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(57) Abrégé(suite)/Abstract(continued):
near the center of the first section. The heat sources are configured such that the average heat input per volume of formation in the first section increases with distance from the production well.
(54) Title: IRREGULAR SPACING OF HEAT SOURCES FOR TREATING HYDROCARBON CONTAINING FORMATIONS

(57) Abstract: A method for treating a hydrocarbon containing formation includes providing heat input to a first section of the formation from one or more heat sources located in the first section. Fluids are produced from the first section through a production well located at or near the center of the first section. The heat sources are configured such that the average heat input per volume of formation in the first section increases with distance from the production well.
IRREGULAR SPACING OF HEAT SOURCES FOR TREATING HYDROCARBON CONTAINING FORMATIONS

BACKGROUND

1. Field of the Invention

[0001] The present invention relates generally to methods and systems for production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Certain embodiments relate to treatment of formations with irregular patterns of heat sources and/or irregularly spaced heat sources.

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] Heaters may be placed in wellbores to heat the formation during an in situ process. Examples of in situ processes utilizing downhole heaters are illustrated in U.S. Patent Nos. 2,634,961 to Ljungstrom; 2,732,195 to Ljungstrom; 2,780,450 to Ljungstrom; 2,789,805 to Ljungstrom; 2,923,535 to Ljungstrom; and 4,886,118 to Van Meurs et al. Heaters, however, may require substantial amounts of energy to provide heat to the formation. In addition, significant amounts of energy provided by the heaters to the formation may be left in the formation after hydrocarbons are produced from the formation.

[0004] Thus, there is a need for improved methods and systems for production of hydrocarbons, hydrogen, and/or other products from various hydrocarbon containing
formations that reduce energy input to the formation and more efficiently treat these formations to produce hydrocarbons while leaving less energy in the formation.

**SUMMARY**

5 [0005] Embodiments described herein generally relate to systems, methods, and heaters for treating a subsurface formation.

[0006] 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.

10 [0007] In certain embodiments, the invention provides a method for treating a hydrocarbon containing formation, comprising: providing heat input to a first section of the formation from one or more heat sources located in the first section; and producing fluids from the first section through a production well located at or near the center of the first section; wherein the heat sources are configured such that the average heat input per volume of formation in the first section increases with distance from the production well.

[0008] In certain embodiments, the invention provides a method for treating a hydrocarbon containing formation, comprising: providing heat input to a first section of the formation from one or more heat sources located in the first section; providing the heat input into the formation from the heat sources such that the heat input to the formation per volume of formation in a first volume of the first section is less than the heat input to the formation per volume of formation in a second volume of the first section and the heat input to the formation per volume of formation in the second volume is less than the heat input to the formation per volume of a third volume of the first section, wherein the first volume substantially surrounds a production well located at or near the center of the section, the second volume substantially surrounds the first volume, and the third volume substantially surrounds the second volume; and producing fluids from the first section through the production well.

[0009] 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.

[0010] In further embodiments, treating a subsurface formation is performed using any of the methods, systems, or heaters described herein.
[0011] In further embodiments, additional features may be added to the specific embodiments described herein.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0012] 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:

[0013] 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.

[0014] FIG. 2 depicts an embodiment of irregular spaced heat sources with the heater density increasing as distance from a production well increases.

[0015] FIG. 3 depicts an embodiment of an irregular spaced triangular pattern.

[0016] FIG. 4 depicts an embodiment of irregular spaced square pattern.

[0017] FIG. 5 depicts an embodiment of a regular pattern of equally spaced rows of heat sources.

[0018] FIG. 6 depicts an embodiment of irregular spaced heat sources defining volumes around a production well.

[0019] FIG. 7 depicts an embodiment of a repeated pattern of irregular spaced heat sources with the heater density of each pattern increasing as distance from the production well increases.

[0020] 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 of the present invention as defined by the appended claims.

**DETAILED DESCRIPTION**

[0021] 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.
“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.

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.

“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.

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.

[0026] 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.

[0027] “Heavy hydrocarbons” are viscous hydrocarbon fluids. Heavy hydrocarbons may include highly viscous hydrocarbon fluids such as heavy oil, tar, and/or asphalt. Heavy hydrocarbons may include carbon and hydrogen, as well as smaller concentrations of sulfur, oxygen, and nitrogen. Additional elements may also be present in heavy hydrocarbons in trace amounts. Heavy hydrocarbons may be classified by API gravity. Heavy hydrocarbons generally have an API gravity below about 20°. Heavy oil, for example, generally has an API gravity of about 10-20°, whereas tar generally has an API gravity below about 10°. The viscosity of heavy hydrocarbons is generally greater than about 100 centipoise at 15 °C. Heavy hydrocarbons may include aromatics or other complex ring hydrocarbons.

[0028] “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 asphalites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilites, 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.
[0029] 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.

[0030] 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.

[0031] “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.

[0032] “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.

[0033] “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.

[0034] “Thickness” of a layer refers to the thickness of a cross section of the layer, wherein the cross section is normal to a face of the layer.

[0035] “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.

[0036] 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.”
[0037] 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. 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 of the formation is raised above mobilization temperatures of hydrocarbons in the sections. In some embodiments, the average temperature of one or more sections of the formation may be raised above pyrolysis temperatures of hydrocarbons in the sections. 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 may be raised to temperatures sufficient to allow synthesis gas production. 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. 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.

[0038] 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.

[0039] 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.

[0040] 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.

[0041] 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 (C₆ and above) in the production well, and/or (5) increase formation permeability at or proximate the production well.

[0042] 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.

[0043] 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.

[0044] 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.

[0045] 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.

[0046] 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, at most 8, or at most 6.
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
visbreak and/or pyrolyze to form lower carbon number compounds.
[0047] 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.

[0048] In certain embodiments, heat sources (for example, heaters) have uneven or irregular spacing in a heater pattern. For example, the space between heat sources in the heater pattern varies or the heat sources are not evenly distributed in the heater pattern. In certain embodiments, the space between heat sources in the heater pattern decreases as the distance from the production well at the center of the pattern increases. Thus, the density of heat sources (number of heat sources per square area) increases as the heat sources get more distant from the production well.

[0049] In some embodiments, heat sources are evenly spaced (equally spaced or evenly distributed) in the heater pattern but have varying heat outputs such that the heat sources provide an uneven or varying heat distribution in the heater pattern. Varying the heat output of the heat sources may be used to, for example, effectively mimic having heat sources with varying spacing in the heater pattern. For example, heat sources closer to the production well at the center of the heater pattern may provide lower heat outputs than heat sources at further distances from the production well. The heater outputs may be varied such that the heater outputs gradually increase as the heat sources increase in distance from the production well.

[0050] In certain embodiments, the uneven or irregular spacing of heat sources is based on regular geometric patterns. For example, the irregular spacing of heat sources may be based on a hexagonal, triangular, square, octagonal, other geometric combinations, and/or combinations thereof. In some embodiments, heat sources are placed at irregular intervals along one or more of the geometric patterns to provide the irregular spacing. In some embodiments, the heat sources are placed in an irregular geometric pattern. In some
embodiments, the geometric pattern has irregular spacing between rows in the pattern to provide the irregular spacing of heat sources.

[0051] FIG. 2 depicts an embodiment of irregular spaced heat sources 202 with the heater density increasing as distance from production well 206 increases. In certain embodiments, production well 206 is located at or near the center of the pattern of heat sources 202. In certain embodiments, heat sources 202 are heaters (for example, electric heaters). FIG. 2 depicts an embodiment of irregular spaced heat sources in a hexagonal pattern. FIG. 3 depicts an embodiment of an irregular spaced triangular pattern. FIG. 4 depicts an embodiment of irregular spaced square pattern. Heat sources may be placed at desired locations along the rows depicted in FIG. 3 and FIG. 4. It is to be understood that the heat sources may be placed in any regular or irregular geometric pattern in the formation. Heat sources may be arranged in any regular or irregular geometric pattern (for example, regular or irregular triangle, regular or irregular hexagonal, regular or irregular rectagonal, circular, oval, elliptical, or combinations thereof) as long as the heat source density increases as distance from the production well increases. In some embodiments, the heat sources are spaced asymmetrically around the production well with the heat source density increasing as the distance from the production well increases. The irregular patterns of heat sources may be a pattern of vertical (or substantially vertical) heat sources in a formation or a pattern of horizontal (or substantially horizontal) heat sources in the formation.

[0052] As shown in FIG. 2, heat sources 202 are represented by solid squares in rows A, B, C, and D. Rows A, B, C, and D may be triangular and/or hexagonal rows (or rows in other shapes) of heat sources that have decreasing space between the rows as the rows move away from production well 206. Heat sources 202 may be distributed regularly or irregularly in rows A, B, C, and D (for example, the heaters may have equal or non-equal spacing in the rows). In certain embodiments, heat sources are placed in the rows such that the density of heat sources increases as the heat sources are further distanced away from production well 206. Thus, the heat output from the heat sources per volume of formation increases with distance from the production well.

[0053] In certain embodiments, the irregular pattern of heat sources has the same number of heat sources per production well as a regular pattern of heat sources but with heat source spacing that decreases with increasing distance from the production well. The decreasing heat source spacing increases the heat input into the formation per volume of formation as
the distance from the production well increases. FIG. 5 depicts an embodiment of a regular pattern of equally spaced rows of heat sources. The embodiments depicted in FIGS. 2 and 5 each have a pattern ratio of 16 heat sources 202 to one production well 206 (for example, 12 (from rows A, B, C) + 1 (from the three heat sources at the vertices of row D because each of these heat sources supplies heat to three patterns) + 3 (from the 6 heat sources located in row D between the vertices because each of these heat sources supplies heat to two patterns)). The heater/producer ratio for both embodiments is 16:1 and the total heat input into the formation per volume of formation in the pattern is substantially equal (assuming equal and constant heat source outputs). The spacing between heat sources in the embodiment depicted in FIG. 2, however, is different than the spacing between heat sources in the embodiment depicted in FIG. 5. Thus, the average heat input per volume of formation increases with increasing distance from the production well in the embodiment depicted in FIG. 2 while the average heat input per volume of formation is substantially uniform throughout the pattern depicted in FIG. 5. In some embodiments, the equally spaced embodiment depicted in FIG. 5 may provide increasing heat input per volume of formation with increasing distance from the production well by adjusting the heat output of the heat sources to increase with increasing distance from the production well.

FIG. 6 depicts an embodiment of irregular spaced heat sources 202 defining volumes with increasing heat input density around production well 206. FIG. 6 depicts the same heater pattern as FIG. 2 with shading defining areas representing volumes 212, 214, 216, and 218. Increases in the shading in FIG. 6 represent increases in the heat input density into the formation (heat input per volume of formation). First volume 212 substantially surrounds production well 206; second volume 214 substantially surrounds first volume 212; third volume 216 substantially surrounds second volume 214; and fourth volume 218 substantially surrounds third volume 216. In certain embodiments, first volume 212 does not include production well 206. In some embodiments, first volume 212 includes production well 206.

In certain embodiments, at least one heat source 202 is located in first volume 212, in second volume 214, in third volume 216, and/or in fourth volume 218. In some embodiments, at least two heat sources 202 are located in first volume 212, in second volume 214, in third volume 216, and/or in fourth volume 218. In some embodiments, at least three heat sources 202 are located in first volume 212, in second volume 214, in third volume 216, and/or in fourth volume 218.
[0056] In certain embodiments, all heat sources 202 located in first volume 212 are closer to production well 206 than any of the heaters in second volume 214. In some embodiments, all heat sources 202 located in second volume 214 are closer to production well 206 than any of the heaters in third volume 216. In some embodiments, all heat sources 202 located in third volume 216 are closer to production well 206 than any of the heaters in fourth volume 218.

[0057] In certain embodiments, the average distance from production well 206 of heat sources 202 in first volume 212 is less than the average distance from production well 206 of heat sources 202 in second volume 214. In some embodiments, the average distance from production well 206 of heat sources 202 in second volume 214 is less than the average distance from production well 206 of heat sources 202 in third volume 216. In some embodiments, the average distance from production well 206 of heat sources 202 in third volume 216 is less than the average distance from production well 206 of heat sources 202 in fourth volume 218.

[0058] In certain embodiments, first volume 212 is approximately equal in volume to second volume 214, third volume 216, and/or fourth volume 218. In some embodiments, second volume 214 is approximately equal in volume to third volume 216 and/or fourth volume 218. In some embodiments, third volume 216 is approximately equal in volume to fourth volume 218.

[0059] In certain embodiments, as shown in FIGS. 2 and 6, first volume 212, second volume 214, third volume 216, and fourth volume 218 have increasing average radial distances from production well 206 with the average radial distance of the first volume being the smallest and the average radial distance of the fourth volume being the largest. Thus, first volume 212 is closer to production well 206 than second volume 214; the second volume is closer to the production well than third volume 216; and the third volume is closer to the production well than fourth volume 218.

[0060] The differences in density of heat sources 202 in rows A, B, C, and D and/or the differences in heat output of the heat sources may produce temperature gradients in the section of the formation heated by the pattern of heat sources shown in FIGS. 2 and 6.

Heat input into the formation from heat sources 202 in row A may approximately define first volume 212. Heat input into the formation from heat sources 202 in row B may approximately define second volume 214. Heat input into the formation from heat sources
202 in row C may approximately define third volume 216. Heat input into the formation from heat sources 202 in row D may approximately define fourth volume 218.

In certain embodiments, volumes 212, 214, 216, and 218 have boundaries that are defined approximately by the differences in heat source density between rows A, B, C, and D. The shapes of the boundaries of volumes 212, 214, 216, and 218 and or the size of the volumes may be defined, for example, by the location of heat sources 202, the heating characteristics of the heat sources, and the thermal and/or geomechanical properties of the formation. The shapes and/or sizes of volumes 212, 214, 216, and 218 may vary based on changes in the above example properties and/or the point in time during heating of the formation. The boundaries of volumes 212, 214, 216, and 218, as shown in FIGS. 2 and 6, approximate measurable temperature differences in the section because of the changes in heater density (or heat source output) at a selected point in time during heating of the section.

In some embodiments, the number of heat sources 202 per volume of formation in a volume increases from first volume 212 to fourth volume 218. Thus, the heat source density increases from first volume 212 to fourth volume 218. Because the heat source density increases from first volume 212 to fourth volume 218, the average heat output of heat sources in first volume 212 is less than the average heat output of heat sources in second volume 214; the average heat output of heat sources in the second volume is less than the average heat output of heat sources in third volume 216; and the average heat output of heat sources in the third volume is less than the average heat output of heat sources in fourth volume 218.

In addition, because of the increasing heater density (or heat output) as distance from production well 206 increases; the heat input to the formation per volume of formation in first volume 212 is less than the heat input to the formation per volume of formation in second volume 214; the heat input to the formation per volume of formation in the second volume is less than the heat input to the formation per volume of formation in third volume 216; and the heat input to the formation per volume of formation in the third volume is less than the heat input to the formation per volume of formation in fourth volume 218. Thus, first volume 212 is at a lower average temperature than second volume 214; the second volume is at a lower average temperature than third volume 216; and the third volume is at a lower average temperature than fourth volume 218.
[0064] Regardless of any change in the shapes and/or sizes of volumes 212, 214, 216, and 218, the spatial relation of the volumes remains constant during heating of the formation (the first volume surrounds the production well with the other volumes surrounding the first volume, respectively). Similarly, heat input into the formation may increase constantly from first volume 212 to fourth volume 218.

[0065] In certain embodiments, the formation has sufficient permeability to allow fluids (for example, mobilized fluids) to flow towards production well 206 from the outermost heat sources in the pattern (heat sources 202 in row D). The flow of fluids from the higher heat density portions of the formation towards the production well provides convective heat transfer in the formation. Fluids may be cooled as the fluids move towards the production well by transferring heat to the formation. Convective heat transfer from fluid flow in the formation may transfer heat through the formation faster than conductive heat transfer. In some embodiments, convective heat transfer may be increased by providing unobstructed or substantially unobstructed flow paths from the outermost heat sources to the production well. Increasing heat transfer in the formation may increase heating efficiency and/or recovery efficiency for treating the formation. For example, fluids mobilized by heat at longer distances from the production well may provide heat to the formation as the mobilized fluids move towards the production well. Providing some heat to the formation from movement of mobilized fluids may be a more efficient use of heat provided to the formation.

[0066] In certain embodiments, fluids produced through production well 206 include a majority of liquid hydrocarbons that are hydrocarbons originally in place in the section the pattern surrounding the production well. The liquid hydrocarbons may be hydrocarbons that are liquids at 25 °C and 1 atm.

[0067] As shown in FIG. 2, hexagonal rows A, B, C, and D have varying spacing between the rows with rows A, B, and C being shifted outwards from production well 206 using an “offset factor”. An offset factor of zero produces rows substantially equally spaced from each other. FIG. 5 depicts an embodiment with equally spaced rows of hexagon. The offset factor may be used in a series of related equations to determine the spacing between rows. For example, equations may be used for a heater pattern with four hexagonal rows surrounding a production well.

[0068] As shown in FIG. 2, the largest hexagon is the outer constraint of the pattern of heat sources around the production well. The largest hexagon has radii R₁ and R₂ with R₁ being
the larger radius (the radius to a vertex of the hexagon) and \( R_2 \) being the smaller radius (the radius to the bisect of a side of a hexagon). In the embodiment with equally spaced hexagons, shown in FIG. 5:

\[ (\text{EQN. 1}) \quad r_1 + r_2 + r_3 + r_4 = R_1; \text{ where } r_1 \text{ is the radius from the center to the vertex of the first hexagon, } r_2 \text{ is the radius from the vertex of the first hexagon to the vertex of the second hexagon, } r_3 \text{ is the radius from the vertex of the second hexagon to the vertex of the third hexagon, and } r_4 \text{ is the radius from the vertex of the third hexagon to the vertex of the fourth hexagon (the largest hexagon).} \]

For the equally spaced hexagon case, the four radii are equal so that:

\[ (\text{EQN. 2}) \quad r_1 = r_2 = r_3 = r_4 = R_1/4. \]

For the case of four hexagons spaced geometrically, shown in FIG. 2, the hexagons may have an offset factor, \( s \). The spacing of the hexagons may be described by:

\[ (\text{EQN. 3}) \quad r'_1 + 4s + r'_2 + 3s + r'_3 + 2s + r'_4 + s = R_1. \]

If \( r'_1 \) is assumed to be a constant \( (r'_1 = r'_2 = r'_3 = r'_4 = r') \), then:

\[ (\text{EQN. 4}) \quad 4r' + 10s = R_1. \]

Certain assumptions may be made on the offset factor, \( s \), so that the dimensions (the distances from the production well) of the four hexagons may be described accordingly:

\[ (\text{EQN. 5}) \quad r' + 4s = \text{distance to the vertex of the first hexagon from the production well}; \]

\[ (\text{EQN. 6}) \quad 2r' + 7s = \text{distance to the vertex of the second hexagon from the production well}; \]

\[ (\text{EQN. 7}) \quad 3r' + 9s = \text{distance to the vertex of the third hexagon from the production well}; \]

\[ (\text{EQN. 8}) \quad 4r' + 10s = \text{distance to the vertex of the fourth hexagon from the production well}. \]

Thus, for an offset factor of zero, the spacing of the hexagons would be equal, as shown in FIG. 5. FIG. 2 depicts hexagons geometrically spaced with an offset factor of about 8.

Decreasing the density of heat sources 202 closer to production well 206, as shown in FIG. 2, provides less heating at or near the production well. Providing less heat at or near the production well may reduce the enthalpy of fluids produced through the production well. Less heating at or near the production well may provide lower temperatures in the production well such that less energy is removed from the formation.
through produced fluids and more energy is kept in the formation to heat the formation. Thus, waste energy from the formation may be decreased. Decreasing waste energy in the formation increases energy efficiency (energy into the formation versus energy out of the formation) in treating the formation.

[0083] In certain embodiments, the average temperature of produced fluids is maintained below a selected temperature. For example, the average temperature of produced fluids when about 50% of the hydrocarbons in place are pyrolyzed may be maintained below about 310 °C, below about 200 °C, or below about 190 °C. In some embodiments, the average temperature of produced fluids when about 50% of the hydrocarbons in place are mobilized may be maintained below about 310 °C, below about 200 °C, or below about 190 °C. In some embodiments, the average temperature of produced fluids when about 50% of the hydrocarbons in place are produced may be maintained below about 310 °C, below about 200 °C, or below about 190 °C.

[0084] In some embodiments, reducing temperatures at or near the production well reduces costs associated with production well completion and/or reduces the potential for failures of piping or other equipment in the production well. For example, treating a formation using the pattern depicted in FIG. 2 may decrease the heating required for heating by about 17% versus treating the formation with a regular triangular pattern of heat sources. The reduced requirement for heat injection likely occurs because of convective heat transfer by the high temperature fluids in the formation from high heat density areas (outer portions of the heater pattern) to portions of the formation around the production well.

[0085] Less heating at or near the production well, however, may decrease recovery efficiency (amount of oil in place recovered) in the formation. The reduced recovery efficiency may be due to more hydrocarbons being left unmobilized or unpyrolyzed in the formation at the end of production and/or higher concentrations of charring or coking from higher temperatures being generated by the higher heater density in the outer portions of the heater pattern. The reduced recovery efficiency may offset some of the benefits from the reduced energy input into the formation. In some embodiments, further increasing the density of heat sources as the distance from the production well increases (for example, increasing the offset factor in FIG. 2) reduces the recovery efficiency to an extent that overtakes any benefits gained from reducing energy input into the formation.

[0086] Larger offset factors may result in shorter time to production ramp up because of accelerated heating from the higher density of heat sources. The larger offset factors,
however, also produce lower peak oil production rates and reduced recovery efficiency. In addition, at larger offset factors, more rock may need to be heated to compensate for reduce liquid recovery from the formation. Lowering the offset factor increases oil production rates and recovery efficiency but reduces the heat efficiency in treating the formation. Thus, a desired offset factor (for example, desired increasing heater density pattern) may be a balance between the above described results.

[0087] In certain embodiments, simulations, calculations, and/or other optimization methods are used to assess or determine a desired heater density pattern (for example, offset factor) for treating the formation. The desired heater density pattern may be assessed based on factors such as, but not limited to, current or future economic conditions, production needs, and properties of the formation. In some embodiments, the simulations or calculations are used to vary the offset factor and assess a desired (for example, optimum) ratio of energy output from the formation versus energy input into the formation.

[0088] Table 1 summarizes data from simulations on three different heater patterns for cumulative oil production (in bbl), gas production (in MMscf), heat injection efficiency (heat injection per barrel oil produced (in MMBtu/bbl)), and cumulative heat injection (MMBtu) on patterns of heaters. Row 1 shows data for a simulation of the equally spaced heater pattern shown in FIG. 5. Row 2 shows data for a simulation of the irregular spaced heater pattern shown in FIG. 2. The simulations that resulted in the data shown in row 1 and row 2 were constrained to have the same constant average formation temperature. Row 3 shows data for a simulation of the irregular spaced heater pattern shown in FIG. 2 with the added feature of leaving the heaters closest to the production well (heaters in row A) on for a longer period of time. The heaters were left on until the cumulative heat injection in the simulation equaled the cumulative heat injection for the simulation of the equally spaced heater pattern (data shown in row 1).

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91,610</td>
<td>2.99 × 10⁴</td>
<td>1.157</td>
<td>1.06 × 10⁵</td>
</tr>
<tr>
<td>2</td>
<td>85,666</td>
<td>1.43 × 10⁴</td>
<td>1.044</td>
<td>8.94 × 10⁴</td>
</tr>
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<td>97,378</td>
<td>3.04 × 10⁴</td>
<td>1.089</td>
<td>1.06 × 10⁵</td>
</tr>
</tbody>
</table>

[0089] As shown by the data in rows 1 and 2 of Table 1, increasing the heat input density as the distance from the production well increases using the irregular heat source pattern increases the heat injection efficiency into the formation and reduces the cumulative heat
injection into the formation. Oil production, however, is reduced using the irregular heat source pattern. The data in row 3 shows that adjusting how heat is injected in the irregular heat source pattern (for example, by keeping heaters closer to the production well on longer) may increase oil production to a value even higher than the value for the regular (equally spaced) heat source pattern while getting a heat injection efficiency that is better than the regular heat source pattern. Further adjustments of how heat is injected in the heat source pattern (for example, turning off heaters in the outer parts of the pattern sooner) may further increase heat injection efficiency and/or increase oil production.

[0090] It is to be understood that the pattern of heat sources and rows depicted in FIG. 2 is merely representative of one possible embodiment for a pattern of heat sources that increase in heater density with distance from the production well. Many other geometric or non-geometric patterns of heat sources may also be used to provide the same function of increasing the heater density, as depicted in FIG. 2. Simulations, calculations, and/or other optimization methods may be used to assess or determine a desired heater density pattern for treating the formation with any desired geometric or non-geometric pattern. For example, simulations, calculations, and/or other optimization methods may be used to assess and optimize the amount of heat output per volume of formation from the heat sources (or the heat source density) at different radial distances from the production well so that the ratio of energy output from the formation versus energy input into the formation is optimized.

[0091] In some embodiments, heat sources 202 in rows A, B, C, and D, depicted in FIG. 2, are turned on and off simultaneously. The heat sources may be turned on and allowed to heat the formation to a selected average temperature before being turned off. The selected temperature may be, for example, a hydrocarbon mobilization temperature, a hydrocarbon visbreaking temperature, or a hydrocarbon pyrolysis temperature. Simulations and/or calculations may be used to assess the selected average temperature for a selected heater density pattern.

[0092] In some embodiments, heat sources 202 nearest production well 206 (for example, heat sources 202 in rows A and/or B) are left on for longer times than heat sources further away from the production well (for example, heat sources 202 in rows C and/or D). Leaving heat sources nearer the production well on for longer times may allow for more hydrocarbon production from the formation. Thus, fewer hydrocarbons may remain in place after production is completed and higher recovery efficiencies may be achieved using
a selected heater density pattern. Simulations and/or calculations may be used to assess desired times for turning on and off heat sources such that the ratio of energy output from the formation versus energy input into the formation is optimized. In some embodiments, it may be possible to increase the recovery efficiency by tailoring the heat output to recovery efficiencies achieved with regular heating patterns (for example, no offset factor).

[0093] In some embodiments, heat sources that are turned on for shorter times (for example, heat sources 202 in row D) are designed for shorter lifetimes. For example, heat sources 202 in row D may be designed to last at most about 3 years or at most about 5 years. Other heat sources in the formation may be designed to last at least about 5 years or at least about 10 years. Shorter lifetime heat sources may use less expensive materials and/or be less expensive to manufacture or install than longer lifetime heat sources. Thus, using the shorter lifetime heat sources may reduce costs associated with treating the formation.

[0094] In some embodiments, heat sources 202, depicted in FIG. 2, are turned on in a sequence from outside in towards production well 206. For example, heat sources 202 in row D may be turned on first, followed by heat sources 202 in row C, then heat sources 202 in row B, and lastly heat sources 202 in row A. Such a heater startup sequence may treat the formation in a staged heating method with one or more of the outside heat sources being spaced so that heat from the heat sources does not superposition or conductively heat the production well and heat is primarily transferred through convection of fluids to the production well. For example, heat sources 202 in rows A-D may be considered to be in a first section of the formation and production well 206 is in a second section adjacent to the first section.

[0095] In some embodiments, the temperature at or near production well 206 is controlled so that the temperature is at most a selected temperature. For example, the temperature at or near the production well may be controlled so that the temperature is at most about 100 °C, at most about 150 °C, at most about 200 °C, or at most about 250 °C. In certain embodiments, the temperature at or near production well 206 is controlled by reducing or turning off the heat provided by heat sources 202 nearest the production well (for example, the heat sources in row A). In some embodiments, the temperature at or near production well 206 is controlled by controlling the production rate of fluids through the production well.
[0096] In certain embodiments, the heater pattern depicted in FIG. 2 is a base unit of a pattern repeated through a large portion of the formation to define a larger treatment area. FIG. 7 depicts three base units in the formation. Additional base units may be formed if desired. The number and/or arrangement of base units in a pattern may depend on, for example, the size and/or shape of the formation being treated. In certain embodiments, production wells 206 are located at or near the center of the repeating base units in the pattern. Heater wells 202 and production wells 206 may be used to treat and produce hydrocarbons from the formation using the pattern depicted in FIG. 7.

[0097] 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 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.
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PPH

CLAIMS:

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

   providing heat input to a first section of the formation from one or more heat
   sources located in the first section; and

   producing fluids from the first section through a production well located at or
   near the center of the first section;

   wherein the heat sources are configured such that the average heat input per
   volume of formation in the first section increases with distance from the production well.

2. The method of claim 1, further comprising providing different heat outputs
   from the heat sources such that the average heat output from heat sources in the first section
   increases with distance from the production well.

3. The method of claim 1, further comprising arranging the heat sources such that
   the number of heat sources per volume of formation increases with distance from the
   production well.

4. The method of claim 1, further comprising:

   providing heat input to a second section of the formation from one or more
   heat sources located in the second section, the second section being located adjacent to the
   first section; and

   producing fluids from the second section through a production well located at
   or near the center of the second section;

   wherein the heat sources are configured such that the average heat input per
   volume of formation in the second section increases with distance from the production well in
   the second section.

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5. The method of claim 1, further comprising:

providing heat input to a third section of the formation from one or more heat sources located in the third section, the third section being located adjacent to the first section; and

producing fluids from the third section through a production well located at or near the center of the third section;

wherein the heat sources are configured such that the average heat input per volume of formation in the third section increases with distance from the production well in the third section.

6. The method of claim 1, further comprising producing hydrocarbons from the first section that are liquid hydrocarbons at 25°C and 1 atm, wherein a majority of such liquid hydrocarbons are hydrocarbons originally in place in the first section.

7. The method of claim 1, wherein the heat sources comprise heaters.

8. The method of claim 1, further comprising providing heat input into the first section from the heat sources such that fluids moving from near heat sources located furthest from the production well in the first section to the production well are at least partially cooled.

9. The method of claim 1, further comprising mobilizing hydrocarbons with heat provided by the heat sources, and producing mobilized hydrocarbons through the production well.

10. The method of claim 1, further comprising providing heat to a portion of the formation near the production well with heat from mobilized fluids moving to the production well from the outside the portion near the production well.

11. The method of claim 1, further comprising reducing or turning off heating in the heat sources near the production well when a temperature at or near the production well reaches a temperature of at least about 100°C.
12. The method of claim 1, further comprising turning on at least a majority of the heat sources in a sequence with at least a majority of the heat sources furthest from the production well being turned on before at least a majority of the heat sources nearest the production well are turned on.

13. The method of claim 1, further comprising turning off or reducing heat output from at least a majority of the heat sources in a sequence with at least a majority of the heat sources furthest from the production well having their heat output turned off or reduced before at least a majority of the heat sources nearest the production well have their heat output turned off or reduced.

14. The method of claim 1, further comprising providing the heat input into the formation from the heat sources such that the heat input to the formation per volume of formation in a first volume of the first section is less than the heat input to the formation per volume of formation in a second volume of the first section and the heat input to the formation per volume of formation in the second volume of the first section is less than the heat input to the formation per volume of a third volume of the first section, wherein the first volume substantially surrounds a production well located at or near the center of the section, the second volume substantially surrounds the first volume, and the third volume substantially surrounds the second volume.

15. The method of claim 14, wherein at least one heat source is located in the first volume, the second volume, and/or the third volume.

16. The method of claim 14, wherein at least two heat sources are located in the first volume, the second volume, and/or the third volume.

17. The method of claim 14, wherein at least three heat sources are located in the first volume, the second volume, and/or the third volume.

18. The method of claim 14, wherein the first volume is approximately equal in volume to the second volume and/or the third volume.
The method of claim 14, wherein the second volume is approximately equal in volume to the third volume.

The method of claim 14, wherein all of the heat sources located in the first volume are closer to the production well than any of the heat sources in the second volume.

The method of claim 14, wherein the average distance from the production well of heat sources located in the first volume is less than the average distance from the production well of heat sources located in the second volume.

A method for treating a hydrocarbon containing formation, comprising:

- providing heat input to a first section of the formation from one or more heat sources located in the first section;
- providing the heat input into the formation from the heat sources such that the heat input to the formation per volume of formation in a first volume of the first section is less than the heat input to the formation per volume of formation in a second volume of the first section and the heat input to the formation per volume of formation in the second volume is less than the heat input to the formation per volume of a third volume of the first section, wherein the first volume substantially surrounds a production well located at or near the center of the section, the second volume substantially surrounds the first volume, and the third volume substantially surrounds the second volume; and
- producing fluids from the first section through the production well.

The method of claim 22, further comprising providing different heat outputs from the heat sources such that the average heat output from heat sources in the first volume is less than the average heat output of heat sources in the second volume.

The method of claim 22, further comprising arranging the heat sources such that the number of heat sources per volume of formation in the first volume is less than the number of heat sources per volume of formation in the second volume.
25. The method of claim 22, wherein the first volume has an average radial
distance from the production well that is less than an average radial distance from the
production well of the second volume.

26. The method of claim 22, wherein the heat sources comprise heaters.

27. The method of claim 22, further comprising providing heat input into the first
section from the heat sources such that fluids moving from at or near the heat sources in the
second volume to the production well are at least partially cooled.

28. The method of claim 22, further comprising providing heat to the portion of the
formation between the first volume and the production well with heat from mobilized fluids
moving to the production well from the second volume.

29. The method of claim 22, further comprising mobilizing hydrocarbons with heat
provided by the heat sources, and producing mobilized hydrocarbons through the production
well.

30. The method of claim 22, wherein the heat sources in the first volume are
different types of heat sources than the heat sources in the second volume.

31. The method of claim 22, further comprising providing the heat input into the
formation from the heat sources such that the heat output to the formation per volume of
formation in a fourth volume of the first section is greater than the heat output to the
formation per volume of formation in the third volume, wherein the fourth volume
substantially surrounds the third volume.

32. The method of claim 22, further comprising reducing or turning off heating in
the heat sources in the first volume when a temperature at or near the production well reaches
a temperature of at least about 100°C.
33. The method of claim 22, further comprising turning on at least a majority of the heat sources in a sequence with at least a majority of the heat sources furthest from the production well being turned on before at least a majority of the heat sources nearest the production well are turned on.

34. The method of claim 22, further comprising turning off or reducing heat output from at least a majority of the heat sources in a sequence with at least a majority of the heat sources furthest from the production well having their heat output turned off or reduced before at least a majority of the heat sources nearest the production well have their heat output turned off or reduced.

35. The method of claim 22, wherein at least one heat source is located in the first volume, the second volume, and/or the third volume.

36. The method of claim 22, wherein at least two heat sources are located in the first volume, the second volume, and/or the third volume.

37. The method of claim 22, wherein at least three heat sources are located in the first volume, the second volume, and/or the third volume.

38. The method of claim 22, wherein the first volume is approximately equal in volume to the second volume and/or the third volume.

39. The method of claim 22, wherein the second volume is approximately equal in volume to the third volume.

40. The method of claim 22, wherein all of the heat sources located in the first volume are closer to the production well than any of the heat sources in the second volume.

41. The method of claim 22, wherein the average distance from the production well of heat sources located in the first volume is less than the average distance from the production well of heat sources located in the second volume.
FIG. 3

FIG. 4