US 20120018120A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2012/0018120 A1**

(43) **Pub. Date: Jan. 26, 2012**

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(54) **GEOTHERMAL ENERGY EXTRACTION SYSTEM AND METHOD**

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(21) Appl. No.: **13/246,567**

(22) Filed: **Sep. 27, 2011**

Related U.S. Application Data

(63) Continuation-in-part of application No. 12/780,538, filed on May 14, 2010.

(60) Provisional application No. 61/178,237, filed on May 14, 2009, provisional application No. 61/386,742, filed on Sep. 27, 2010.

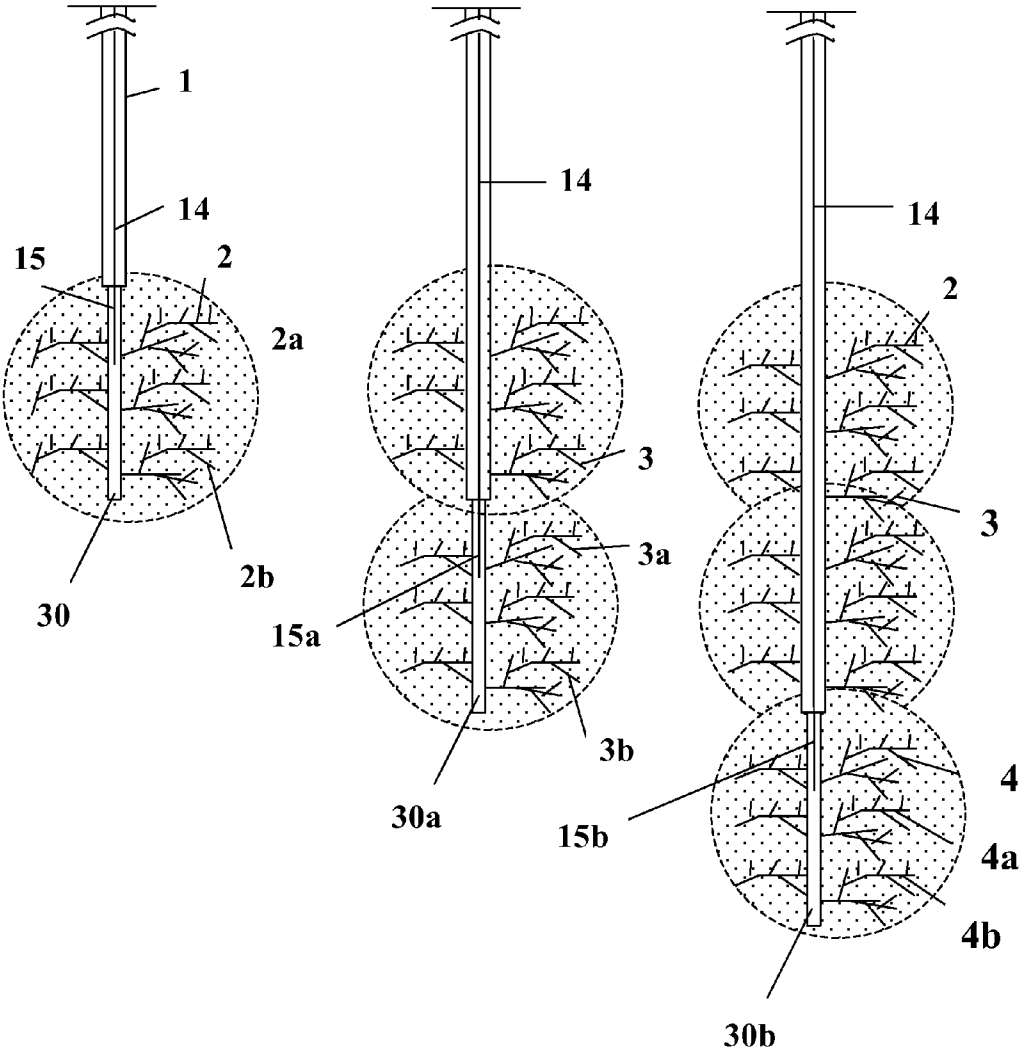
Publication Classification

(51) **Int. Cl.**
F24J 3/08 (2006.01)

(52) **U.S. Cl.** **165/45**

(57) **ABSTRACT**

The present disclosure provides a system and process for extracting geothermal energy from a geologic formation. According to an embodiment of the method, coolant fluid is introduced into a first location, at a first height in the formation. The geologic coolant fluid is collected from a second location, at second height in the geologic formation. The second height is typically lower than the first height. Geologic coolant fluid introduced into the first location migrates through the geologic formation to the second location, extracting heat from the geologic formation. Pressure is lowered at the second location relative to the surrounding areas. In a particularly advantageous solution, the pressure is lowered at the second location using a pump, which is integrated into an energy conversion implement. The energy conversion implement is installed at, or close, to the second location. The pump delivers the cooled geologic coolant fluid to the first location.



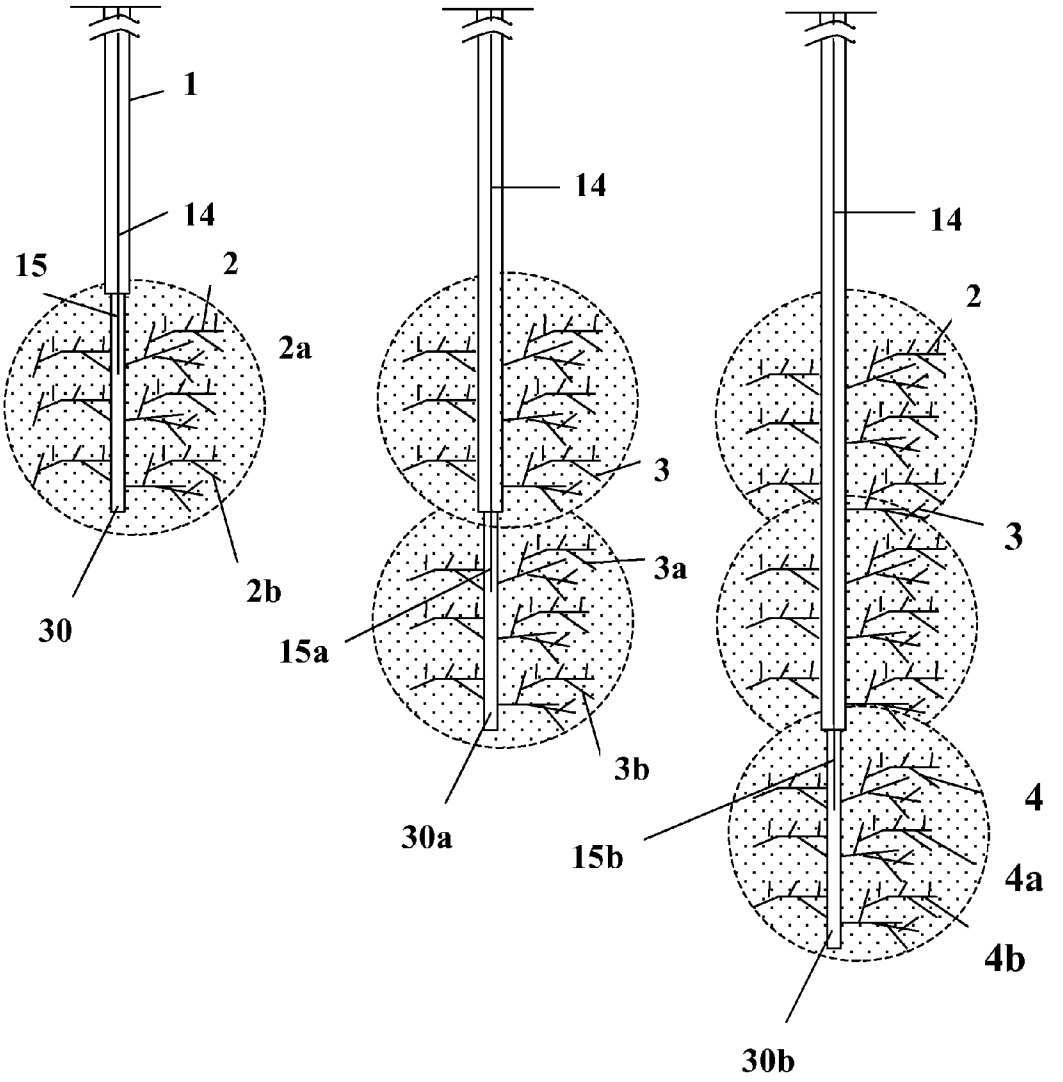


FIG. 1

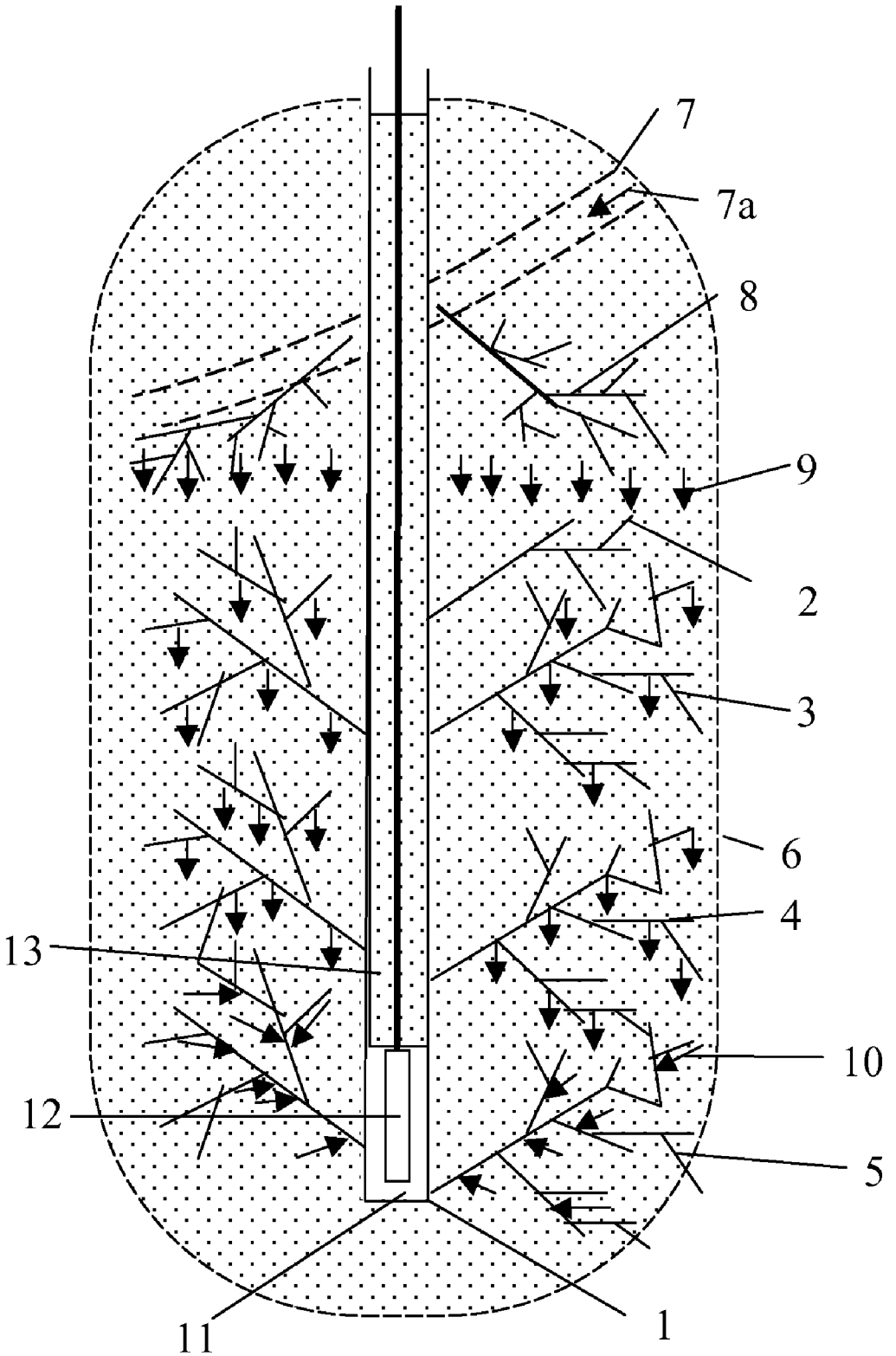


FIG. 2

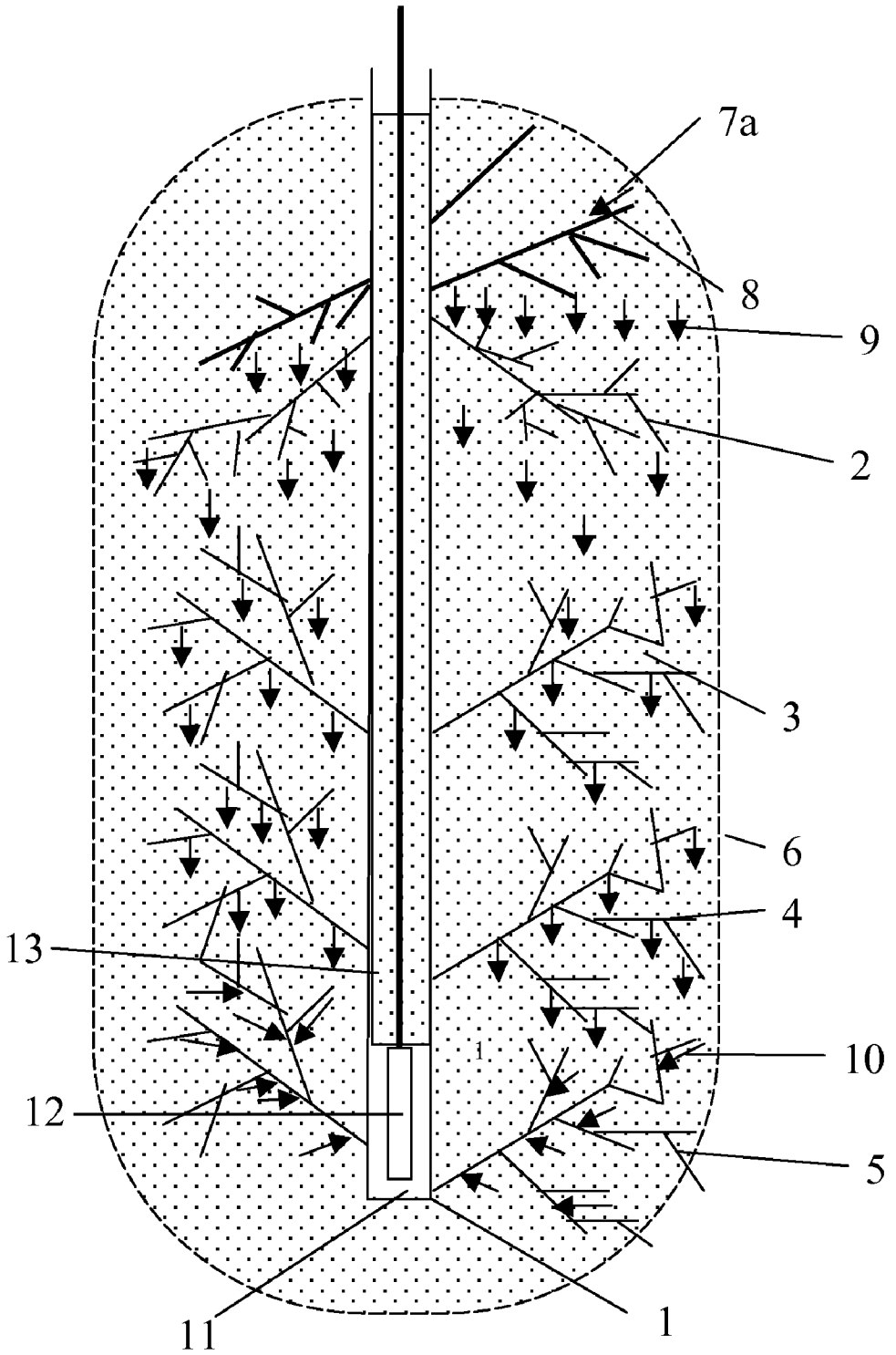


FIG. 3

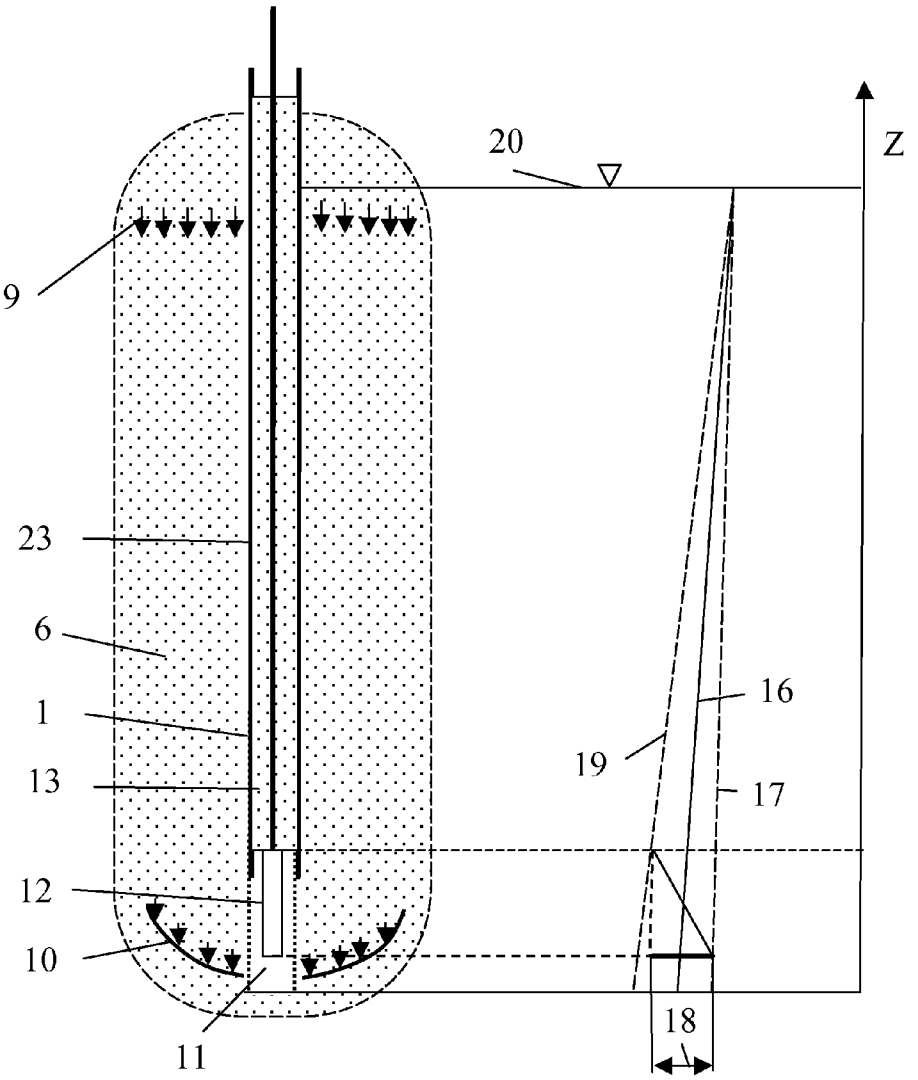


FIG. 4

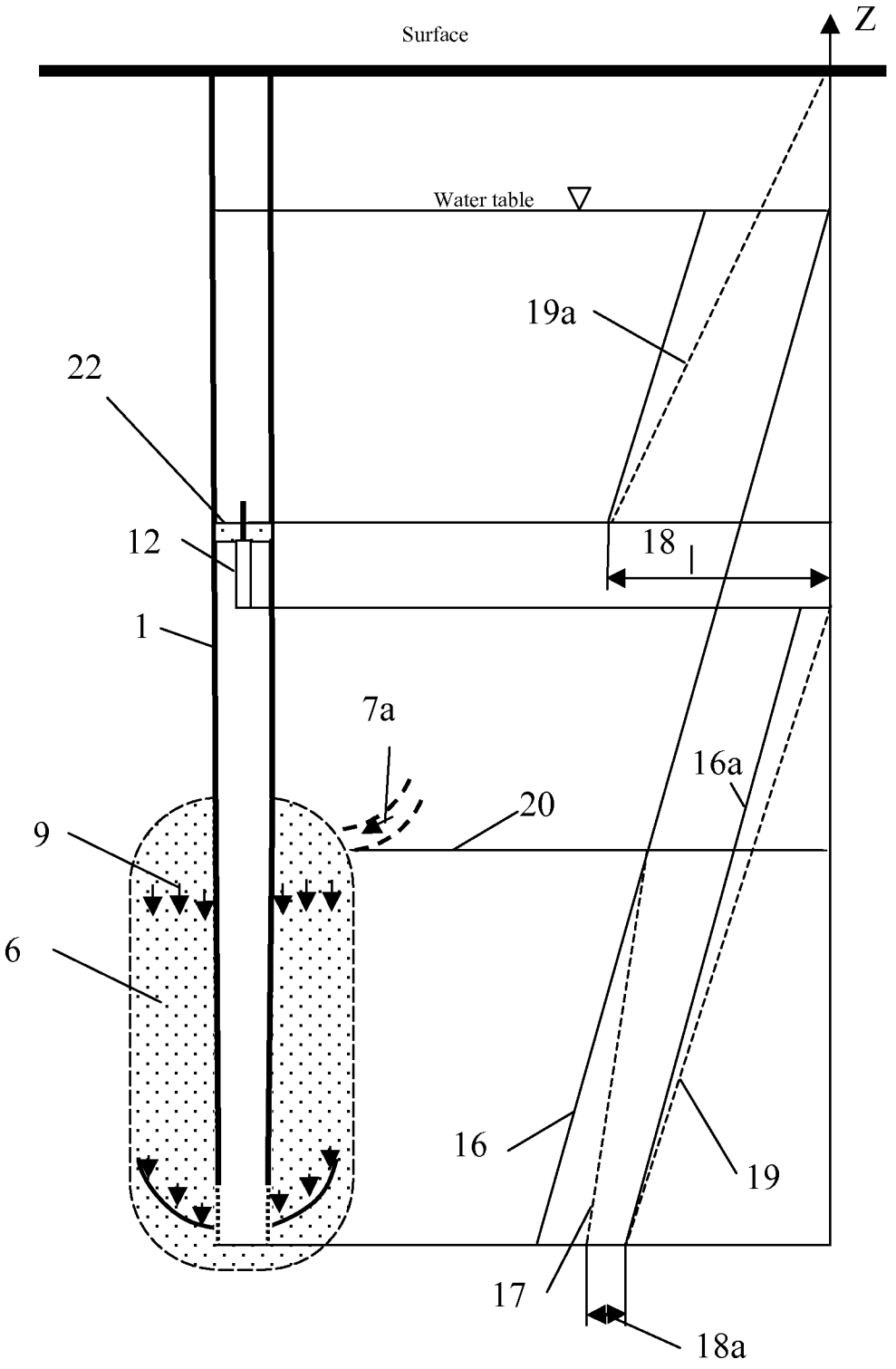


FIG. 5

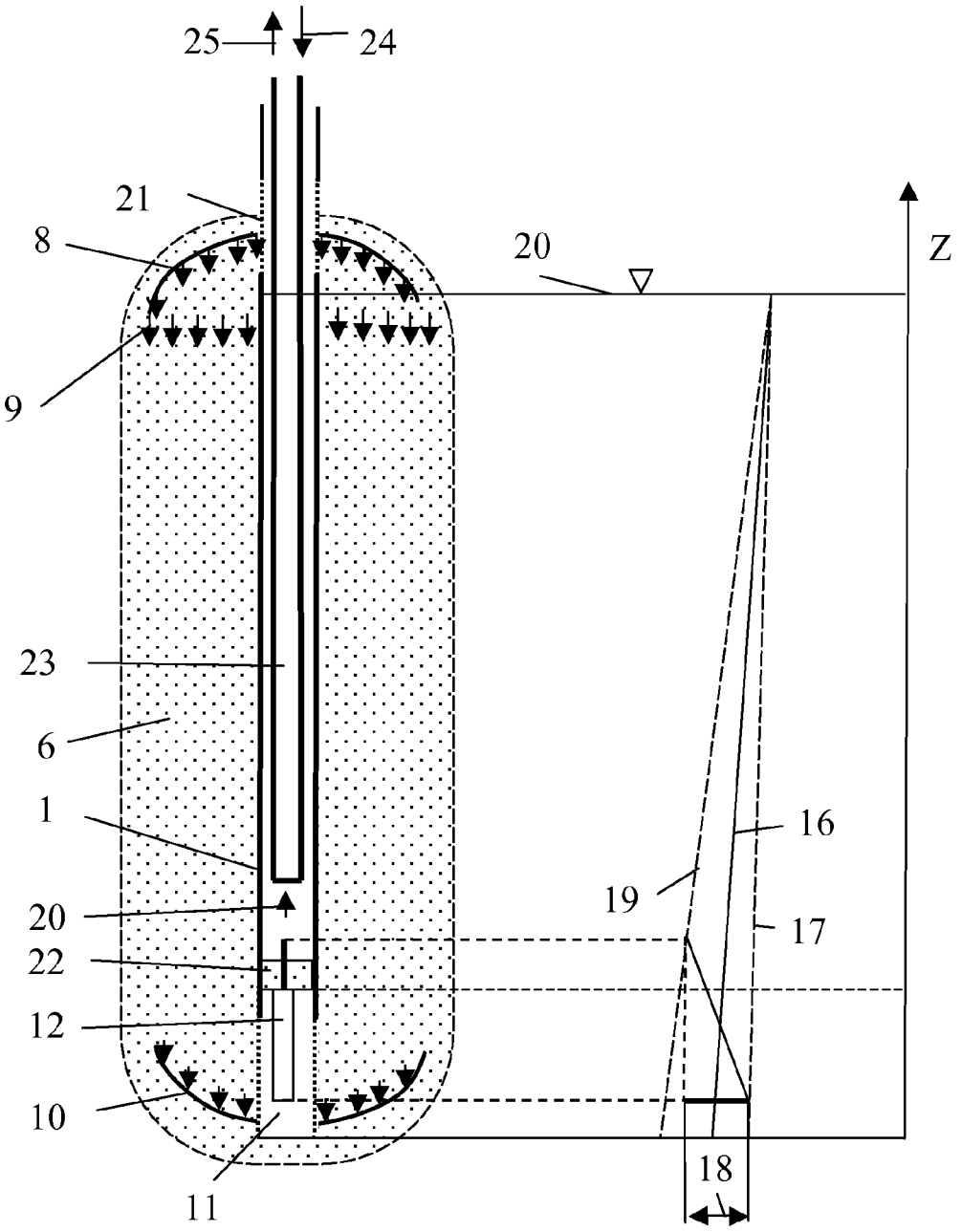


FIG. 6

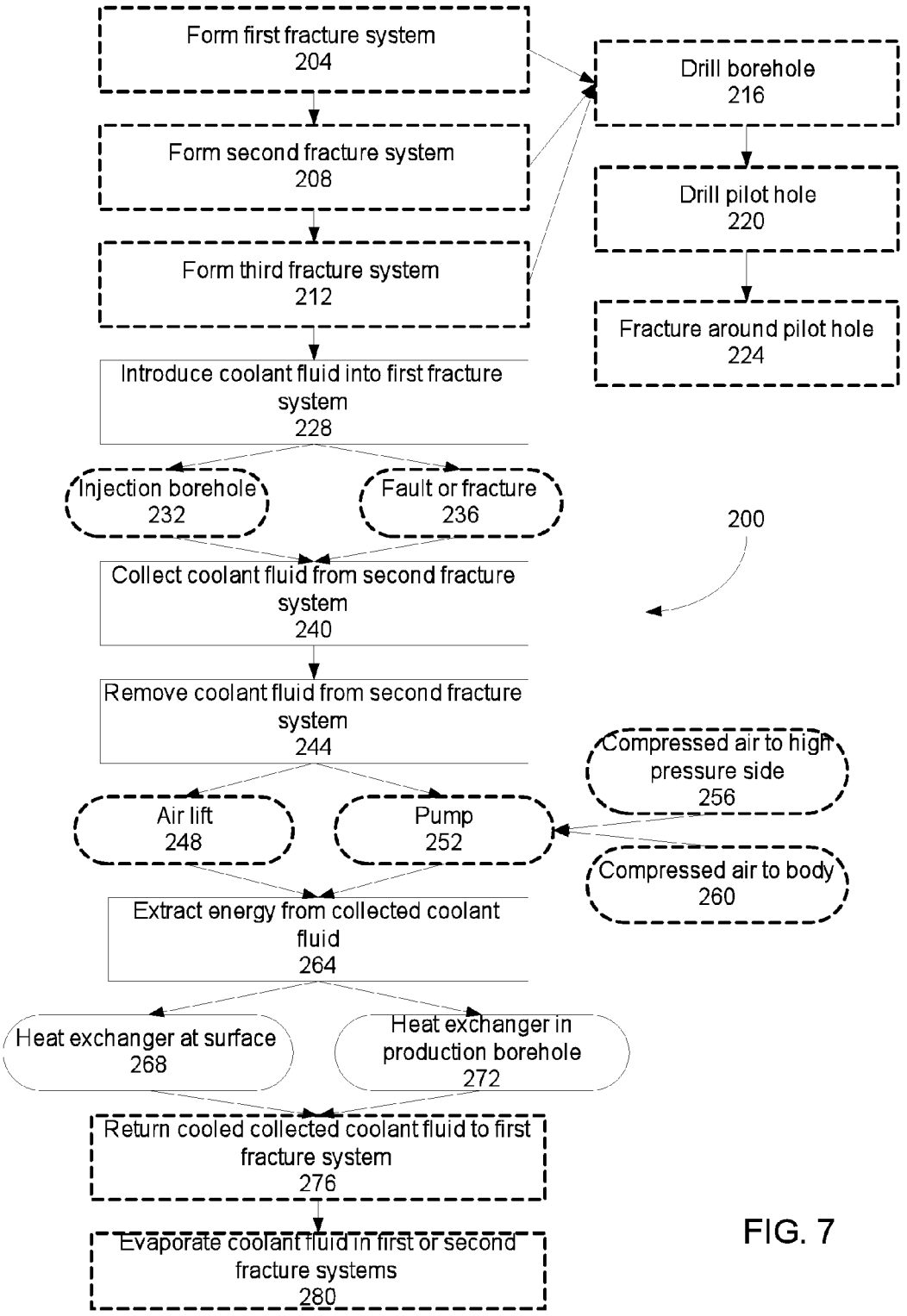

Form first fracture system
204
Form second fracture system
208
Form third fracture system
212
Drill borehole
216
Drill pilot hole
220
Fracture around pilot hole
224
Introduce coolant fluid into first fracture system
228
Injection borehole
232
Fault or fracture
236
200
Collect coolant fluid from second fracture system
240
Remove coolant fluid from second fracture system
244
Compressed air to high pressure side
256
Air lift
248
Pump
252
Compressed air to body
260
Extract energy from collected coolant fluid
264
Heat exchanger at surface
268
Heat exchanger in production borehole
272
Return cooled collected coolant fluid to first fracture system
276
Evaporate coolant fluid in first or second fracture systems
280

FIG. 7

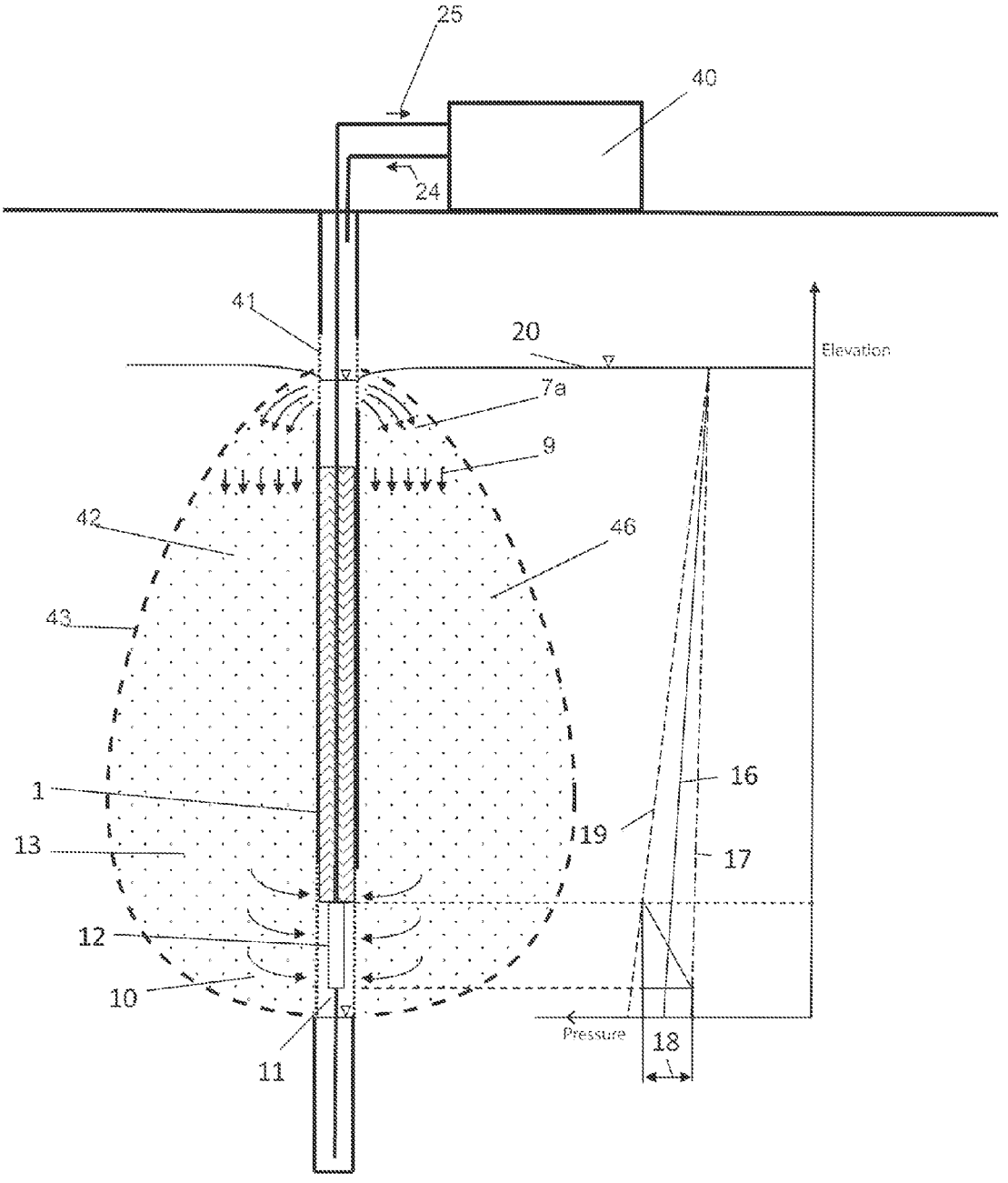
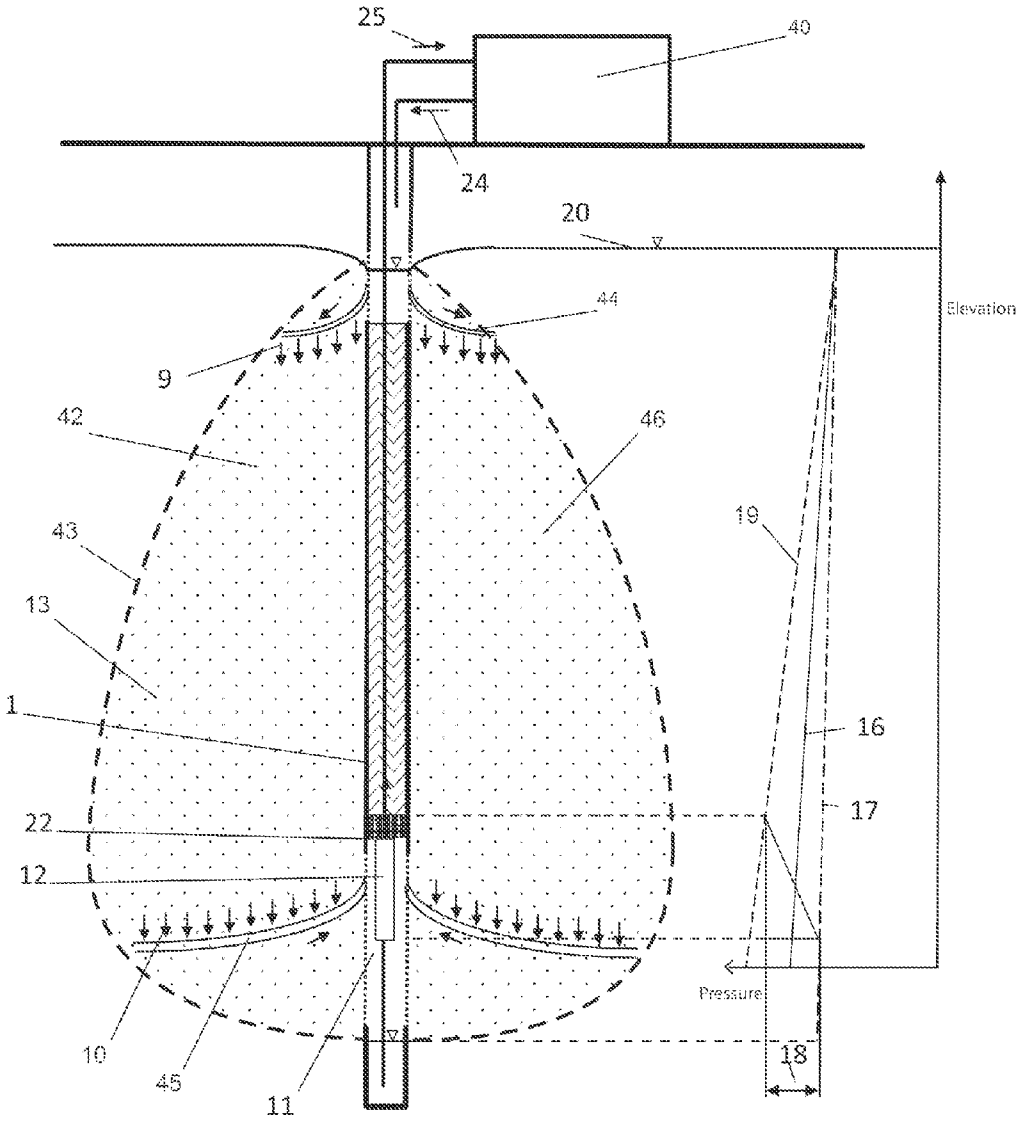

25
40
24
41
20
Elevation
7a
9
42
46
43
1
13
12
10
11
16
19
17
Pressure
18

FIG. 8


25
40
24
20
44
9
42
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13
1
16
17
22
12
Elevation
Pressure
10
45
11
18

FIG. 9

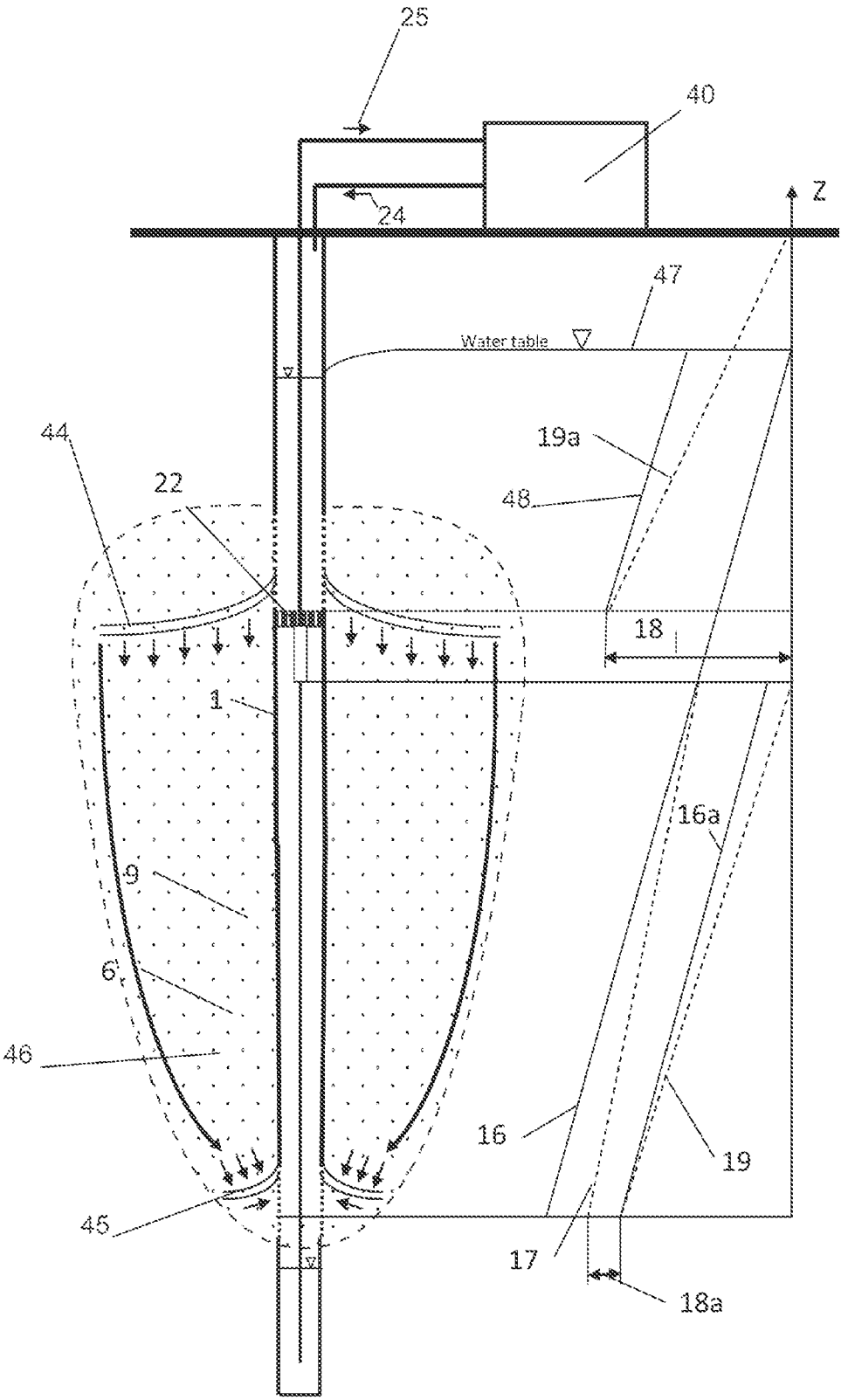


Figure 10.

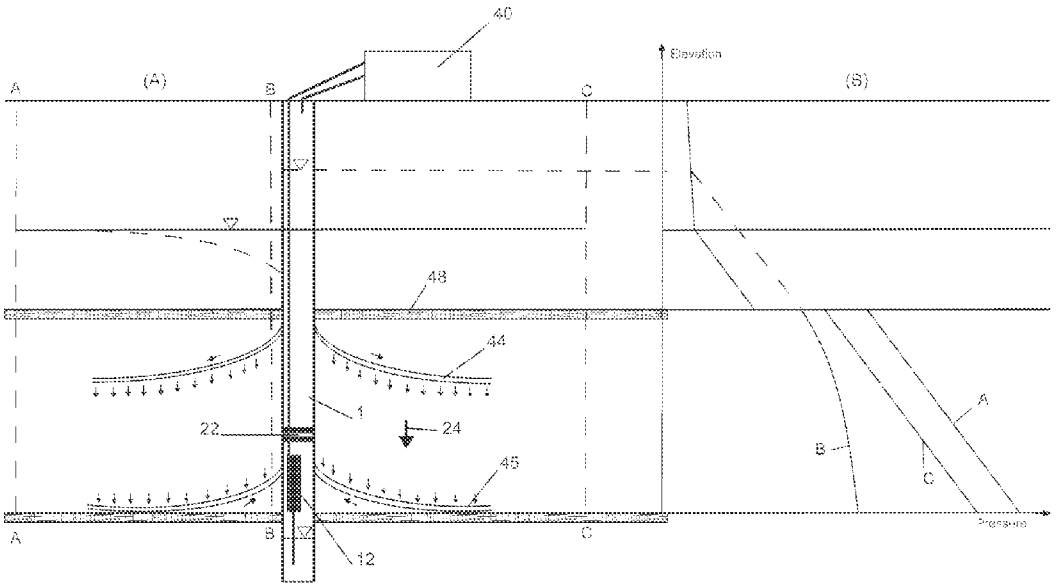
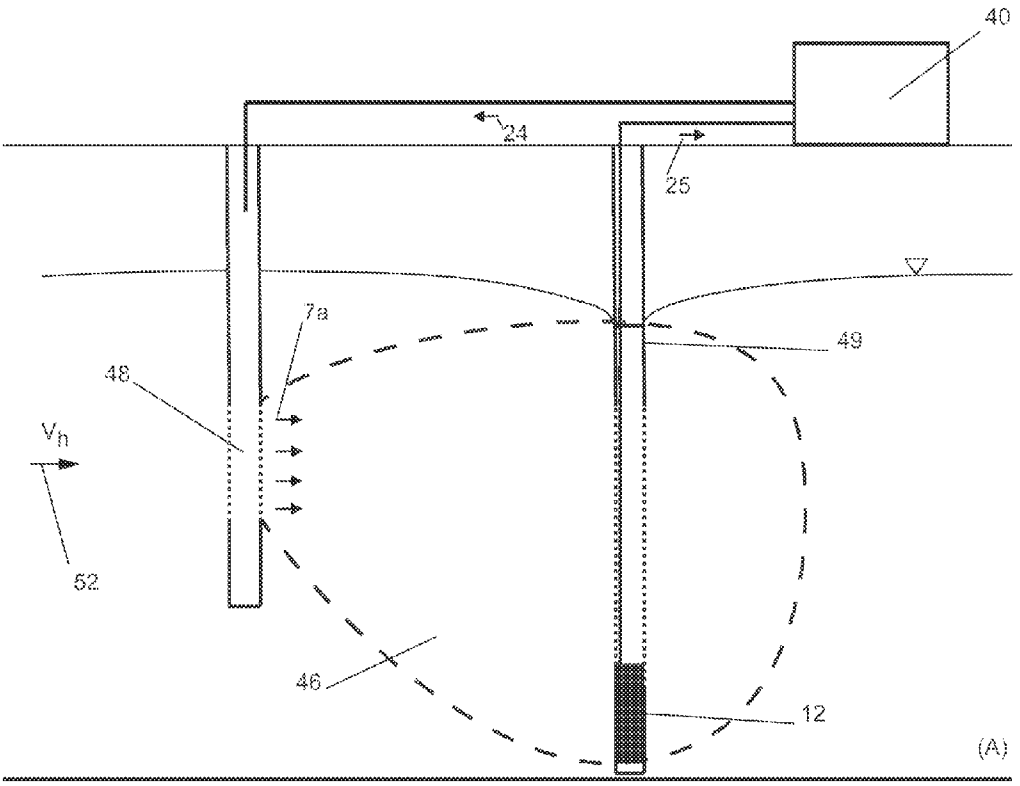


Figure 11



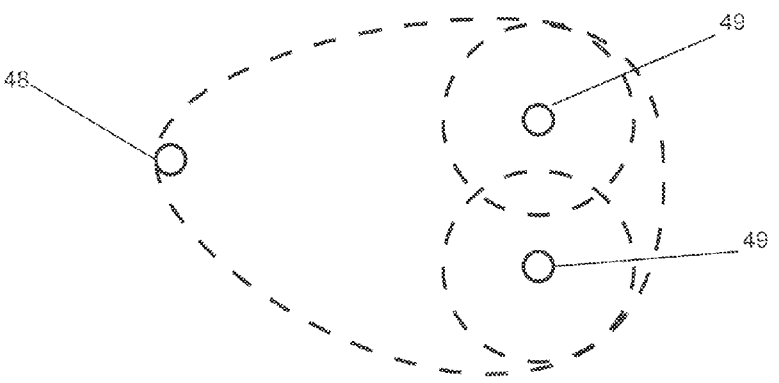


Figure 12.

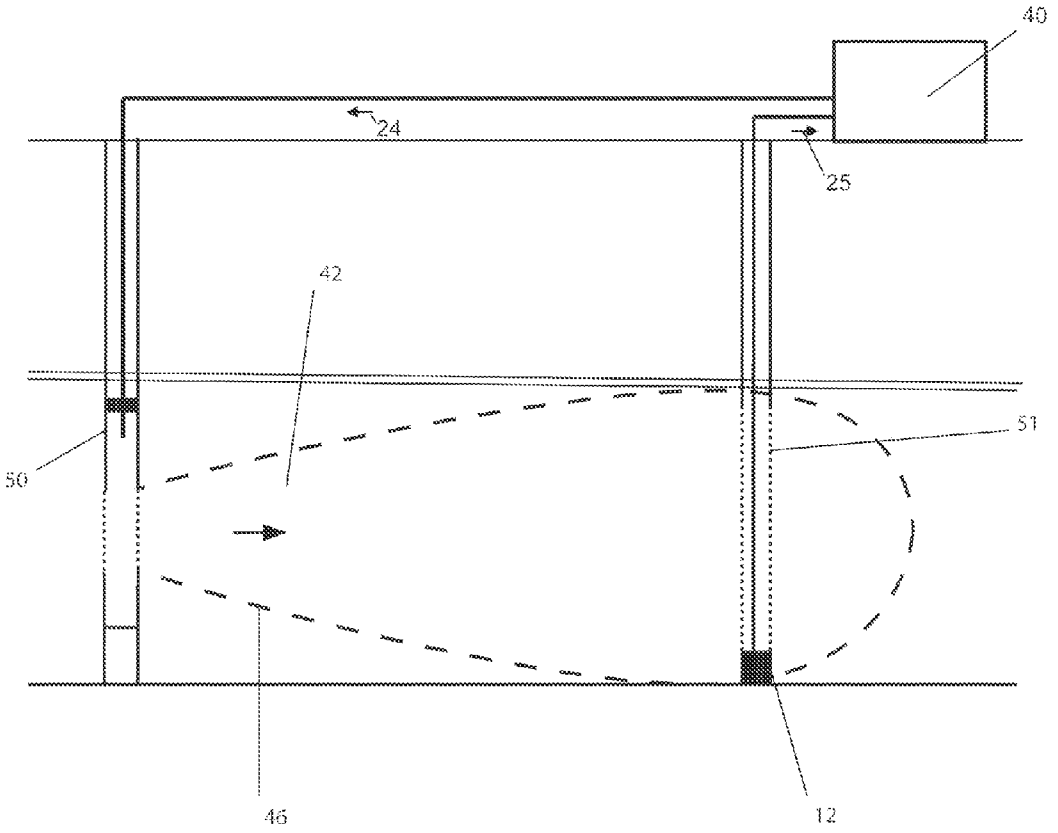


Figure 13.

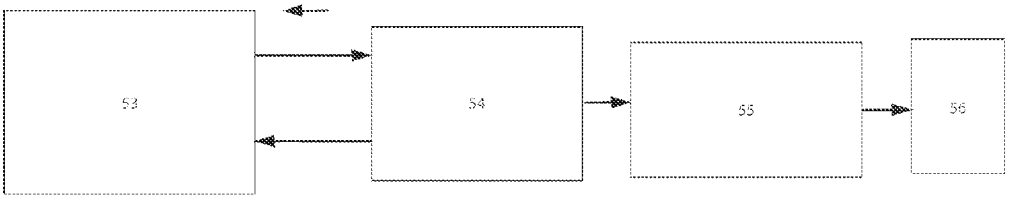


Figure 14.

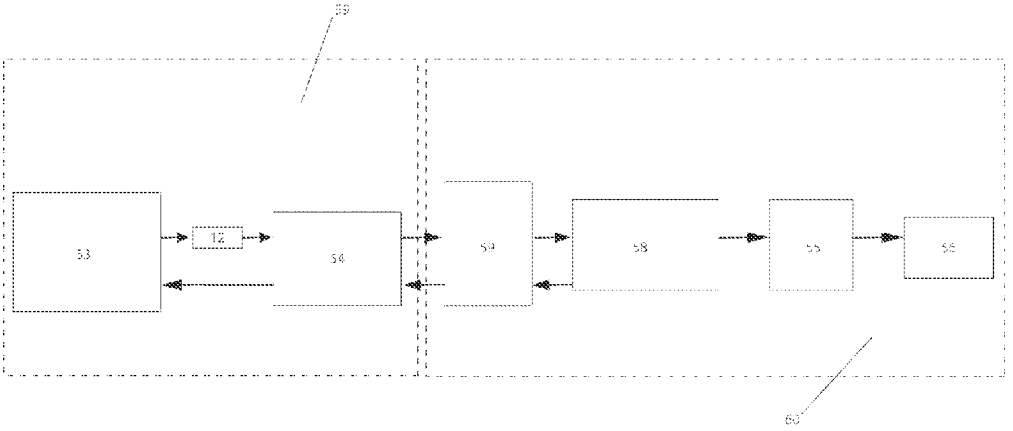


Figure 15

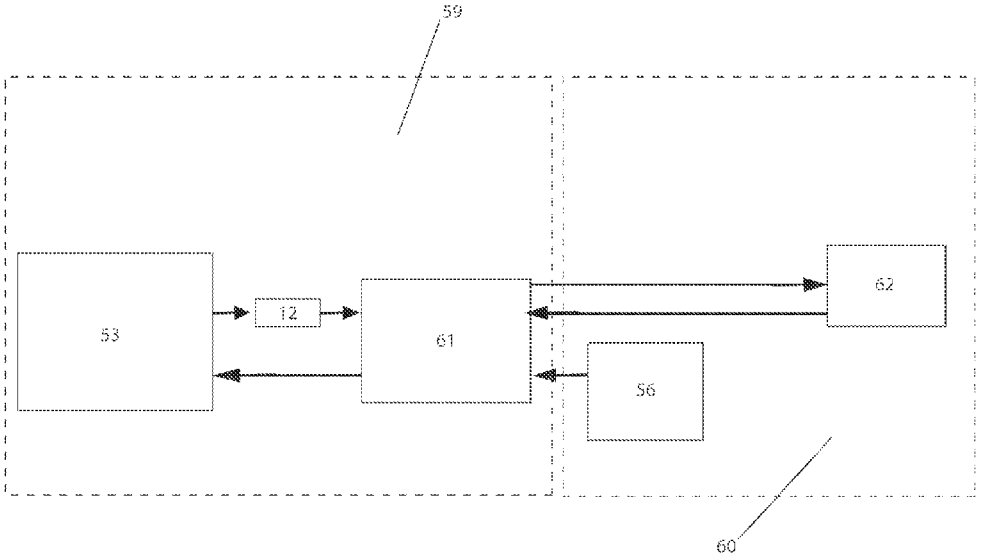


Figure 16.

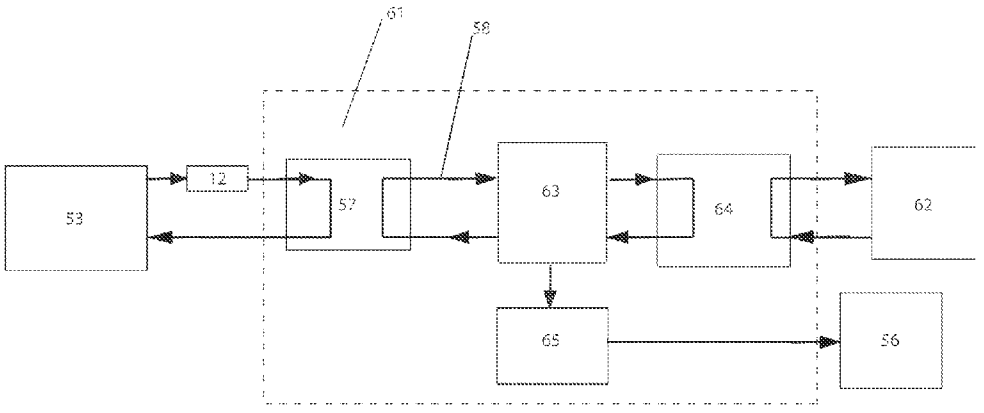


Figure 17

GEOTHERMAL ENERGY EXTRACTION SYSTEM AND METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of, and incorporates by reference, U.S. Provisional Patent Application Ser. No. 61/386,742, filed Sep. 27, 2010. This application is also a continuation in part of, and claims the benefit of, U.S. patent application Ser. No. 12/780,538, filed May 14, 2010, which in turns claims the benefit of U.S. Provisional Patent Application Ser. No. 61/178,237, filed May 14, 2009. Each of these applications is incorporated by reference herein in its entirety.

FIELD

[0002] The present disclosure relates, generally, to a method and a system for increasing the thermodynamic efficiency of extracting geothermal energy.

SUMMARY

[0003] One embodiment of the present disclosure provides a geothermal energy extraction method. According to the method, in a geologic formation, coolant fluid is introduced into a first fracture system at a first height. Water is collected from a second fracture system a second height, which is lower than the first height. The first and second fracture systems are in fluid communication. Coolant fluid introduced into the first fracture system percolates through a geologic formation from the first fracture system to the second fracture system, collecting heat from the geologic formation. In some examples, the second fracture system has a higher temperature than the first fracture system.

[0004] In some implementations, the method includes forming the first or second fracture system. The method can also include a third fracture system intermediate, and in fluid communication with, the first and second fracture systems. In another implementation, the fracture system may be natural as it often occurs in fractured or sedimentary rock formations. According to a particular example, the first, second, or third fracture system is formed by creating a borehole, creating a pilot hole ahead of the borehole, and fracturing the geologic formation proximate the pilot hole.

[0005] In a further implementation, coolant fluid is removed from the second fracture system. In one example, the coolant fluid is lifted from the geologic formation. For example, the coolant fluid can be removed to the surface for energy extraction. Energy can be extracted at the surface using a heat exchanger. In another example, energy is extracted in situ and the cooled coolant fluid is circulated within the geologic formation, such as entering through the first fracture system. When energy is extracted in situ, a heat exchanger may be located in a production borehole. Yet in another implementation, the geologic thermal energy is directly converted into electrical energy in situ, that is, the hot geothermal reservoir fluid is circulated in an energy conversions implement, whereas coolant fluid is delivered underground to facilitate the energy conversion. The energy conversion implement may include a heat exchanger as a boiler, a binary liquid steam Ranke cycle, a turbine, an electrical generator, and a condenser; which is cooled by the coolant fluid circulation from the surface

[0006] Energy may be extracted under steady or variable geologic coolant fluid flow. Pressure control means, such as a pump, can be used to lower the pressure of the second fracture system below that of the surrounding area. This can discourage loss of coolant fluid to the surrounding geologic area by reducing or eliminating the driving pressure difference.

[0007] Coolant fluid can be removed from second fracture system using any suitable techniques. One technique is pumping. Another suitable technique is air lifting. When pumping is used, in one example compressed air is injected to the high pressure side of the pump, contributing to air lifting. In another example when pumping is used, compressed air is introduced into the body of the pump. The compressed air expands in the pump, contributing to pump cooling. In another example, pumping is used to lower the pressure of the second fracture system, which can increase the flow of coolant fluid into the second fracture system from the first fracture system. In yet another example, a pump is located at a higher level than the bottom of the second fracture system. This can aid in opening fractures within the first or second fracture systems.

[0008] In another implementation, coolant fluid is provided to the first fracture system. In one example, the coolant fluid is supplied by an injection borehole. In another example, the coolant fluid is supplied from a natural geologic feature, such as a fracture or fault to/in a hydrothermal reservoir.

[0009] According to another embodiment, which may be combined with the above embodiment, fluid within first and/or second fracture systems is periodically evaporated in order to increase the active surface area of the first or second fracture systems. In one example, evaporation is achieved by lowering the pressure of the first or second fracture systems below the saturated or dissolution pressure limit of the coolant fluid. When the pressure is suitably lowered, a phase change is induced and liquid phase coolant is purged from fractures by the gas phase in one cycle. The pressure can then be raised, or allowed to rise, above the saturated or dissolution limit to deliver liquid phase coolant to the fractures in another cycle. Liquid phase and gas phase cycles are alternated, in one embodiment, in order to increase heat extraction, such as by contacting a greater surface area of the fracture system. Between cycles, a vigorous fluid flow field and latent heat exchange, in addition to sensible heat exchange, is created between the coolant fluid and the fracture system (rock). The implementation can be used to promote delivery of coolant fluid to stagnant, hard to reach fracture areas.

[0010] In another embodiment, the present disclosure provides a geothermal energy extraction system at least partially located in a geologic formation. The system includes a first fracture system at a first height and a second fracture system at a second height. The second height is lower than the first height. The first and second fracture systems are in fluid communication. The system includes a fluid transport means, such as a pump or gaseous fluid source, such as an, air source, for gaseous lifting, such as air lifting, of coolant fluid. An energy recovery unit, such as a heat exchanger, is also included in the system. A coolant fluid source is in fluid communication with the first fracture system.

[0011] In operation, coolant fluid is provided to the first fracture system from the coolant fluid source. The coolant fluid travels through the first and second fracture systems. Coolant fluid is transported from the second fracture system to the energy recovery unit using the fluid transport means.

[0012] In some implementations, the system includes a gaseous fluid source, such as a compressed air source. In one example, the gaseous fluid source is coupled to the high

pressure side of a pump, wherein it can be used to aid gaseous lifting of the coolant fluid from the second fracture system. In another example, the gaseous fluid source is coupled to the body of a pump, where it can be used to help cool the pump.

[0013] In another implementation, the system includes a third fracture system intermediate and in fluid communication with the first and second fracture systems.

[0014] In a particular example, the coolant fluid source includes an injection borehole. In another example, the coolant fluid source includes a natural geologic feature, such as a fracture or fault in/to a hydrothermal reservoir.

[0015] In a further example, the heat exchanger is located in a production well. In a yet further example, the pump is located higher that the bottom of the second fracture system, where is can aid in opening fractures in the first or second fracture systems.

[0016] In a further example, the geologic coolant fluid circulates through a heat exchanger in one side whereas the other side of the heat exchanger is a boiler for a binary steam cycle. The binary steam cycle powers a turbine which turns an electrical generator. Another heat exchanger is included to condense the returning steam.

[0017] In a further example, the entire power version implement is installed in the hot reservoir area underground. In this case the hot geologic fluid is not lifted to the surface, therefore, heat and energy can be reduced. The temperature of the coolant fluid for energy conversion, used in the heat exchanger of the condenser, is closer to the temperature of the surrounding rock along the circulation pathway to the surface, reducing parasite heat exchange and energy loss relative to the known solutions in which the hot geologic coolant fluid is circulated.

[0018] There are additional features and advantages of the subject matter described herein. They will become apparent as this specification proceeds.

[0019] In this regard, it is to be understood that this is a summary of varying aspects of the subject matter described herein. The various features described in this section and below for various embodiments may be used in combination or separately. Any particular embodiment need not provide all features noted above, nor solve all problems or address all issues in the prior art noted above.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIG. **1** is a schematic diagram of a method of producing a multilayered fracture system according to an embodiment of the present disclosure, and of the fracture system formed thereby.

[0021] FIG. **2** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure having an injection borehole.

[0022] FIG. **3** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure not having an injection borehole.

[0023] FIG. **4** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure showing pressure fields within the system.

[0024] FIG. **5** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure where the system/process use increased injection pressure showing pressure fields within the system.

[0025] FIG. **6** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure where the system/process lacks an injection borehole showing pressure fields within the system.

[0026] FIG. **7** is a flowchart of a method of extracting geothermal energy according to an embodiment of the present disclosure.

[0027] FIG. **8** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a formation having sufficiently high permeability and employing a pump to create a pressure differential.

[0028] FIG. **9** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a formation having sufficiently high permeability, employing a pump to create a pressure differential, and having coolant delivery boreholes and collection boreholes.

[0029] FIG. **10** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a formation having sufficiently high permeability and employing a pump to create a pressure differential, the pump being at a comparatively higher elevation.

[0030] FIG. **11**(A) is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a formation having sufficiently high permeability and employing a pump to create a pressure differential in a confined aquifer bounded by two impermeable layers. FIG. **11**(B) illustrates the pressure distribution of the system of FIG. **11**(A).

[0031] FIG. **12**(A) shows a cross sectional and **12**(B) shows a plan view a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a formation having sufficiently high permeability and employing a pump to create a pressure differential in an unconfined aquifer with multiple boreholes.

[0032] FIG. **13** is a schematic diagram of an energy extraction system and process according to an embodiment of the present disclosure in a confined permeable formation used for carbon dioxide sequestration and having an injection borehole, a production borehole, and using a pump for carbon dioxide circulation.

[0033] FIG. **14** is a block diagram illustrating energy flow between thermal energy from a geothermal reservoir and electrical energy using a circulating conductive geologic coolant.

[0034] FIG. **15** is a block diagram illustrating energy flow between thermal energy from a geothermal reservoir and electrical energy according to an embodiment of the present disclosure, using a circulating conductive geologic coolant that is transmitted to a surface installation.

[0035] FIG. **16** is a block diagram of an energy extraction system and process according to an embodiment of the present disclosure having a direct energy conversion unit.

[0036] FIG. **17** is a block diagram of a direct energy conversion unit according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0037] Unless otherwise explained, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. In case of conflict, the present specification, including explanations of terms, will control. The singular terms "a," "an," and "the" include plural referents unless

context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise. The term "comprising" means "including;" hence, "comprising A or B" means including A or B, as well as A and B together. All numerical ranges given herein include all values, including end points (unless specifically excluded) and any and all intermediate ranges between the endpoints.

[0038] Geologic coolant fluid, as used in the present disclosure, may be a liquid, has, or a mixture of liquid and gas, or a liquid with disclosed gas. In a specific example, the liquid is water. In further examples, the gas is air, carbon dioxide, or the vapor or steam from evaporated liquid. In a more specific example, the liquid is water and the gas is air, carbon dioxide, or water vapor or steam.

[0039] Phase changes due to pressure changes may be in the form of evaporation and/or condensation or solution and/or dissolution.

[0040] Latent heat refers to energy change due to phase change in general, including latent heat for evaporation/condensation and latent heat for solution/dissolution.

[0041] Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present disclosure, suitable methods and materials are described herein. The disclosed materials, methods, and examples are illustrative only and not intended to be limiting.

[0042] A new geothermal energy extraction system is described with an improved subsurface heat exchanging process. The new system increases the output temperature of the geologic cooling fluid used for energy recovery, and this way increases the efficiency of the power system with an increased thermodynamic efficiency for a given geologic setting. The solutions described in the disclosure pertain, in particular examples, to a conventional hydrothermal system with low hydrologic permeability and low natural flow rates, or a system involving the geothermal energy of dry hot rock which does not have a substantial natural fluid flow system, or a high-permeability, e.g. sedimentary rock formation which cannot be utilized with conventional geothermal recovery methods and systems due to unacceptable fluid and energy loss.

[0043] Natural geothermal energy systems with low permeability and water flow rates in large and hot rock areas have similar problems to those in deep geological settings with dry hot rock with regard to energy recovery. They both need convective fluid flows to be established in order to exploit significant amounts of thermal energy. They both need an artificial fracture system in the rock to be established for the facilitation of convective fluid flows.

[0044] Enhanced geothermal systems often rely on the principle of hydro-fracturing of dry rock mass deep underground. The fracture system at any location around the borehole typically depends upon the in situ stress field of the rock mass and the hydraulic pressure applied to the fracturing process. Since hydrostatic pressure greatly varies with elevation, more control can be exercised when the fracturing along the borehole is created sequentially, one fracture network system at one elevation at a time.

[0045] In the following description, it is assumed that a sufficiently long section of a deep borehole stretching across a hot geologic area can be fractured at various depths. It is further assumed that the fractured zone around the borehole can extend in radial direction into the rock mass several tens or hundreds of meter. A particularly advantageous sequence of fracture network creation is described along a deep borehole drilled in dry hot rock or hot rock in a hydrothermal field with low permeability, such permeability insufficient for creating convective flows.

[0046] The process of generating multiple levels of fracture network around a borehole is described with the use of FIG. **1**. When the depth of borehole **1** reaches the desired depth at which useful temperature is found for geothermal energy extraction, the drilling is stopped and a smaller diameter pilot hole **10** is drilled ahead of the larger-diameter borehole **1** to some depth, e.g., 300 m, to create fractures starting at that depth. The pilot hole **10** is used to create a fracture network around it. In some examples, the fracture network is substantially spherical or ellipsoidal in shape.

[0047] For fracturing, the pilot hole section **10** is sealed at its collar with pressure seal **15**. Hydro-pressure is generated around it by pumping a sufficient flow rate of water into it through the fracturing pressure pipe **14**. A fracture network system **2** is created to a desired depth or degree, such as having a radial diameter of about 300 m. Orientations of the fractures typically depend on the in situ stress field and the planes of weakness of the rock formation. The development of the fractures in a radial direction typically results from the fracturing process, and the network occurs with a random structure in spite of dominant fracture planes. However, in some embodiments, the fracture system is developed in a more controlled manner, such as by adjusting the applied hydraulic pressure or the pumping flow rate, which can influence fracturing velocity. In yet further examples, the fracture apertures are treated to help them remain open, such as by pumping in solid particles, e.g., screened sand or gravel, called propants.

[0048] Multiple branches of the fracture network **2***a* and **2***b* may be created along the first pilot hole section **30**, as shown in FIG. **1**. The fracture network system is, in some implementations, assessed and completed after sufficient fracture volume and apertures are established. Assessment may be made by suitable methods, including measuring the volume of the fracturing fluid pumped into the fracture network; pumping and extracting tracer elements and observing the variation of concentration with time; micro-seismic wave reflection measurements, and combinations thereof.

[0049] Once the fracture system is created at one depth area, the fracturing pressure pipe **14** is extracted, and the pilot hole **30** is re-drilled, removing pressure seal **15** at that depth, and extending borehole **1** to a greater depth below the area of fracture network **2***b*. At this second depth, shown in FIG. **1**, the fracturing process is repeated by means of drilling a pilot hole **30***a*; insertion of fracturing pressure pipe **14**; and creating a pressure seal **15***a;* and creating a new fracture network system **3**, with possible fracture network branches **3***a* and **3***b*. The assessment of the fracture network system **3**, **3***a*, and **3***b* is conducted again and re-fracturing is continued until satisfaction. Fracturing is completed when hydrologic flow connection between branches of fracture network **2**, **2***a*, and **2***b* and branches of fracture network **3**, **3***a*, and **3***b* has been established and positively confirmed by assessment means.

[0050] Once the fracture system is completed at the second depth area, the fracturing pressure pipe **14** is extracted, and the pilot hole **30***a* is re-drilled, removing pressure seal **15***a* at that depth, and extending borehole **1** to a greater depth below the area of fracture network **3***b*. At this third depth, shown in FIG. **1**, the fracturing process is repeated by means of drilling

a pilot hole **30***b*; insertion of fracturing pressure pipe **14**; and creating a pressure seal **15***b;* and creating a new fracture network system **4**, with possible fracture network branches **4***a* and **4***b.* The assessment of the fracture network system **4**, **4***a* and **4***b* is conducted again and re-fracturing is continued until satisfaction. Fracturing is completed when hydrologic flow connection between branches of fracture network **3**, **3***a,* and **3***b* and branches of fracture network **4**, **4***a,* and **4***b* has been established and positively confirmed by assessment means.

[0051] Once the fracture system is completed at the third depth area, the process may continue to even greater depths. For example, it may be advantageous to fracture the rock mass around a borehole from 4,000 m depth down to 6,000 m depth, or even deeper. Shallower depths can be sufficient in a natural geothermal area. The fracture system will be a high-permeability fracture network around borehole **1**, forming fractured zone **6**, capable of carrying convective cooling fluid for geothermal energy extraction from the top of fractured zone **6** to its bottom. The advantage of creating a multiple-level fracture network system through a series of pilot holes is that the process does not interfere with the completion of borehole **1** and the placement of its liner in long, constant-diameter sections.

[0052] The completion of the geothermal energy extraction system in FIG. **2** involves several more steps. A cooling fluid delivery fracture network system **8** is created within the fractured zone **6**. This can be done from borehole **1**, effectively designating the first fractured system **2** as delivery fracture network **8**. The fracture network system **8** is also connected to a second borehole, borehole **7**, for injecting geothermal cooling fluid **7***a* if a hot dry rock area is used. Optionally, delivery fracture network **8** may be created from borehole **7** in a similar manner described regarding fracture creation around borehole **1**.

[0053] As shown in FIG. **3**, injection borehole **7** is omitted in some configurations, such as if the hot rock area is connected to a natural hydrothermal system. For example, injection borehole **7** may be replaced by a major natural fracture or fault in a geologic system of a hydrothermal reservoir. In this case, injection fluid **7***a* is percolation fluid flow from the natural system.

[0054] Referring primarily to FIG. **2**, although a similar system/process takes place in FIG. **3** (with the exception of the injection borehole **7**), collection fracture network **5** is created at the bottom of fractured rock zone **6**, carrying hot fluid flow **10** to borehole **1** which is used as a production borehole to lift hot fluid for power generation. This can be done from borehole **1**, effectively designating the last fracture network system (such as system **4** in the rightmost panel of FIG. **1**) as collection fracture network **5**.

[0055] Multiple levels of fracture network systems around borehole **1** can be created by other ways. For example, borehole **1** can first be drilled, observed for assessing geology, lithography, fracture and/or faults, and completed with casing. Fractured zone **6** can then be created as a next step around borehole **1** over the desired length by sequentially, level-by-level (1) jet-drilling through the casing; (2) sealing of a section around the jet-drilled holes; and (3) hydro-fracturing at each level. According to an embodiment of the present disclosure, the access holes in the casing drilled for fracturing are sealed off, except for those connected to injection fractures **8** and collection fractures **5**. Sealing may be accomplished by inserting another liner or casing into borehole **1** or by other means.

[0056] FIG. **2** illustrates the connected fracture network system in a simplified fashion, depicting the delivery fracture network **7**, transmission fracture network branches **2**, **3** and **4** as examples for a possible solution with a large-enough vertical extent, and the collection fracture network **5** around borehole **1** all within fractured rock zone **6**. FIG. **2** also shows pump **12** with its delivery pipe to carry upward the hot fluid.

[0057] At least one delivery fracture system **8** for the introduction of cooling fluid **7***a* at a higher elevation and one collection fracture system **5** at a lower elevation are used according to an embodiment of the present disclosure. The two fracture systems are connected as an integral flow system in fractured zone **6**. An arbitrary number of intermittent, transmission fracture network systems may be inserted between the delivery and the collection fracture systems to increase the volume and surface area along the working length of borehole **1** for heat exchange.

[0058] The geothermal energy extraction system according to an embodiment of the present disclosure operates on a reversed flow principle relative to known solutions. The flow direction of the convective cooling fluid is from top to bottom, allowing for increasing the temperature of the cooling fluid along its flow path as it reaches hotter rock areas at increasing depths. This way, the heat extracted from the rock mass will be delivered at the highest possible temperature, allowing the thermodynamic efficiency of the energy conversion to be increased from thermal energy to mechanical energy in the turbine system. Heat is typically more valuable at higher temperature than at lower temperature, increasing the thermodynamic efficiency. If the flow direction of the hydrothermal fluid is in the direction of the geothermal gradient, the exit temperature is increased, and the entropy is decreased, relative to other flow directions. Therefore, the geothermal extraction principle according to an embodiment of the present disclosure can be more efficient that prior techniques. This increased efficiency is due, in some implementations, by the enhanced convective heat exchanging system and the extraction of the counter-current percolation flow relative to natural, buoyancy-driven circulation directions.

[0059] In typical existing systems, the geothermal fluid flow direction is upward, reaching rock areas at lower temperature as the cooling fluid collects thermal energy, impeding the overall thermal efficiency, and increasing entropy. A system according to an embodiment of the present disclosure allows for converting a larger portion of the gross thermal energy lifted from the ground into usable mechanical or electrical energy. Buoyancy-driven, small-scale flow eddies moving upward may develop within certain areas in fractured zone **6**. Natural, thermal siphon-type circulation loops involving vertical upward flows locally may also be formed in certain areas. These circulation loops will not impede, but rather further enhance local convective heat transport within the overall, dominantly downward flow direction for convective thermal energy transport.

[0060] Downward coolant flow encounters hotter rock and removes heat from it, while increasing its own temperature and energy content. At the same time, the fracture aperture opens up due to thermal contraction of the rock under cooling. In comparison, in case of upward coolant flow direction in the current practices, the hot fluid may encounter colder rock, effectively losing its cooling ability, and making the heat exchange surface inefficient. The fracture aperture may tend

to close under heating by the hotter fluid, increasing the pressure loss and the required pumping pressure, and/or decreasing the flow velocity.

[0061] The flow system is explained with the use of FIG. **2**. Injection fluid **7***a* enters the fractured zone **6** of the hot rock area as induced percolation **9**, originating from injection borehole **7** through injection fracture network **8**, in fractured, enhanced dry hot rock application; or from natural percolation through fractures and faults in fractured, enhanced hydrothermal reservoir application. The induced percolation continues throughout the vertical extent of the fractured zone **6** until it reaches the collection fracture network **5** and flows back as hot fluid flow **10** into the low pressure chamber **11** of the bottom of production borehole **1**. Pressure lowering is accomplished by a suitable fluid extraction means for removing coolant fluid from the geologic formation, such as employing a pump **12** or applying gaseous lifting, such as air lifting, which elevates fluid from a well by mixing well fluid with compressed air bubbles. FIG. **2** shows pump **12** with the suction side connected to the low pressure chamber **11** and a delivery pipe which carries the hot reservoir fluid to the surface. Heat and pressure insulation **13** is used to fill the annulus between the delivery pipe and borehole **1**.

FIG. **4** provides another embodiment of a flow system for an enhanced hydrothermal reservoir with a major fracture or fault. Injection or natural groundwater fluid **7***a* enters the fractured zone **6** of the hot rock area as induced percolation **9**, originating from a fracture or fault and replacing borehole **7** in FIG. **2**, through a fracture network **8** which, in one example, is created from borehole **1**. The induced percolation continues throughout the vertical extent of the fractured zone **6** until it reaches the collection fracture network **5** and flows back as hot fluid flow **10** into the low pressure chamber **11** of the bottom of production borehole **1**. Pressure lowering is accomplished by employing a pump **12** or applying air lifting, elevating fluid from a well by mixing well fluid with compressed air bubbles. FIG. **3** shows pump **12**, with the suction side connected to the low pressure chamber **11** and a delivery pipe which carries the hot reservoir fluid to the surface. Heat and pressure insulation **13** is used to fill the annulus between the delivery pipe and borehole **1**.

[0062] FIG. **4** shows the main elements of the geothermal energy extraction system as well as the outside hydrostatic pressure field **16** within the outside of the fractured zone and the inside pressure field **17** within the inside of the fractured zone. As shown, inside pressure field **17** inside the fractured zone is lowered relative to the in situ pressure due to the friction loss caused by the downward flow field, placing and keeping the rock mass in fractured zone **6** under lower pressure, i.e., depression, relative to the surrounding rock formation. This advantageous pressure field can be maintained due to the placement of the pump at the lowest elevation, provided that induced percolation **9** does not require increased pressure relative to the in situ hydrostatic pressure. This case is shown in FIG. **4** with matching pressure lines **16** and **17** at the injection elevation **20** at the top of fractured zone **6**. It must be noted that pump delivery pressure line **19** may be increased arbitrarily to meet the necessary pressure demand to lift the hot fluid to the surface, i.e., pressure **19** does not have to intersect pressure lines **16** and **17** at elevation **20**. The pressure field according to FIG. **4** can eliminate or reduce the potential loss of hot fluids. Pump **12** increases the pressure within its length by a pressure difference **18** until it reaches delivery pressure in the delivery pipeline creating an upward flow.

[0063] The fractured zone can be made sufficiently large in volume (to access stored heat) as well as large in outside surface area (to access convective-conductive heat from the hot surrounding rock mass), and therefore, can be designed to extract large amounts of geothermal energy for sufficiently long time periods without significant depletion.

[0064] In some configurations, pump **12** operates at relatively high temperatures, which can exceed 300° C. In some cases, according to an embodiment of the present invention, pump **12** is operated by applying compressed air injection to the high pressure side of the pump, contributing to air lifting. In another example, compressed air is delivered to the body of the pump at a higher pressure than needed for air lifting injection. The compressed air is expanded to the injection delivery pressure within the casing of the motor. This way, expansion power, effectively a cooling power, may be created, which can advantageously decrease the operating temperature of the pump. Alternatively, in another embodiment of the present disclosure, the pump is omitted and another technique, such as air lifting, is used to move upward the hot reservoir production fluid.

[0065] The elevation of pump **12** may be increased if an increased injection pressure at elevation **20** is required for maintaining fracture apertures in an open state; however, opening and stabilizing fracture apertures by propants may also be carried out, in addition to or in place of pressure opening. Such a case is shown in FIG. **5** as an example, delivering an injection pressure from a high water table head along hydrostatic pressure **16** to the fractured zone at elevation **20**. Note that the hydrostatic head may be above the surface, not shown. Inside pressure field **17** under percolation flow **9** starts from hydrostatic pressure **16** at elevation **20** in the example. Suction pressure difference **18***a* is created by pump **12** at which the absolute suction pressure at the intake is lowered to the physical minimum, shown as near zero in the example for simplicity. During pumping, this pressure must typically be kept higher than the saturated water pressure at that temperature, which can be quite high itself. The intake pressure at pump **12** is decreased by the pressure loss in borehole **1** due to friction, shown as a gradient difference between line **19** and line **16**, as well as parallel line to it **16***a*, also depicted for clarity. Pump **12** delivers hot fluid to the surface along pressure line **19***a*, which assumes zero pressure at surface elevation. In some implementations, the hot fluid enters a heat exchanger to remove its thermal energy and convert it to mechanical and electrical energy. In a closed control volume in which the coolant fluid may be considered conserved, the cooled coolant fluid is re-injected into the circulation system. Such a case may be interpreted by connecting the end of pressure line **19***a* at the surface vertically to the beginning of pressure line **19** at the water table elevation, assuming that the pressure loss of fluid handling at the power plant as well as the pressure loss of the discharge of the coolant fluid to the water table is compensated by the elevation difference. A total pressure difference **18** typically must be provided by pump **12** to move hot fluid from the bottom of borehole **1** to the surface, a significant component in the pumping energy requirement for energy production.

[0066] An advantageous variation of the geothermal energy extraction system described in the foregoing is discussed with the use of FIG. **6**. In this solution variation, injection borehole

7 is eliminated, and pump **12** lifts hot fluid from the collection fracture network system **10** to injection fracture network **8** directly. Pump **12** effectively establishes a thermal fluid circulation within the fractured rock zone **6**, engineered to be counter-current direction to the direction of natural re-circulation under buoyancy driving forces. The outside hydrostatic pressure field **16** within the outside of the fractured zone and the inside pressure field **17** within the inside of the fractured zone are both shown to understand the flow system.

[0067] Pump **12** increases the pressure within borehole **1** to delivery pressure **19**, creating an upward flow **20** in borehole **1** which is cased to prevent radial fluid flow to or from fractured zone **6**, except for the upper section of fractured zone **6** around the fluid delivery fracture network **8**. Along this discharge section **21**, the casing of borehole **1** is screened, or punched, e.g., by jet drilling. Pressure seal **22** is used to prevent back-flow to the low pressure chamber **11**.

[0068] As shown, the pressure increase **18** across the pump is engineered to overcome the flow friction and momentum losses as well as the natural buoyancy pressure differences within the recirculation system. A standing water level **20** in borehole **1** is stabilized just above the screened discharge section **21** in order to maintain cooling fluid delivery to injection fracture network **8** and percolation flux **9**. The energy recovery is accomplished by evaporative heat exchanger **23**, basically a U-tube arrangement with a downward coolant fluid flow **24** in one leg and upward steam flow **25** in the other leg. This coolant fluid recirculation loop assumes at least in some examples, that the fractures are kept open without pressurizing them above the hydrostatic pressure at any location, e.g., injecting propants during hydrofracturing.

[0069] Another implementation of this variation applies compressed air injection for cooling and relieving pump **12** from excessive thermal load. Yet another implementation applies solely compressed air injection for maintaining recirculation of cooling water against natural buoyancy driving forces, if water is the coolant fluid. In this implementation, an air bubble and water mixture in borehole **1** is created to maintain upward flow and the desired circulation direction. The air bubble-water mixture at cooled-down temperature by heat exchanger **23** can still have lower density than the density of the hottest water in fractured zone **6**, therefore, it can effectively drive the circulation loop in the desired direction without using pump **12**.

[0070] A long section along borehole **1** is used for extracting thermal energy from the hot fluid by evaporative heat exchanger **23**, as part of a secondary steam cycle that is completed in the power plant with turbines and condensers. A small amount of fluid can be replenished to maintain standing water level **20** if loss occurs from the circulation loop. The hot water is not lifted to the surface in this implementation. An advantage of this implementation is that thermal energy loss can be reduced along borehole **1** from the geothermal energy production level to the power plant level where the thermal-to-mechanical energy conversion takes place. The advantage is seen in transporting thermal energy in latent heat form from a greater depth (at high pressure) to a lower depth (at lower pressure) in gaseous, compressible physical phase. As evaporated steam **25** flows upward from heat exchanger **23** which acts as a boiler, it decompresses and cools, reducing the temperature difference and resulting heat loss between the carrying pipeline and the surrounding rock mass. On the other hand, sufficiently high pressure can be maintained in the steam cycle loop to avoid condensation of the stem as it flows upward in spite of cooling and decompressing.

[0071] A two-phase coolant fluid system may also be created in fractured zone **6** by lowering the pressure level by adjusting the pressure at elevation **20**. Pressure lowing at elevation **20** may be accomplished, for example, by removing liquid from the borehole **1**, or lowering the pressurization of borehole **1** by another pump (not shown) at another elevation or at the surface. The differential pressure in the circulation loop is maintained by pump **12**. The absolute pressure in that loop can be independently controlled. For example, a pressure difference **18** can be carried by adjusting the working point of pump **12** (for example, changing its speed); whereas the pressure level at both the intake and delivery points of pump **12** can be simultaneously increased or decreased by adjusting the pressure at elevation **20**.

[0072] If the pressure at any given location is set lower than the saturated pressure for the coolant fluid at the temperature of the given location, the result will be evaporation. It may be advantageous to induce periodic evaporation by decreasing the pressure level below the saturated pressure limit or dissolution pressure limit for some time in a purging cycle and allowing the gas-phase coolant to repel stagnant liquid-phase coolant packets. During this purging cycle, the coolant circulation is suspended by stopping pump **12** and avoiding gas-phase digestion. Pressure then can be increased above the saturated limit or dissolution limit in another cycle, condensing steam or absorbing the gas-phase component and flooding the fracture system with liquid-phase coolant. The two-phase huff-puff operation may alleviate the loss of active surface area in the heat exchange process between convective coolant fluid and the fractured rock formation. Pressure variations in zone **6** may be accomplished by pumping pressure control from the surface, or pressure control at the subsurface pump, or a combination of the two.

[0073] In one variation, multiple vertical boreholes with coalesced fractured zones around them can be used to create an even greater rock mass volume with convective heat transfer surface area within it. Boreholes or borehole sections running horizontally and fractured zones created in between can also be used. In this case, extraction of the hot fluid is accomplished at a comparatively low elevation and, therefore, at increased temperature. The fluid extraction system is then typically engineered to maximize the temperature of the hot fluid carrying thermal energy; and minimize the potential heat loss during carrying the hot fluid to the energy conversion implement.

[0074] A method **200** of extracting geothermal energy according to an embodiment of the present disclosure is presented in the flowchart of FIG. **7**. According to the method **200**, first, second, and/or third fracture systems are formed in optional steps **204**, **208**, **212**. According to an implementation of the method **200**, steps **204**, **208**, **212** can involve drilling a borehole in step **216**, drilling a pilot hole ahead of the borehole in step **220**, and fracturing around the pilot hole in step **224**.

[0075] Coolant fluid is introduced in the first fracture system in step **228**. In one implementation, coolant fluid is introduced into the first fracture system through an injection borehole in step **232**. In another implementation, coolant fluid is introduced into the first fracture system through a fault or fracture in step **236**, such as from a natural hydrothermal reservoir.

[0076] Coolant fluid collects in the second fracture system in step **240**, optionally after it has passed through a third fracture system, when present. In step **244**, the coolant fluid is removed from the first fracture system. In one implementation, coolant fluid is removed by air lifting in step **248**. In another implementation, coolant fluid is removed by a pump in step **252**. In a particular example, compressed air is added to the high side of the pump in step **256**, which can assist with air lifting. Step **260** shows another example where compressed air is added to the body of the pump, which can aid in cooling the pump during operation.

[0077] Energy is extracted from the collected coolant fluid in step **264**. In one implementation, step **268**, heat is extracted using a heat exchanger located at the surface. In another implementation, step **272**, heat is extracted using a heat exchanger located in a production borehole.

[0078] In optional step **276**, cooled collected coolant fluid is returned to the first fracture system. In another optional step, **280**, coolant fluid is cyclically evaporated/liberated and condensed/dissolved in the first, second, and/or third fracture systems, such as by cyclically lowering and increasing the pressure using a pump. Sufficient time periods in the cycle are provided for pursing stagnant cooling fluid from the fractures during evaporation or has liberation in one cycle and delivering coolant fluid during condensation or gas absorption in another cycle.

[0079] An innovative geothermal energy production method and apparatus are further described from permeable rock formations. Fractured or sedimentary rocks with moderate permeability of 20 to 90 millidarcy are found abundantly in the earth crust at favorable depth and temperature, and represent a great capacity for targeted geothermal energy exploitation.

[0080] Such formations may be found within a natural geothermal system in areas of favorable groundwater level, hydrologic conditions, and high geothermal gradient. The natural geothermal systems may need coolant water injection to increase flow as well as energy extraction capacity.

[0081] Injection water, however, may escape the flow path towards production well(s), using conventional techniques; a new solution for energy-carrying hot water extraction is sought for capturing the injection water entirely or with minimal loss.

[0082] Another target geologic rock formation for the new solution is sedimentary rock with sufficient permeability and flow characteristics under a hydraulic gradient. Some formations around depleted natural hydrocarbon fields already have enhanced flow systems from previous production. This would be a desirable target formation for geothermal energy extraction with the new technique.

[0083] In general, the innovative geothermal energy extraction method and apparatus will be applicable broadly to the following target formations: (1) hot sedimentary rocks with a moderate permeable range, e.g., of 20 to 90 millidarcy, saturated with groundwater; (2) fractured rock with moderate permeability within a natural geothermal area with available groundwater but with low or no natural flow or circulation; (3) depleted hydrocarbon field with moderate permeability and sufficient groundwater level but with no significant flow: and (4) depleted hydrocarbon or another sedimentary, confined field, used for CO_2 sequestration.

[0084] A formation with sufficiently high permeability and ground water level is shown in FIG. **8**. Induced percolation is created by delivering geologic cooling fluid that returns from the power conversion unit **40**, which is situated on the surface in this example. Induced percolation from the geologic cooling fluid **7***a* enters through natural or engineered channels, such as perforated borehole section **41** and heats up as it encounters hot rocks of increasing temperature with depth. The natural or enhanced, permeable rock **42** of sufficiently high hydraulic permeability is cooled by convection of gravitationally-driven percolation **9**, providing calorimetric heat from the percolated zone **43** within the percolation plume. The flow zone **42** is under negative gage pressure relative to the ambient in situ hydrostatic pressure at the outside hydrostatic pressure field **16** at any vertical location, forming an inside pressure field **17**. The suction pressure difference **18** is created by pump **12**, which is installed deep in the low pressure chamber **11**. The pressure difference **8** is created by pump **12** gradually decreases with elevation within the powered pressure zone **46**, which coincides with the percolation zone. At the delivery point, of the recalculating geologic cooling fluid **7***a*, that is, at the injection elevation **20**, the pressure field is balanced with the ambient hydrostatic pressure in an ideal geologic formation with sufficiently high permeability. The arrangement includes active control for adjusting pump pressure difference AP according to maintaining a sufficient water level in the suction collection part of production borehole **1**, and preventing a dry run for pump **12**. On-off, or variable-speed control of pump **12** is useable for this task.

[0085] FIG. **9** shows an example with coolant delivery boreholes **44** to deliver geologic cooling fluid **7***a* farther, and to increase the lateral size of the percolation zone **43**. Collection boreholes **45** are also added to widen the area of influence of the suction pressure and to achieve a larger lowered pressure zone **46**. Otherwise, the working principle is the same as described for FIG. **8**.

[0086] FIG. **10** shows the effects of elevating the location of pump **12**, which may be accomplished when the ambient hydrostatic pressure is high, such as corresponding to a high water table level **47**. As shown, the total pressure difference **18** of the pump gradually decreases with depth, gradually diminishing the suction pressure difference **18***a*. This, in turn, shrinks the lateral size of the lowered pressure zone and risks the loss of the circulating geologic cooling fluid. This is why pumped systems with high suction elevation tend to lose coolant fluid, a disadvantage.

[0087] Other examples are variations of the concept of creating a lowered pressure zone by a pump and establishing a re-circulatory geologic heat exchanger system in situ. These variations are shown in FIGS. **11** through **13**

[0088] FIG. **11**(A) shows a single borehole application example of the flow collection concept using pressure lowering by pump **12** in a confined aquifer bounded by two impermeable layers **48**. Coolant delivery boreholes **49** as well as coolant collection boreholes **45** are shown, both applied for circulation and capacity increase. The coolant fluid flow direction **24** is downward and converging towards the low pressure side of the borehole under the pressure distribution shown in FIG. **11**(B). Three pressures, A, B, and C are shown at three different vertical cross sections, as marked in FIG. **11**(A): A-A, B-B, and C-C.

[0089] FIG. **12** shows an application variation of the geologic cooling fluid collection system using pressure-lowering in a horizontal arrangement in an unconfined aquifer using multiple boreholes. FIG. **12**(A) is a cross-sectional view, while FIG. **12**(B) is a plan view of the arrangement. Injection

boreholes **49** deliver geologic cooling fluid **7***a* into the lowered pressure zone **46**. Two production boreholes **50** are shown in the example with their area of influence zone **51** in the extraction of geologic cooling fluid **7***a*. It may be advantageous to re-inject the geologic coolant fluid downstream from the production borehole **50** as opposed to the upstream position as shown in FIG. **12**, in case of horizontal groundwater flow in the formation.

[0090] FIG. **13** illustrates a multi-borehole design in a confined permeable formation used for CO_2 sequestration where one borehole serves as an injection well **50** and the other serves as a return production borehole **51**. In between the boreholes, permeable rock **42** serves as both a CO_2 storage volume as well as a geologic heat exchanger with a lowered pressure zone **46**, using pump **12** for controlled coolant CO_2 circulation.

[0091] FIG. **14** shows the conventional energy flow from thermal energy exploited from geothermal reservoir **53** to electrical energy **56** with the use of the convective geologic coolant fluid circulation **54** in between. In conventional applications, the convective geologic coolant fluid circulation **54** transports energy along the production borehole where energy loss tends to be encountered as heat and pressure loss, a disadvantage.

[0092] FIG. **15** is an improved arrangement in which the geologic coolant fluid circulation **54** transmits energy to transmission coolant fluid **58** through heat exchanger **57** which is part of the equipment installed in borehole **50** including pump **12** in previous figures. The transmission coolant fluid **58** is transmitted to the surface installation **60**. Such transmission may be accomplished by a single-phase or binary, secondary fluid circulation loop connected to energy conversion unit **55**.

[0093] FIG. **16** is a compact arrangement in which subsurface installation **59** includes the geothermal reservoir **53**, a geologic coolant fluid circulation pump **12**, and a direct energy conversion unit **61** which supplies electrical energy **56** through an electrical power connection to the surface. The necessary energy conversion coolant fluid circulation unit **62** for the direct energy conversion unit **61** is powered by surface installation **60**. Since cold coolant fluid is circulated along the long production borehole, the thermal energy loss is minimized, an advantage.

[0094] The direct energy conversion unit **61** may be realized by the application of conventional components, shown in FIG. **17**, including heat exchanger **57**, heating binary transmission coolant fluid **58**, a turbine **63**, condenser **64**, which is cooled by energy conversion coolant fluid circulation unit **62** delivered from the surface. Turbine **63** drives generator **65** to produce electrical energy **56**.

[0095] It is to be understood that the above discussion provides a detailed description of various embodiments. The above descriptions will enable those of ordinary skill in the art to make and use the disclosed embodiments, and to make departures from the particular examples described above to provide embodiments of the methods and apparatuses constructed in accordance with the present disclosure.

[0096] The embodiments are illustrative, and not intended to limit the scope of the present disclosure. The scope of the present disclosure is rather to be determined by the scope of the claims as issued and equivalents thereto.

I claim:

1. A geothermal energy extraction-method comprising:
- using a deep well pump to create a decreased pressure zone;
- establishing a converging flow circulation in a hot geologic formation for convective heat exchange within the decreased pressure zone towards the pump;
- circulating collected hot fluid through an energy-conversion unit for electrical energy production; and
- re-injecting cooled coolant fluid into the geologic formation at a circulation injection point for zero net coolant fluid loss.

2. The method of claim **1**, further comprising establishing coolant fluid flow in a downward direction.

3. The method of claim **1**, further comprising engineering the pressure difference at any elevation between ambient (P_A) and low (P_L) pressure zones using a pump to overcome an upward-driving natural buoyancy pressure difference to create a net downward percolation plume.

4. The method of claim **3**, further comprising controlling the pressure difference between P_A and P_L during performance of the method in order to balance convective coolant fluid re-circulation within the natural, ambient hydrologic system in order to provide a desired degree of pressure-lowering.

5. The method of claim **3**, further comprising actively controlling the pressure difference between P_A and P_L according to a water level in a suction collection part of a production borehole.

6. The method of claim **1**, wherein the circulation injection point is selected close to an undisturbed water level in the geologic formation.

7. The method of claim **1**, wherein the pump comprises a submersible, high temperature pump and the energy conversion unit comprises a direct energy conversion unit and both the pump and the energy conversion unit are installed in the production borehole in situ and cooling power for the energy conversion unit is supplied from the surface at low temperature.

8. The method of claim **1**, wherein the energy conversion unit comprises a binary-phase heat exchanger comprising a boiler heated by the hot geothermal fluid, a turbine, a condenser comprising a heat exchanger cooled by coolant fluid circulation from the surface, an electrical generator driven by the turbine, and an electrical transmission line that carries electrical energy from a production borehole to the surface.

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