conductor to at least a portion of the subsurface formation such that hydrocarbons in the formation are mobilized.

25. The method of claim 21, further comprising allowing heat to transfer from the ferromagnetic conductor to at least a portion of the subsurface formation such that hydrocarbons in the formation are mobilized, and producing at least some of the mobilized hydrocarbons from the formation.

26. The method of claim 21, further comprising resistively heating at least one additional ferromagnetic conductor located in the formation, and providing heat from one or more of the ferromagnetic conductors such that heat from at least two of the ferromagnetic conductors is superpositioned in the formation and mobilizes hydrocarbons in the formation.

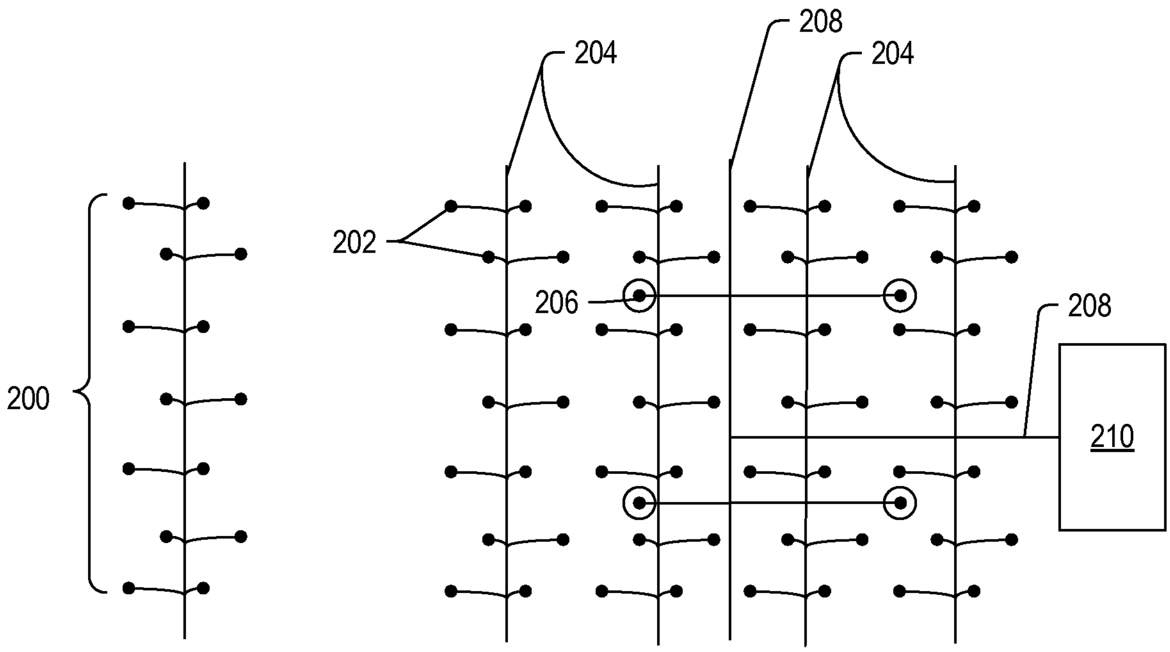
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FIG. 1

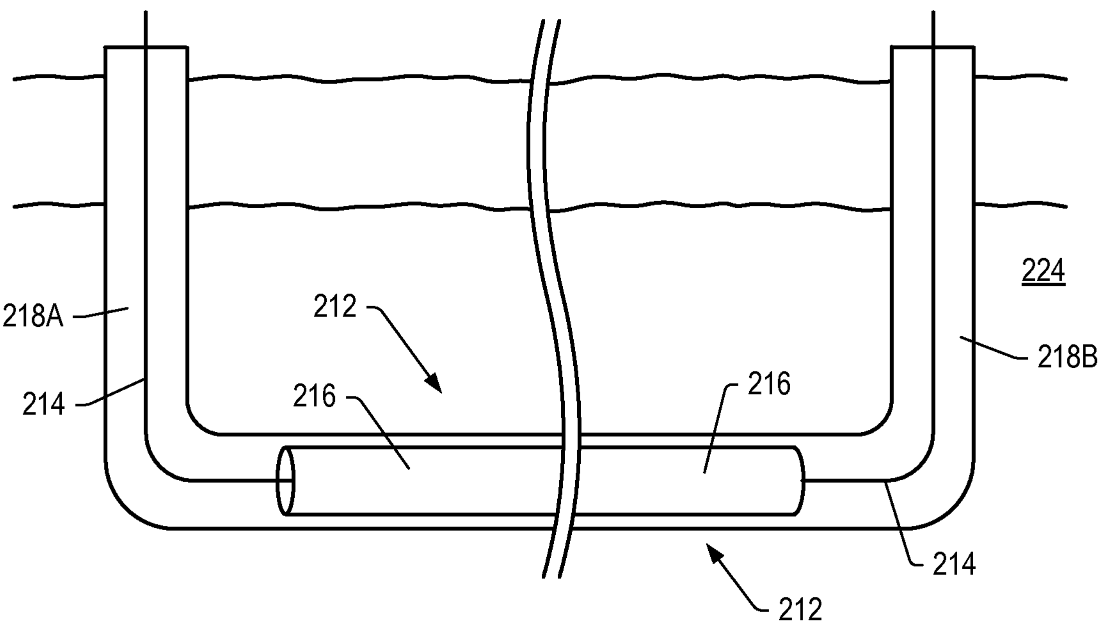
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FIG. 2

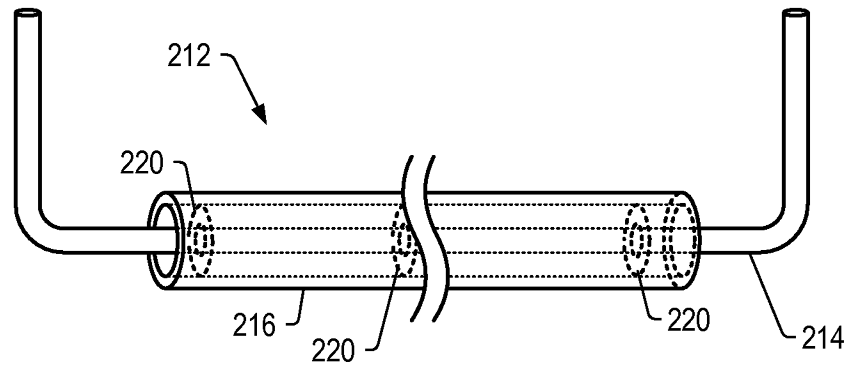

FIG. 3

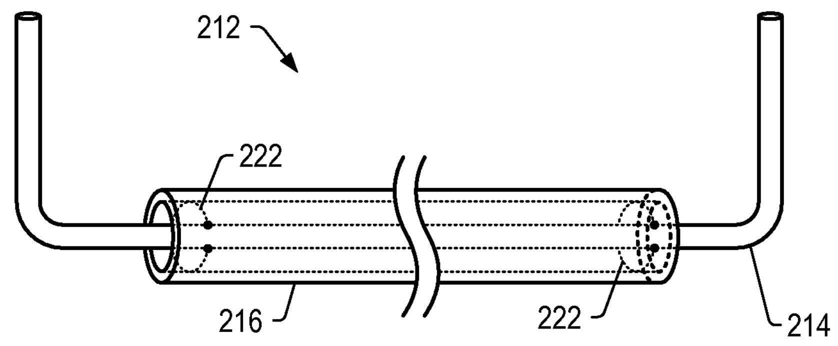

FIG. 4

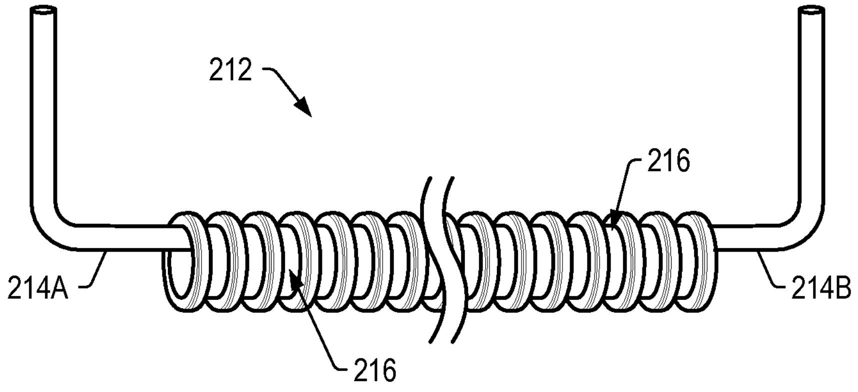

FIG. 5

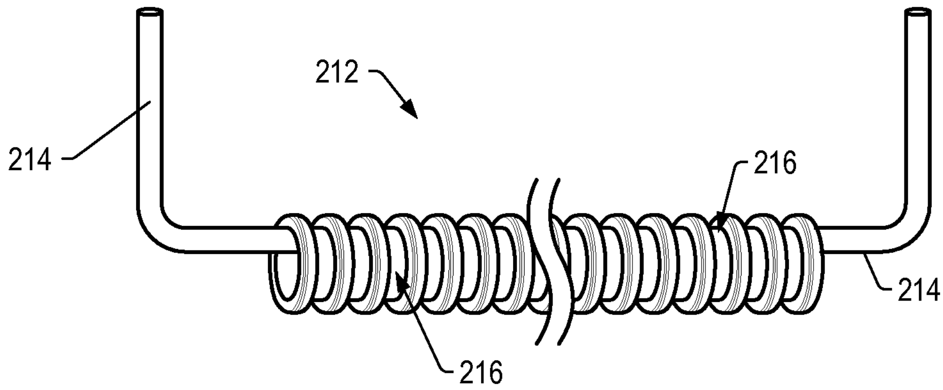

FIG. 6

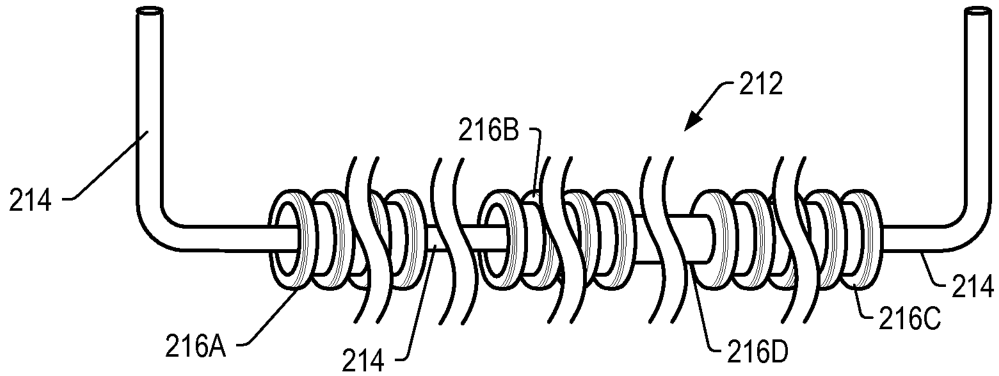

FIG. 7

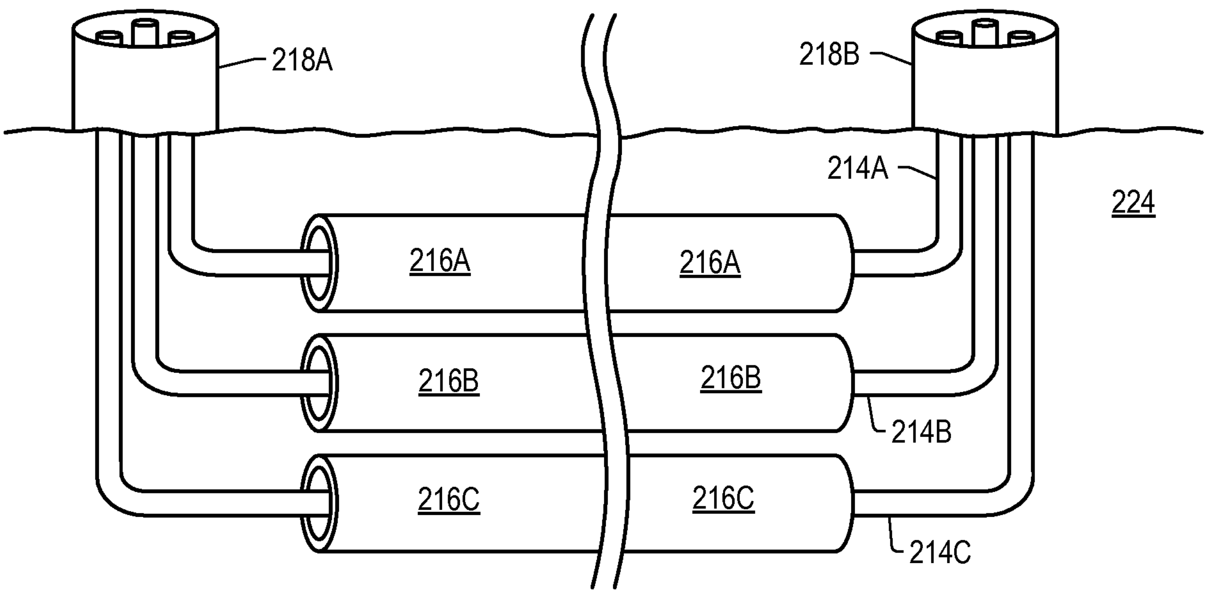

FIG. 8

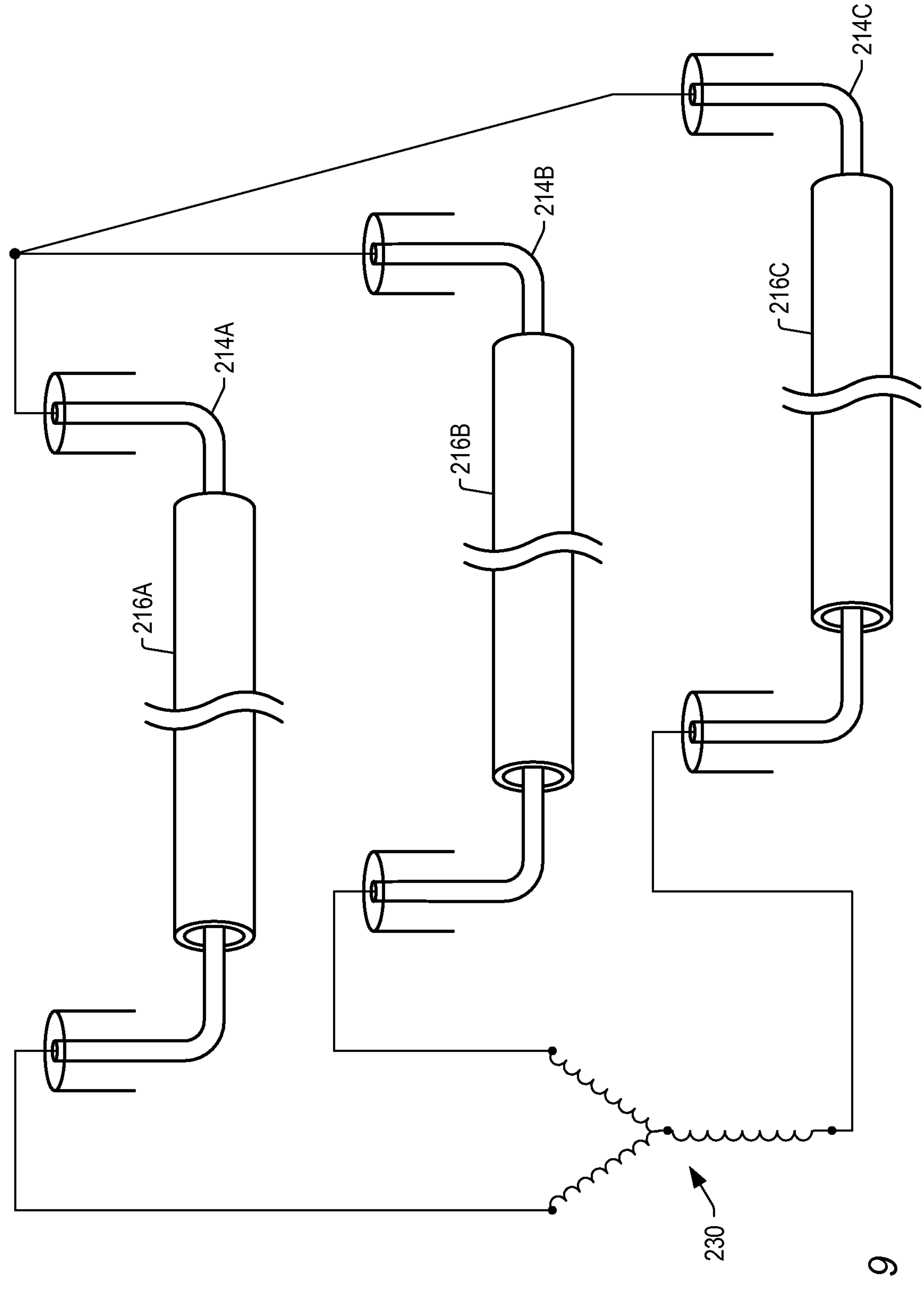

FIG. 9

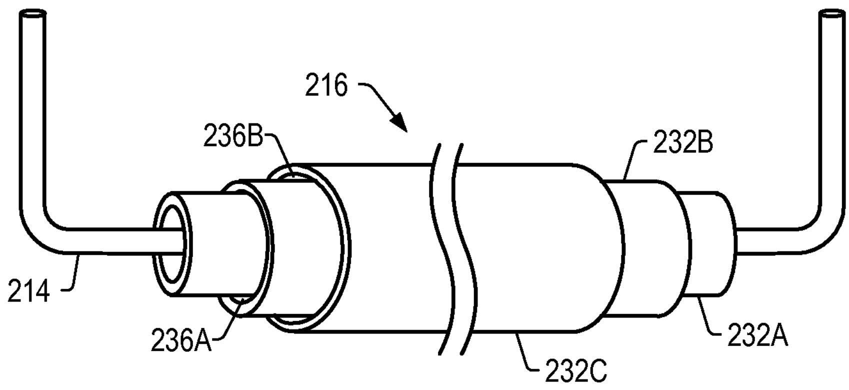

FIG. 10

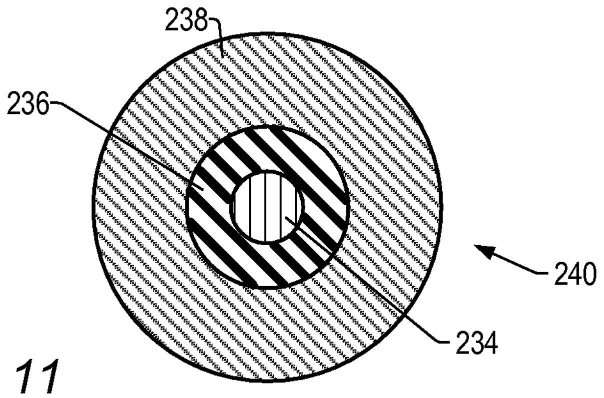

FIG. 11

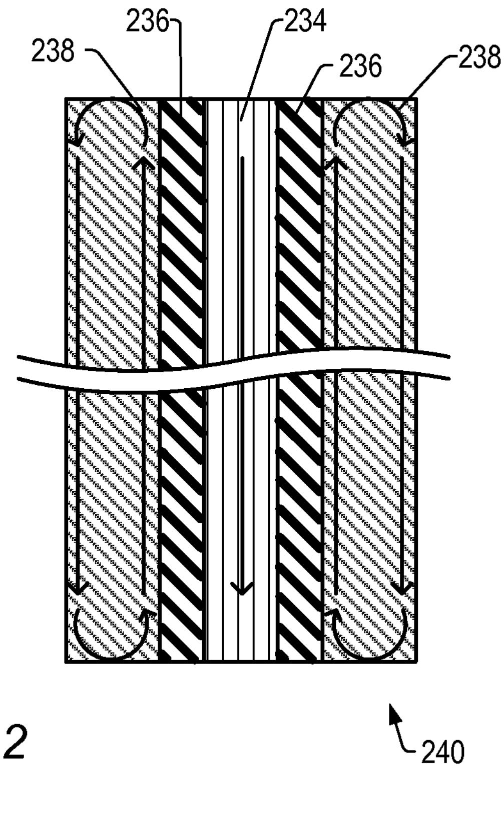

FIG. 12

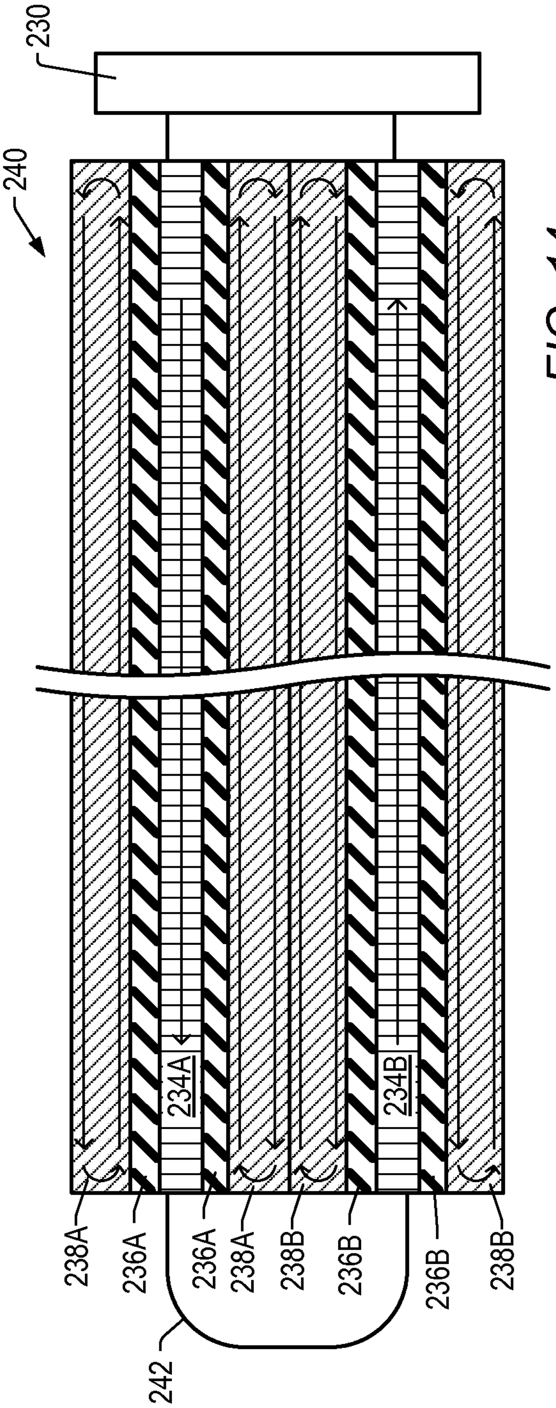

FIG. 14

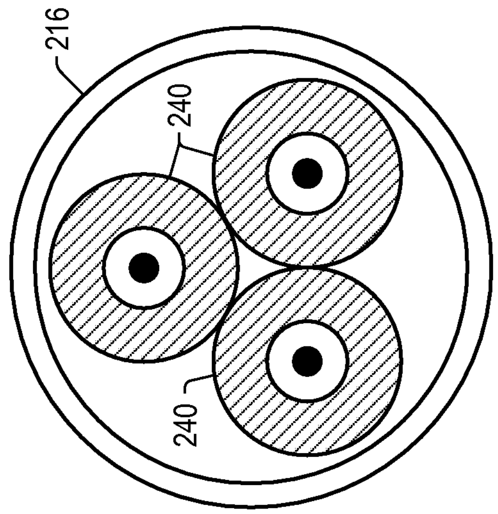

FIG. 16

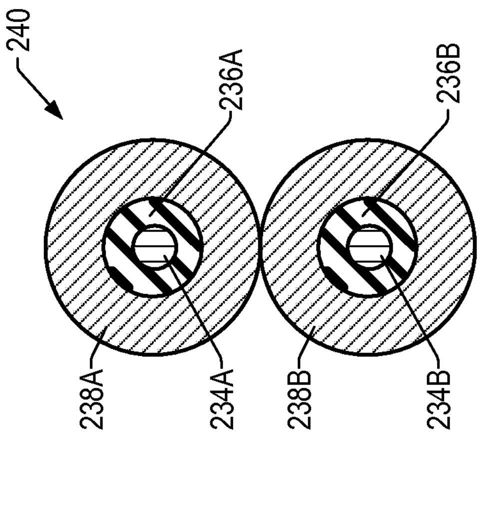

FIG. 13

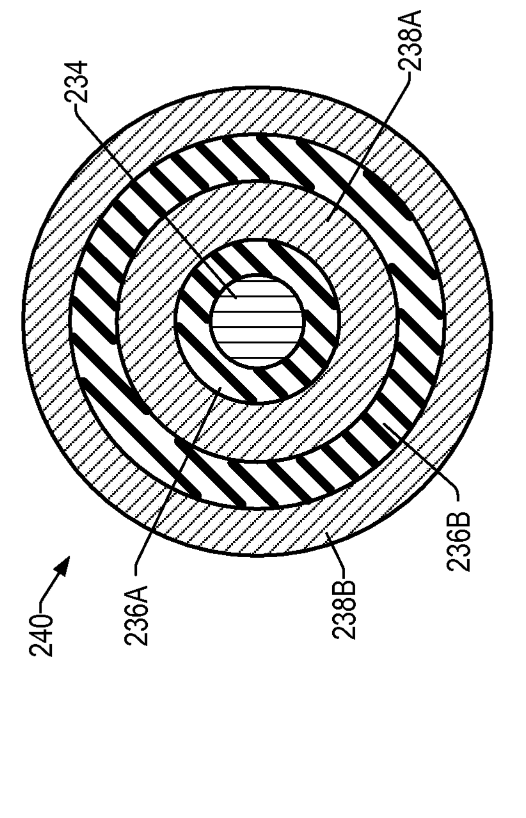

FIG. 15

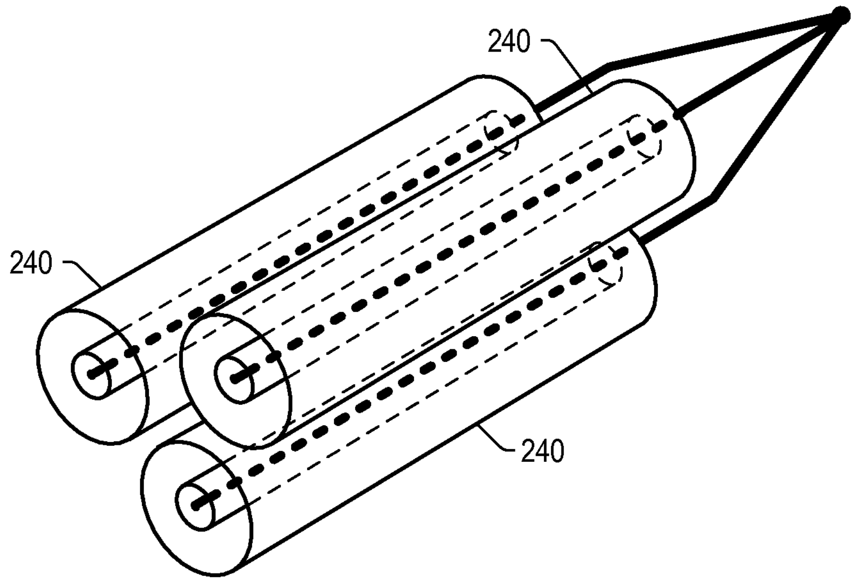

FIG. 17

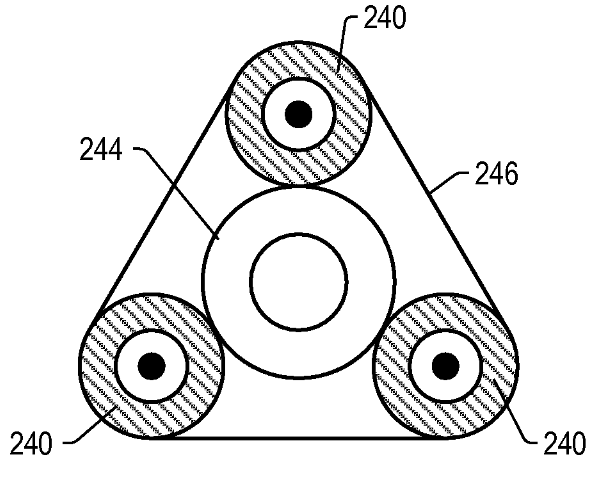

FIG. 18

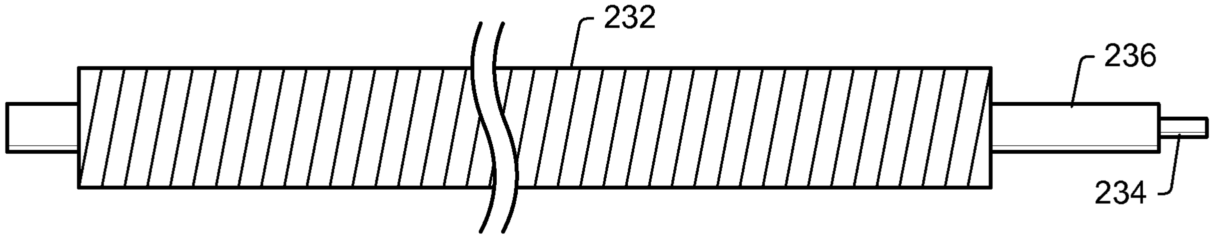

FIG. 19

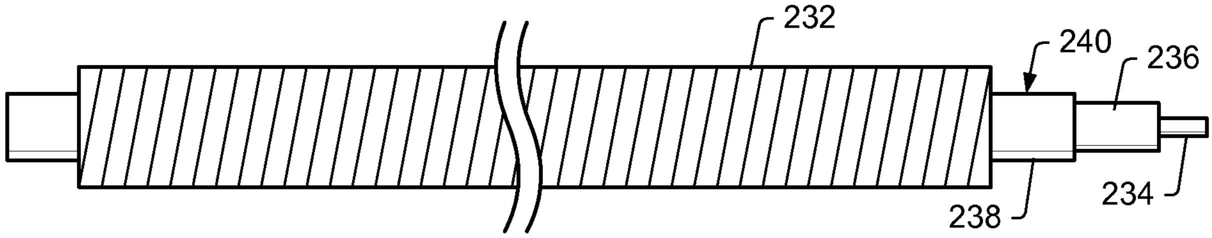

FIG. 20

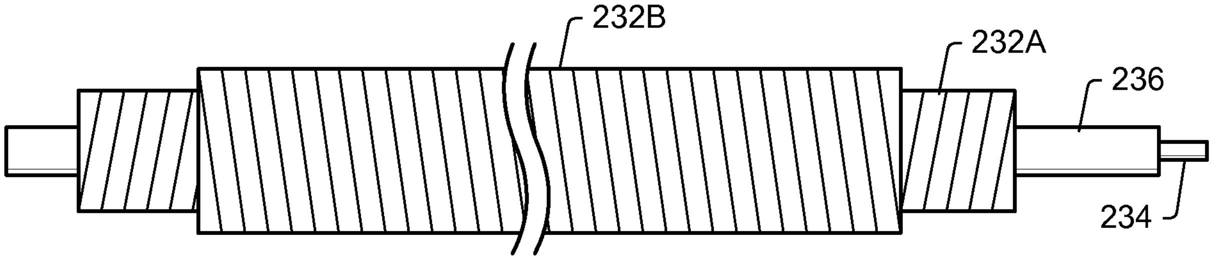

FIG. 21

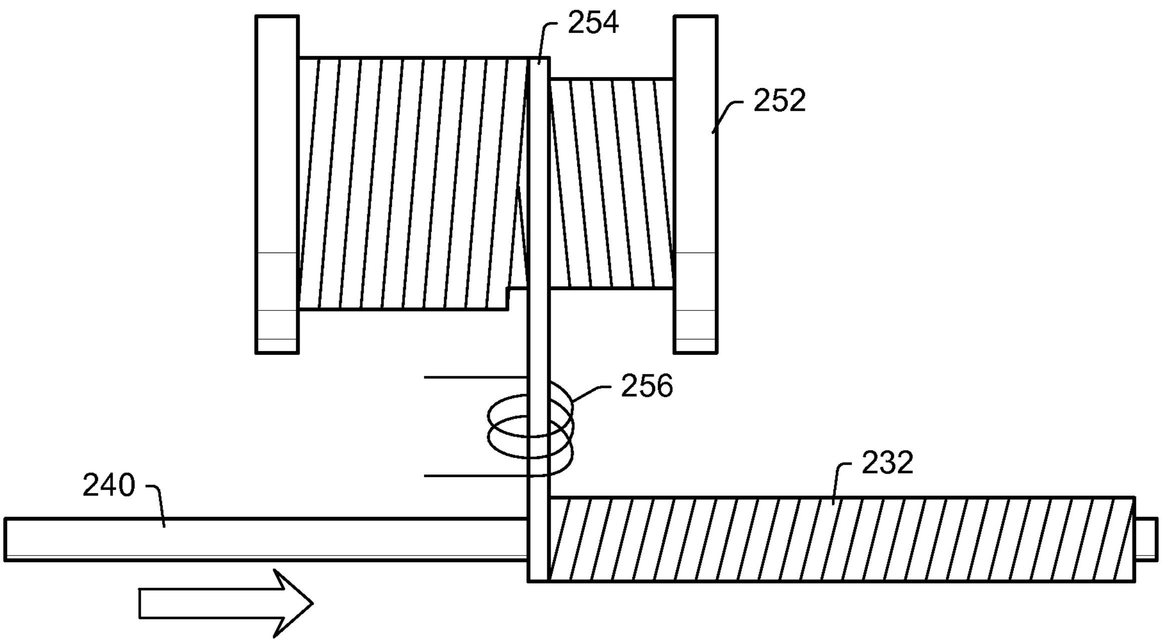

FIG. 22

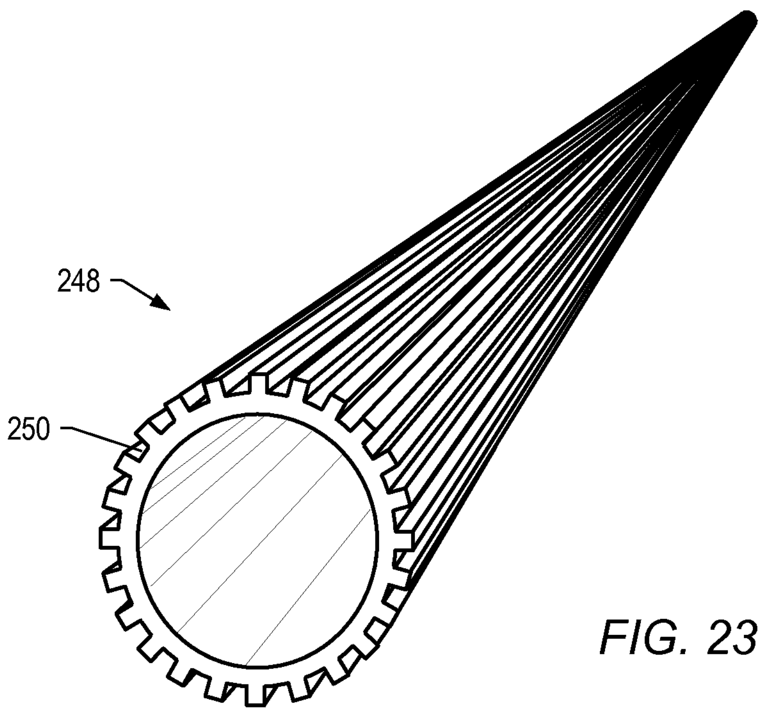

FIG. 23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 08/79707

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H05B 6/10 (2008.04)
USPC - 219/635
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H05B 6/10 (2008.04)
USPC - 219/635

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 219/635; 219/672; 219/673

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Electronic Databases Searched: Google Scholar; PubWest (US Patents full-text, US PGPubs full-text, EPO Abstracts, and JPO Abstracts) Terms Used: oil, well, petroleum, hydrocarbon, exploration, time-varying, induction, heater, heating, formation, subsurface, downhole, 300, degree, 700, induce

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/0005968 A1 (VINEGAR et al.) 12 January 2006 (12.01.2006) entire document especially Fig. 26, Fig. 29, Fig. 48A, Fig. 48B, Fig. 54, Fig. 66A, Fig. 67, Fig. 74, Fig. 75, Fig. 76, Fig. 81A, Fig. 81B, Fig. 95, abstract, para [0467], para [0468], para [0477], para [0490], para [0516], para [0567], para [0582], para [0590], para [0603], para [0604], para [0636]	1-20, 21/(1-20), 22/21/(1-20), 23/21/(1-20), 24/21/(1-20), 25/21/(1-20), 26/21/(1-20),
		1-26
A	US 5,070,533 A (BRIDGES et al.) 3 December 1991 (03.12.1991)	1-26
A	US 5,065,818 A (VAN EGMOND) 19 November 1991 (19.11.1991)	1-26
A	US 6,112,808 A (ISTED) 5 September 2000 (05.09.2000)	1-26
A	US 6,942,032 B2 (LA ROVERE et al.) 13 September 2005 (13.09.2005)	

☐ Further documents are listed in the continuation of Box C. ☐

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

Date of the actual completion of the international search	Date of mailing of the international search report
5 December 2008 (05.12.2008)	15 DEC 2008

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774