

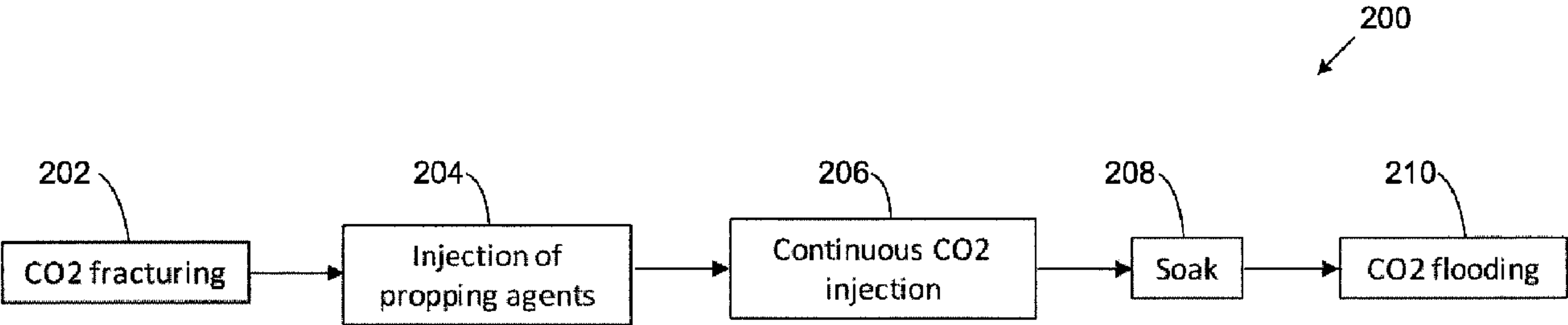


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(54) Titre : METHODE DE REALISATION DE FRACTURATION ET RECUPERATION AMELIOREE DE PETROLE DANS
LES RESERVOIRS DE PETROLE A FAIBLE PERMEABILITE

(54) Title: METHODS FOR PERFORMING FRACTURING AND ENHANCED OIL RECOVERY IN TIGHT OIL
RESERVOIRS



(57) **Abrégé/Abstract:**
A method of recovering oil from a reservoir is described herein. The method includes introducing CO₂ through a well bore into the reservoir, the well bore having a bottom-hole pressure greater than a fracture pressure of the reservoir to produce fractures within the reservoir and greater than a minimum miscibility pressure between the CO₂ and the oil to produce a miscible zone; stopping the introduction of CO₂ through the well bore for a first period of time to reduce the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure; re- introducing the CO₂ to maintain the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure to maintain the miscible zone; shutting in the well bore to promote displacement of the CO₂ through the reservoir in a direction away from the well bore; and recovering the oil from the reservoir.

Abstract

A method of recovering oil from a reservoir is described herein. The method includes introducing CO₂ through a well bore into the reservoir, the well bore having a bottom-hole pressure greater than a fracture pressure of the reservoir to produce fractures within the reservoir and greater than a minimum miscibility pressure between the CO₂ and the oil to produce a miscible zone; stopping the introduction of CO₂ through the well bore for a first period of time to reduce the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure; re-introducing the CO₂ to maintain the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure to maintain the miscible zone; shutting in the well bore to promote displacement of the CO₂ through the reservoir in a direction away from the well bore; and recovering the oil from the reservoir.

Methods for Performing Fracturing and Enhanced Oil Recovery in Tight Oil Reservoirs

Technical Field

[0001] The embodiments disclosed herein relate to enhanced oil recovery and, in particular to methods for performing fracturing and enhanced oil recovery in tight oil reservoirs.

Background

[0002] During primary recovery of oil from a target formation, reservoir drive of the oil from the formation comes from natural mechanisms such as natural water displacing oil downward into the well, expansion of the natural gas at the top of the reservoir, expansion of gas initially dissolved in the crude oil, and gravity drainage resulting from the movement of oil within the reservoir from the upper to the lower parts where the wells are located.

[0003] After natural reservoir drive diminishes, secondary recovery methods are applied. Secondary recovery methods generally rely on supplying external energy into the reservoir, such as in the form of injecting fluids, to increase reservoir pressure, thereby replacing or increasing the natural reservoir drive with an artificial drive.

[0004] Hydraulic fracturing is a well stimulation technique in which an oil reservoir is fractured by a pressurized liquid such as water. The technique involves injecting a fracking fluid (primarily water, containing sand or other proppants) at a high pressure into a wellbore to create cracks in the deep-rock formations of the oil reservoir. When the hydraulic pressure is removed from the well, small grains of proppants hold the fractures open.

[0005] Carbon dioxide (CO₂) has recently been used as a fracturing fluid to stimulate oil reservoirs. Studies exploring the use of CO₂ as a fracturing fluid indicate that its use has the potential to reduce water requirements during oil production.

[0006] Traditional CO₂ fracturing processes tend to be relatively complex and produce fractures that are small relative to fractures formed during hydraulic fracturing with a water-based fracturing fluid. Further, traditional CO₂ fracturing requires a flow-

back step where at least a portion of the CO₂ injected into the reservoir is recovered through the well bore. During this flow-back step, there is risk that the proppant may flow out of the reservoir back to the wellbore. Further, during CO₂ fracturing where CO₂ is mixed with a hydraulic fluid such as water, a large amount of CO₂ needs to be recycled through transpiration, recapturing, separation of solids and liquids, and oil-gas separation. Therefore, in traditional CO₂ fracturing, efficiency of CO₂ utilization is low, while processing time and capital costs are high.

[0007] CO₂ flooding is a process of injecting CO₂ into a target formation at a pressure lower than the fracture pressure of the formation to stimulate oil production. Between hydraulic fracturing and CO₂ flooding, the drilling well head needs be changed to a production wellhead.

[0008] Similar to CO₂ flooding, CO₂ huff-n-puff is a three-step process consisting of: injecting CO₂ into an oil reservoir, soaking the CO₂ within the oil reservoir and producing oil from the oil reservoir. CO₂ huff-n-puff is generally used after secondary extraction techniques such as hydraulic flooding (e.g. with water) have been used. During the injecting step of CO₂ huff-n-puff, the CO₂ is generally injected in an immiscible condition to displace mobile fluid near the wellbore and to pressurize the well drainage area. During the soaking step, the CO₂ is allowed to interact and dissolve into the oil in the reservoir. This interaction generally leads to swelling of the oil in the reservoir and reducing the viscosity of the oil. During the producing step, the well is returned to production by reducing the wellbore pressure, thereby drawing the oil mixed with CO₂ towards the wellbore. Although CO₂ huff-n-puff can be an effective EOR technique, its use after other secondary extraction techniques generally requires additional capital cost and leads to inefficiencies.

Summary

[0009] According to some embodiments, a method of recovering oil from a reservoir is provided. The method includes introducing CO₂ through a well bore into the reservoir, the well bore having a bottom-hole pressure greater than a fracture pressure of the reservoir to produce fractures within the reservoir and greater than a minimum miscibility pressure between the CO₂ and the oil to produce a miscible zone; stopping

the introduction of CO₂ through the well bore for a first period of time to reduce the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure; re-introducing the CO₂ to maintain the bottom-hole pressure to be less than the fracture pressure and greater than the minimum miscibility pressure to maintain the miscible zone; shutting in the well bore to promote displacement of the CO₂ through the reservoir in a direction away from the well bore; and recovering the oil from the reservoir.

[0010] According to some embodiments, the recovering the oil from the reservoir includes introducing additional CO₂ through the well bore into the reservoir to displace the miscible zone through the reservoir towards a production well for recovering the oil, the bottom-hole pressure being less than the minimum miscibility pressure during the introduction of the additional CO₂.

[0011] According to some embodiments, the recovering the oil from the reservoir includes, once the calculated bottom hole pressure is less than the minimum miscibility pressure, producing oil in the miscible zone flow from the well bore.

[0012] According to some embodiments, the introducing CO₂ into the reservoir includes injecting a propping agent into the fractures to inhibit closure of the fractures upon the bottom-hole pressure falling below the fracture pressure.

[0013] According to some embodiments, the method further includes shutting in the well bore for a second period of time to promote displacement of the additional CO₂ through the reservoir in a direction away from the well bore.

[0014] According to some embodiments, the method further includes repeating the introducing additional CO₂ step and the shutting in the well bore for a period of time step to encourage displacement of the miscible zone.

[0015] According to some embodiments, the production well is spaced apart from the well bore.

[0016] According to some embodiments, the first period of time is in a range of about 30 minutes to about 3 hours.

[0017] According to some embodiments, the second period of time is in a range of about two days to about four weeks.

[0018] According to some embodiments, the second period of time is in a range of about one week to about four weeks.

[0019] According to some embodiments, during the introducing of the CO₂ into the reservoir the bottom-hole pressure is in a range of about 25 to about 50 MPa.

[0020] According to some embodiments, the minimum miscibility pressure between the CO₂ and the oil is in a range of about 20 to about 30 MPa.

[0021] According to some embodiments, during the re-introducing the CO₂ through the well bore into the reservoir the bottom-hole pressure is in a range of about 25 to about 40 MPa.

[0022] According to some embodiments, the CO₂ comprises liquid CO₂.

[0023] According to some embodiments, the CO₂ supercritical CO₂.

[0024] Other aspects and features will become apparent, to those ordinarily skilled in the art, upon review of the following description of some exemplary embodiments.

Brief Description of the Drawings

[0025] The drawings included herewith are for illustrating various examples of articles, methods, and apparatuses of the present specification. In the drawings:

[0026] Figure 1 is a block diagram of a traditional CO₂ fracturing and recycle process;

[0027] Figure 2 is a block diagram of an integrated CO₂ fracturing and CO₂ flooding process where CO₂ is injected at a high pressure to fracture the formation and enhance oil recovery, according to one exemplary embodiment;

[0028] Figure 3 is a diagram showing a CO₂ injection step of the CO₂ fracturing process where CO₂ is injected into an oil reservoir to produce fractures within the oil reservoir, according to one exemplary embodiment;

[0029] Figure 4 is a diagram showing a propping agent injection step of the CO₂ fracturing process where propping agents are injected into the fractures in the oil reservoir, according to one exemplary embodiment;

[0030] Figure 5 is a diagram showing a subsequent CO₂ injection step of the CO₂ fracturing process where CO₂ is subsequently injected into the oil reservoir after the propping agent injection step, according to one exemplary embodiment;

[0031] Figure 6 is a diagram showing a soak step of the CO₂ fracturing process where the oil well is shut down and CO₂, under a pressure gradient, flows away from the wellbore for a period of time ranging from one to ten weeks, according to one exemplary embodiment; and

[0032] Figure 7 is a diagram showing a CO₂ flooding step of the CO₂ fracturing process where the CO₂ is injected continuously to displace oil to the production wells, according to one exemplary embodiment.

Detailed Description

[0033] Various methods will be described below to provide an example of each claimed embodiment. No embodiment described below limits any claimed embodiment and any claimed embodiment may cover methods that differ from those described below. The claimed embodiments are not limited to methods having all of the features of any one method described below or to features common to multiple or all of the methods described below.

[0034] Terms of degree such as “about” and “approximately” as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed. These terms of degree should be construed as including a deviation of at least $\pm 5\%$ or at least $\pm 10\%$ of the modified term if this deviation would not negate the meaning of the word it modifies.

[0035] The term “comprising” and its derivatives, as used herein, are intended to be open ended terms that specify the presence of the stated features, elements, components, groups, integers, and/or steps, but do not exclude the presence of other unstated features, elements, components, groups, integers and/or steps. The foregoing

also applies to words having similar meanings such as the terms, “including”, “having” and their derivatives.

[0036] The term “consisting” and its derivatives, as used herein, are intended to be closed terms that specify the presence of the stated features, elements, components, groups, integers, and/or steps, but exclude the presence of other unstated features, elements, components, groups, integers and/or steps.

[0037] The term “consisting essentially of”, as used herein, is intended to specify the presence of the stated features, elements, components, groups, integers, and/or steps as well as those that do not materially affect the basic and novel characteristic(s) of features, elements, components, groups, integers, and/or steps.

[0038] The term “shut-in”, as used herein, is intended to specify that a well bore is temporarily closed to restrict gas and/or liquid from flowing through the well bore to the surface, with the intention of re-opening the well bore thereafter.

[0039] The term “tight oil”, as used herein, is intended to specify light crude oil contained in a petroleum-bearing formation of low porosity (e.g. <15%) and low permeability (e.g. <1 mD), such as but not limited to shale or tight sandstone.

[0040] Throughout this document, reference is made to use of “CO₂” for fracturing oil formations and for recovery and exploitation of tight oil from tight oil reservoirs therein. It should be noted that the term “CO₂” is used generally and may refer to either liquid CO₂ or supercritical CO₂, depending on the flow rates and/or pressures of the injected fluid and depending on the desired outcome of its use (e.g. oil production rate, size and dispersion of fractures, composition of target formation, etc.). Further, it should also be noted that any appropriate fluid comprising CO₂ and/or having with similar physical characteristics to CO₂, in either its liquid form or its supercritical form, may be used in the methods described herein to achieve formation of fractures and enhanced oil recovery (EOR).

[0041] The methods described herein relate to recovery and exploitation of tight oil from tight oil reservoirs. To inhibit complex operations in traditional CO₂ fracturing and CO₂ flooding, and to reduce the risk of propping agents flowing back into the

wellbore, the methods described herein build upon traditional CO₂ fracturing and CO₂ flooding to form an integrated process for efficient recovery and exploitation of tight oil from tight oil reservoirs. This integration eliminates the step of flow-back of CO₂ that is required during traditional CO₂ fracturing and therefore may reduce negative effects associated with CO₂ flow-back. Further, the integrated methods described herein may reduce the amount of CO₂ needed to perform CO₂ fracturing and CO₂ flooding when compared to the separate, traditional CO₂ fracturing and CO₂ flooding processes.

[0042] The methods described herein incorporate a soaking step where the well bore is shut-in and CO₂ injected into the oil reservoir following the injection of propping agents is left to soak into the formation of the oil reservoir over a period of time (as described below). The soaking step may facilitate penetration of the CO₂ into the formation and improve contact with the crude oil therein to reduce the viscosity of crude oil, thereby improving its mobility.

[0043] The methods described herein describe injecting CO₂ to increase pressure within a target formation and to enhance contact and mixing between CO₂ and oil therein. As the CO₂ is injected at a high pressure (e.g. a pressure above the fracture pressure of the formation) the CO₂ and the oil within the formation may become miscible. The CO₂ and the oil within the formation being miscible may reduce the interface tension and viscosity of the oil in the target formation.

[0044] The methods described herein may utilize intermittent and pulse CO₂ injection. Intermittent and pulse CO₂ injection may be favorable for opening (e.g. forming) and extending micro-fractures in the subject formation. Intermittent and pulse CO₂ injection may therefore increase an area (i.e. volume or space) of the reservoir impacted by the CO₂ fracturing.

[0045] Referring to the Figures, Figure 1 shows a schematic diagram of a traditional CO₂ fracturing and recycling process 100. Traditionally, CO₂ fracturing and recycling process 100 begins with a CO₂ fracturing step 101. As outlined earlier, during CO₂ fracturing step 101, CO₂, either in liquid or supercritical form, is injected into a target reservoir through a well bore. CO₂ is injected into the target reservoir at a

pressure above a fracture pressure of the oil formation in the target reservoir to induce fracking (e.g. formation of cracks in the target formation) within the formation.

[0046] After fractures are formed in the formation, CO₂ injection is stopped and propping agents such as sand are injected into the oil reservoir to seep into the cracks and inhibit closure of the cracks at propping agent injection step 102.

[0047] Following propping agent injection step 102, flow-back step 103 includes collecting at least a portion of the CO₂ injected into the reservoir. For flow-back step 103 to occur, the wellhead of the well bore should be changed from an injection head to a production head.

[0048] At step 104, CO₂ is transported from the well bore (e.g. through pipelines) to a CO₂-solids separation facility, for example, where solids are removed (at step 105). At step 106, oil and liquid water are separated from the CO₂ and methane is removed from CO₂ by, for example, membrane gas separation-based processed that can last up to approximately 12 days. At step 107, CO₂ is collected for recycling. At step 108, CO₂ is reused at step 108. The above process generally results in CO₂ having a purity of greater than 98%.

[0049] Turning to Figure 2, illustrated therein is a schematic diagram of a method 200 of fracturing an oil reservoir with CO₂ and performing an enhanced oil recovery technique according to one embodiment of the application. Method 200 includes CO₂ fracturing at step 202, injecting propping agents at step 204, subsequently injecting CO₂ at step 206, CO₂ soaking at step 208 and CO₂ flooding at step 210. Each of these steps is described in greater detail below.

[0050] At CO₂ fracturing step 202, a diagram of which is provided at Figure 3, CO₂ (indicated by reference number 306) is introduced (e.g. injected) in to a reservoir 308 having oil to be recovered to form fractures 310 and micro-fractures 314 in the reservoir 308. Specifically, well bore 302 is shown as being drilled from a surface through an impermeable rock formation 315 to reservoir 308 for extraction of oil from reservoir 308. Well bore 306 provides a conduit for injector (e.g. a wellhead) 304 to inject CO₂ 306 into reservoir 308.

[0051] As CO₂ 306 is injected into reservoir 308, the bottom-hole pressure ($P_{\text{bottom-hole}}$) increases until $P_{\text{bottom-hole}}$ exceeds a fracture pressure (P_{fracture}) within the reservoir 308. When $P_{\text{bottom-hole}}$ exceeds P_{fracture} , fractures 310 and microfractures 314 form in the reservoir 308. $P_{\text{bottom-hole}}$ may increase from an initial reservoir pressure (in a range from about 15 MPa to about 30 MPa) to about 60 MPa. P_{fracture} is generally in a range between about 35 MPa and about 50 MPa.

[0052] Fractures 310 generally begin to form at the well bore 302 and extend into the reservoir 308 away from the well bore 302. Generally, the size (e.g. diameter or cross-sectional area) of fractures 310 decreases along their length. Accordingly, microfractures 314 generally extend from fractures 310 and generally have a smaller size (e.g. diameter or cross-sectional area) than fractures 310.

[0053] In some embodiments, P_{fracture} generally exceeds a minimum miscibility pressure (MMP) between the CO₂ 306 and the oil in the reservoir 308. As such, upon injection of CO₂ 306 and upon $P_{\text{bottom-hole}}$ exceeding P_{fracture} , a miscible zone 312 forms within reservoir 308 adjacent to the well bore 302. In the miscible zone 312, the CO₂ 306 and the oil are miscible with one another. The mixture of oil and CO₂ 306 in the miscible zone 312 generally has a lower viscosity than the oil in the reservoir outside of the miscible zone 312 and, therefore, the miscible zone 312 can generally be moved more easily within reservoir 308 towards a production well spaced apart from well bore 302 (as described further below). Further, mixing of CO₂ 306 and crude oil within the miscible zone 312 may reduce interfacial tension relative to the crude oil in reservoir 308 and may improve the displacement efficiency of the CO₂ 306. The minimum miscibility pressure can be in a range from about 20 to about 30 MPa.

[0054] In some embodiments, the CO₂ 306 injection can be alternated with injection of another fluid (e.g. water) and the other fluid can act to sweep the oil towards the production zone.

[0055] In other embodiments, CO₂ 306 injection may be intermittent and/or pulsed. Intermittent and/or pulsed injection of CO₂ 306 may be favorable for opening (e.g. forming) and extending micro-fractures 314 in the reservoir 308. Intermittent and/or pulsed injection of CO₂ 306 may also increase a size (i.e. a volume) of the reservoir 308

impacted by the CO₂ 306 fracturing. For instance, intermittent and/or pulsed injection of CO₂ 306 may also increase the size of miscible zone 312 relative to a size of miscible zone 312 formed without intermittent and/or pulsed injection of CO₂ 306.

[0056] It should be noted that the bottom hole temperature should remain below about 31 °C during the CO₂ fracturing process as, the CO₂ will remain a liquid below this temperature. Additionally, liquid CO₂ at 31 °C may generate sufficient fracture width to provide for proppant to flow through the fractures created therein.

[0057] Referring now to Figure 4, illustrated therein is a diagram showing the introduction of propping agents 316 into reservoir 308 according to another embodiment of the application. Propping agents 316 are carried through well bore 302 to the fractures 310 by CO₂ 306. Propping agents 316 generally collect within the fractures 310 and microfractures 314 and keep the fractures 310 and microfractures 314 open as the pressure within reservoir 308 decreases below P_{fracture} .

[0058] In some embodiments, the propping agents are carried through the well bore 302 and into the fractures 310 of reservoir 308 at a pressure that is close to or higher than the MMP.

[0059] Examples of propping agents include but are not limited to: sand, synthetic propping agents (e.g. polymer-based propping agents, etc.),

[0060] The propping agents concentration depends on injection rate and depth of reservoirs. Proppant concentration typically varies in a range from about 5% to about 35%. The smaller mesh size of propping agents with 30-50 and 40-60 works well for higher fracture conductivity of low permeability reservoirs.

[0061] Propping agents 316 near the well bore 302 can be driven away from well bore 302 towards fractures 310 in reservoir 308, thereby avoiding deposition of the propping agents 316 near the well bore 302 which can lead to damage to the well bore 302.

[0062] Figure 5 shows a diagram of a subsequent CO₂ injection step 206 of the method 200, according to one embodiment. After propping agent injection step 204, CO₂ injection step 206 begins by briefly stopping injection of CO₂ 306 through the well

bore into the reservoir. Stopping CO₂ 306 injection may be used to controllably reduce the bottom-hole pressure of the well bore to be less than the fracture pressure and greater than the minimum miscibility pressure. The stopping of the CO₂ 306 injection can be for a period of time in a range of about 30 minutes to about 3 hours. CO₂ 306 injection is then re-introduced through well bore 302 to maintain the suspension state of oil within the reservoir 308 and the CO₂ 306 (e.g. to maintain the miscible zone 312). Subsequent CO₂ injection step 206 may encourage further migration of the propping agents 316 into the fractures of the deep formation. Subsequent CO₂ injection step 206 may also contribute to expansion of fractures 310 and improving the permeability of the rock with reservoir 308.

[0063] During subsequent CO₂ injection step 206, CO₂ 306 may be injected at a rate in a range of about 1.1 to about 5.5 ton/min to maintain suspension of the propping agents 316 in the fractures 310. The injection rate may depend on the reservoir permeability, well type, fracture width, the development of microfractures, and/or the pumping conditions. Subsequent CO₂ injection step 206 generally inhibits formation damages that may occur during flow back (as occurs in the prior art process) and may promote the formation of larger fractures 310 in reservoir 308. Accordingly, during the subsequent CO₂ injection step 206, $P_{\text{bottom-hole}}$ is maintained above the MMP between CO₂ 306 and the crude oil of reservoir 308 but below P_{fracture} . Maintaining $P_{\text{bottom-hole}}$ above the MMP may reduce an interface tension and viscosity of the crude oil in reservoir 308 and therefore improve CO₂ molecular diffusivity through the reservoir 308.

[0064] It should be noted that, in an alternative embodiment, a flow-back step (not shown) can be added to the method 200 to specifically encourage deposition of the propping agents 316 within fractures 310 and microfractures 314. In this embodiment, CO₂ 306 can flow back through well bore 302 and out of the wellhead (e.g. injector 304) to a manifold system (not shown), and then be re-introduced into reservoir 308 at a pressure that is less than P_{fracture} but higher than the previous $P_{\text{bottom-hole}}$.

[0065] When the $P_{\text{reservoir}}$ is above the MMP, miscibility between CO₂ 306 and the oil within the reservoir is achieved. The intermediate and higher molecular weight hydrocarbons from the oil within the reservoir generally vaporize into the CO₂ 306 and

part of the injected CO₂ 306 dissolves into the oil. This mass transfer between the oil and CO₂ 306 may provide for the two phases to become completely miscible without any interface and may help to develop a transition zone (not shown) that is miscible with oil in the front (e.g. a portion of the transition zone distal to the well bore 302 and proximate to a production well) and with CO₂ 306 in the back (e.g. a portion of the transition zone proximate to the well bore 302).

[0066] Figure 6 shows a diagram of a soaking step 208 of the method 200, according to one embodiment. After the CO₂ injection step 206, a region of high pressure (e.g. a pressure higher than the MMP) exists in the well bore 302 and in at least a portion of the reservoir 308 adjacent to the well bore 302. After the CO₂ injection step 206, injector 304 is shut down and well bore 302 is shut in. A resultant pressure gradient between well bore 302 and reservoir 308 forces CO₂ trapped in the reservoir 308 to diffuse through the reservoir 308 in a direction away from well bore 302 and towards production well 326 (see Figure 7).

[0067] Over a period of time that typically ranges from about 2 days to about 4 weeks, $P_{\text{bottom-hole}}$ decreases gradually as the CO₂ 306 expands into reservoir 308. As $P_{\text{reservoir}}$ decreases, the fractures 310 and microfractures 314 may tend to close.

[0068] Movement of the CO₂ 306 from the well bore 302 throughout reservoir 308, as driven by the aforementioned pressure gradient, can displace oil in reservoir 308 in a direction away from the well bore 302 and towards production well 326. Further, $P_{\text{reservoir}}$ exceeding the MMP at the beginning of step 208 may be beneficial for mixing CO₂ 306 and oil in the miscible zone 312. Further still, $P_{\text{reservoir}}$ exceeding the MMP at the beginning of step 208 may also be beneficial for reducing the viscosity of the oil within the reservoir 308 more generally.

[0069] Figure 7 shows a diagram of a CO₂ flooding step 210 of the method 200, according to one embodiment.

[0070] After soaking step 208, $P_{\text{bottom-hole}}$ can be calculated from the P_{wellhead} through $P_{\text{bottom-hole}} = P_{\text{wellhead}} + P_{\text{hh}} - P_{\text{f}}$. P_{hh} is the pressure due to hydrostatic head and P_{f} is the pressure loss due to the fraction. When $P_{\text{bottom-hole}}$ is lower than the MMP, the size of

and mixing within miscible zone 312 can be considered to be maximized. At this point, the oil within reservoir 308 can be extracted (e.g. the well can be put into production).

[0071] During the CO₂ flooding step 210, it is an embodiment that CO₂ 306 is continuously injected into the reservoir 308 through well bore 302 to displace extracted oil 324 from reservoir 308. Extracted oil 324 passes through perforations 322 into a production well 326. In this embodiment, the pressure of the CO₂ 306 injected into well bore 302 (e.g. $P_{\text{bottom-hole}}$) is maintained less than the MMP. Accordingly, the CO₂ 306 injected into the reservoir 308 during step 210 does not achieve miscibility with the crude oil of reservoir 308. Miscible zone 312 therefore does not grow in size during step 210. Rather, injection of CO₂ 306 during step 210 establishes a non-miscible zone 318 in reservoir 308. Non-miscible zone 318 is predominantly CO₂ 306 and pushes miscible zone 312 across reservoir 308 towards production well 326 for extraction. In addition, because of the subsequent injection of CO₂ 306 during step 210, fractures 310 and micro-fractures 314 are generally expended. This may further improve the swept area and displacement efficiency of oil from reservoir 308.

[0072] During step 210, well bore 302 can be used as an injection well to continuously inject CO₂ 306 to displace oil within reservoir 308 to production well 326. As a result of continuous injection of CO₂ 306 into well bore 302, micro-fractures 314 can be further expanded.

[0073] In some embodiments of the CO₂ flooding step 210, $P_{\text{bottom-hole}}$ may be is optimized and reduced gradually through manipulation of P_{wellhead} and the rate of injection of CO₂ 306 to maintain the miscible zone 312 and to encourage production of oil at production well 326.

[0074] In an alternate embodiment (not shown), well bore 302 can be used intermittently as an injection well and as a producer well. For example, well bore 302 can first be used as previously described to form a mixture of CO₂ 306 and crude oil within reservoir 308 (miscible zone 312) and to produce oil at production well 326. When the oil production rate slows and lower than a critical value, $P_{\text{bottomhole}}$ may be further reduced to increase the pressure gradient between $P_{\text{bottomhole}}$ and $P_{\text{reservoir}}$ and the oil production rate. In this process, the adjacent CO₂ injection wells can be shut

down to take full advantage of the expansion effect of CO₂ and formation pressure as well as reducing the fingering phenomenon of CO₂. Because the oil viscosity is usually much higher than that of CO₂, the injected CO₂ tends to penetrate and bypass the oil in reservoirs and form the finger-like pattern at their contact zone. This phenomenon is called viscous fingering which tends to reduce the oil recovery. At this time, well bore 302 can be shut in and CO₂ can be injected into adjacent wells (e.g. production well 326). When the $P_{\text{reservoir}}$ reaches an expected pressure, CO₂ injection through the adjacent wells is stopped and well bore 302 is re-opened for production. During this production, the adjacent wells can be shut down.

[0075] When the $P_{\text{reservoir}}$ again decreases during production, CO₂ can again be injected (e.g. through the adjacent wells) to increase the formation pressure. A soak step (not shown) can again follow this subsequent CO₂ injection to encourage the injected CO₂ and crude oil mix efficiently for the next production. This process can be repeated several times.

Examples

[0076] Example 1

[0077] The methods of integrated CO₂ fracturing and flooding described herein were tested in the Chang 8 of Shangping 5 formation in Yanchang Oil Field.

[0078] The experiments showed that the MMP of a CO₂-crude oil mixture in this area is in the range of 22-24 MPa. In the CO₂ fracturing of a horizontal well, 70 tonnes of supercritical CO₂ in the liquid state was injected into each layer of a reservoir. Then, in a subsequent step, 100 tonnes of CO₂ were injected into the reservoir.

[0079] As there were eight fracturing segments in this horizontal well, the total amount of initial CO₂ fluid was approximately 540 tonnes with 435 m³ sand as a propping agent. 750 tonnes CO₂ were further injected with a rate of 1.1-5.5 ton/min. Following this injection, the well was shut down for a soaking period.

[0080] The fracture pressure of the oil formation in this example was 35-45 MPa, while the bottom-hole pressure during fracturing was in the range of 38-48 MPa, which is above the MMP of CO₂ and crude oil. The wellhead pressure when shut down was

27.2 MPa. After the soaking period of one week, the well was put back into production and adjacent wells were shut down. The results showed that the oil production rate improved by 35-50% relative to the adjacent wells.

[0081] Example 2

[0082] The integrated CO₂ fracturing and flooding process was also used in a vertical well, the Huang 69-2 well in Change 6 formation in Yanchang Oil Field. In this example, 90 tonnes of ahead supercritical CO₂ in fluid state were injected into the well to perform CO₂ fracturing with 55 m³ as a propping agent. Followed this injection, 75 tonnes of additional CO₂ was injected to displace oil and maintain the propping agents suspended in fractures of the oil well. Following this, the well was shut down for a soaking period of 6.2 hours. At the end of the soaking period, 60 tonnes of CO₂ were injected into the well. This intermittent and pulse CO₂ injection may enhance the expansion of micro-fractures in the formation.

[0083] The fracture pressure of the oil formation was in the range of 25-35 MPa, while the bottom-hole pressure was in the range of 28-38 MPa. At this time, the wellhead pressure is 22.6 MPa. This well is then shut down and begins to produce oil after a soak for 5 days. The well performance showed that oil production was improved by 41-100% when compared to adjacent wells.

[0084] While the above description provides examples of one or more methods, , it will be appreciated that other methods, may be within the scope of the claims as interpreted by one of skill in the art.

Claims

What is claimed is:

1. A method of recovering oil from a reservoir, the method comprising:

introducing CO₂ through a well bore into the reservoir, the well bore having a bottom-hole pressure greater than a fracture pressure of the reservoir to produce fractures within the reservoir and greater than a minimum miscibility pressure between the CO₂ and the oil to produce a miscible zone in the reservoir, the miscible zone comprising at least a portion of the CO₂ and at least a portion of oil to be recovered;

stopping the introduction of CO₂ through the well bore into the reservoir for a first period of time to reduce the bottom-hole pressure of the well bore to be less than the fracture pressure and greater than the minimum miscibility pressure;

re-introducing the CO₂ into the reservoir to maintain the bottom-hole pressure of the well bore to be less than the fracture pressure and greater than the minimum miscibility pressure to maintain the miscible zone within the reservoir;

shutting in the well bore for a second period of time, the bottom-hole pressure being less than the fracture pressure and greater than the minimum miscibility pressure during the second period of time to promote displacement of the CO₂ through the reservoir in a direction away from the well bore; and

recovering the oil from the reservoir.

2. The method of claim 1, wherein the recovering the oil from the reservoir comprises introducing additional CO₂ through the well bore into the reservoir to displace the miscible zone through the reservoir towards a production well for recovering the oil, the bottom-hole pressure being less than the minimum miscibility pressure during the introduction of the additional CO₂.

3. The method of claim 1, wherein the recovering the oil from the reservoir comprises, once the calculated bottom hole pressure is less than the minimum miscibility pressure, recovering oil in the miscible zone flow from the well bore.

4. The method of any one of claims 1 to 3, wherein the introducing CO₂ into the reservoir includes injecting a propping agent into the fractures to inhibit closure of the fractures upon the bottom-hole pressure falling below the fracture pressure.
5. The method of any one of claims 1 to 4, further comprising shutting in the well bore for a third period of time to promote displacement of the additional CO₂ through the reservoir in a direction away from the well bore.
6. The method of claim 5 further comprising repeating the introducing additional CO₂ step and the shutting in the well bore for another period of time step to encourage displacement of the miscible zone.
7. The method of claim 2, wherein the production well is spaced apart from the well bore.
8. The method of any one of claims 1 to 7, wherein the first period of time is in a range of about 30 minutes to about 3 hours.
9. The method of any one of claims 1 to 8, wherein the second period of time is in a range of about two days to about four weeks.
10. The method of any one of claims 1 to 9, wherein the second period of time is in a range of about one week to about four weeks.
11. The method of any one of claims 1 to 10, wherein during the introducing of the CO₂ into the reservoir the bottom-hole pressure is in a range of about 25 to about 50 MPa.
12. The method of any one of claims 1 to 11, wherein the minimum miscibility pressure between the CO₂ and the oil is in a range of about 20 to about 30 MPa.

13. The method of any one of claims 1 to 12, wherein during the introducing additional CO₂ through the well bore into the reservoir the bottom-hole pressure is in a range of about 25 to about 40 MPa.
14. The method of any one of claims 1 to 13, wherein the CO₂ comprises liquid CO₂.
15. The method of any one of claims 1 to 14, wherein the CO₂ supercritical CO₂.

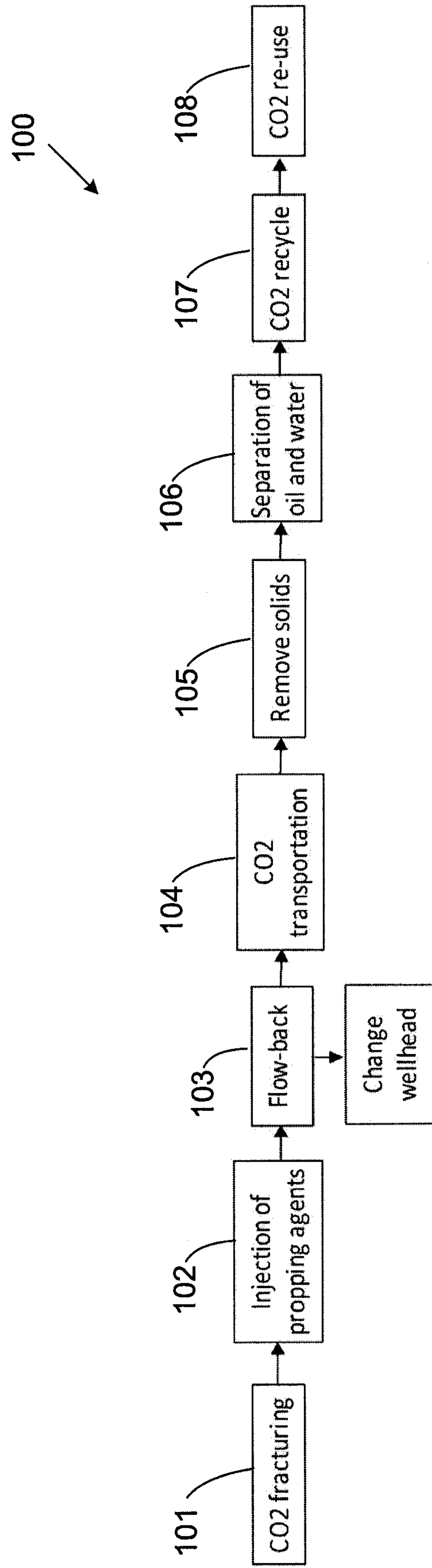


FIG. 1

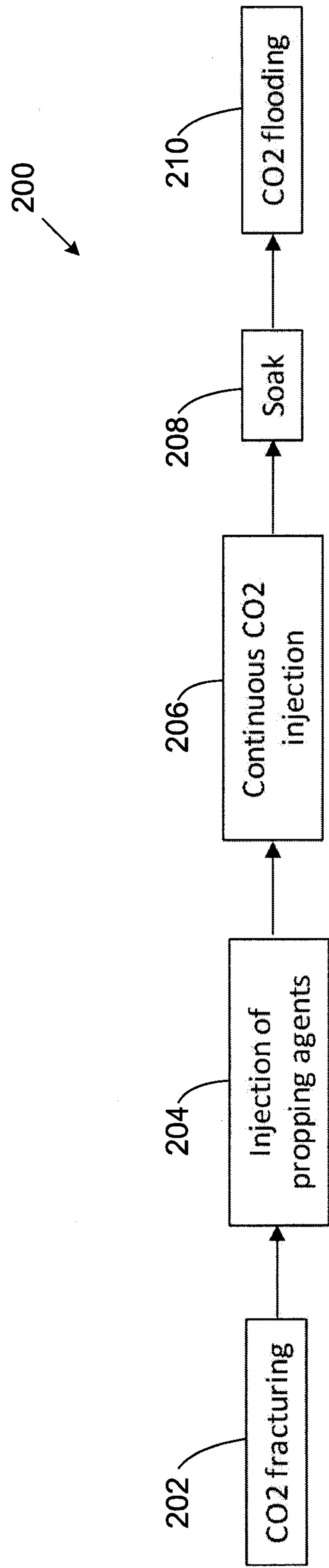


FIG. 2

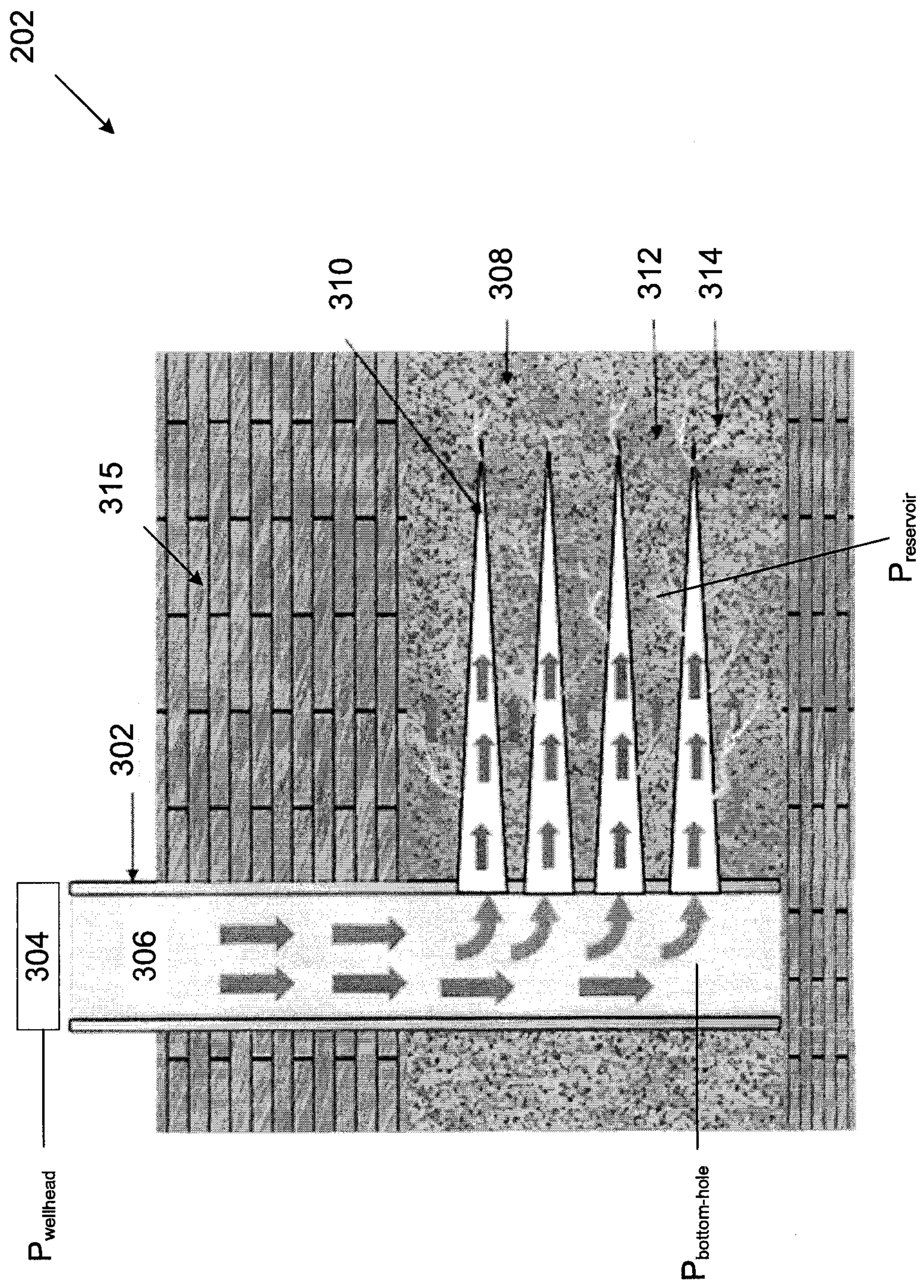


FIG. 3

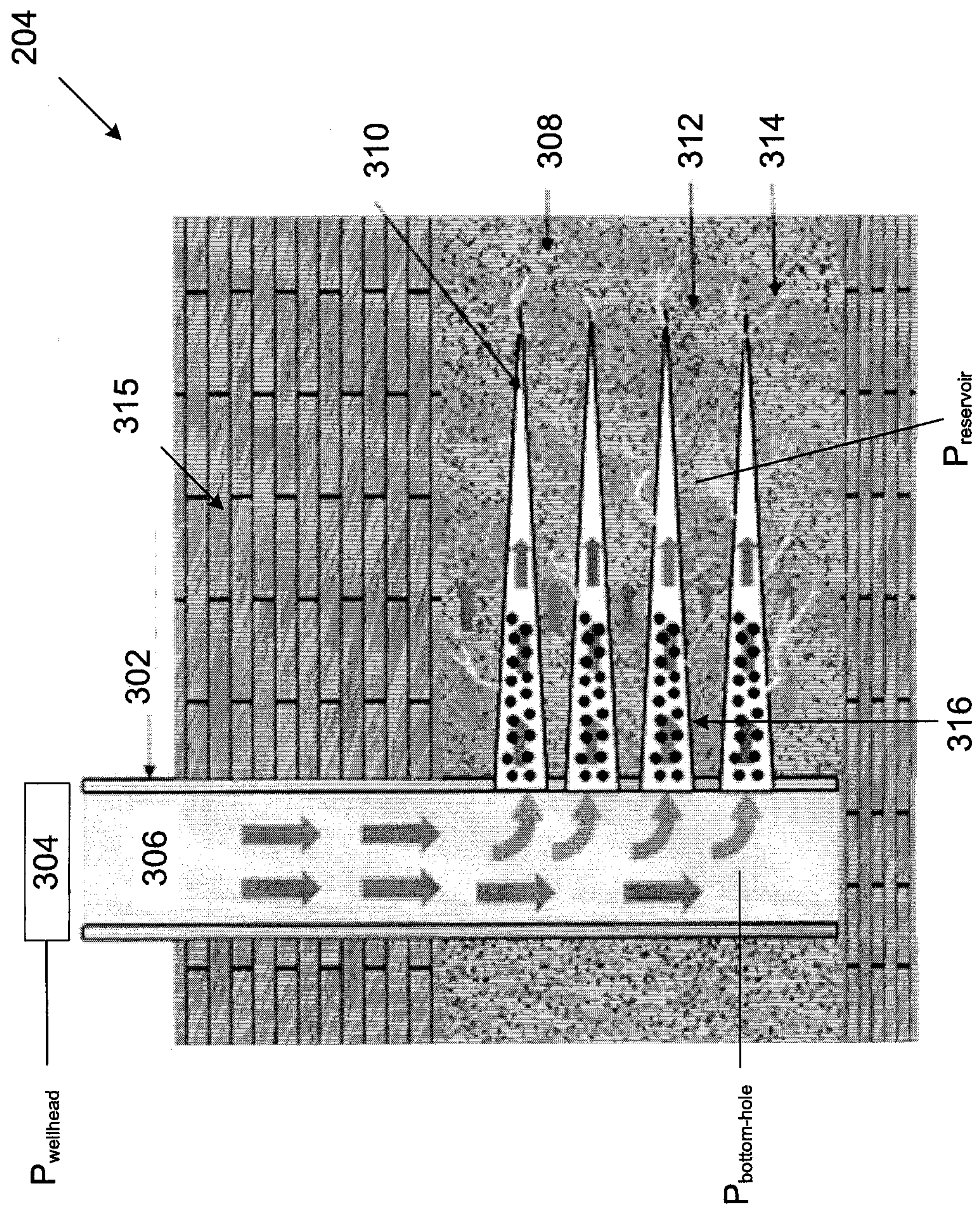


FIG. 4

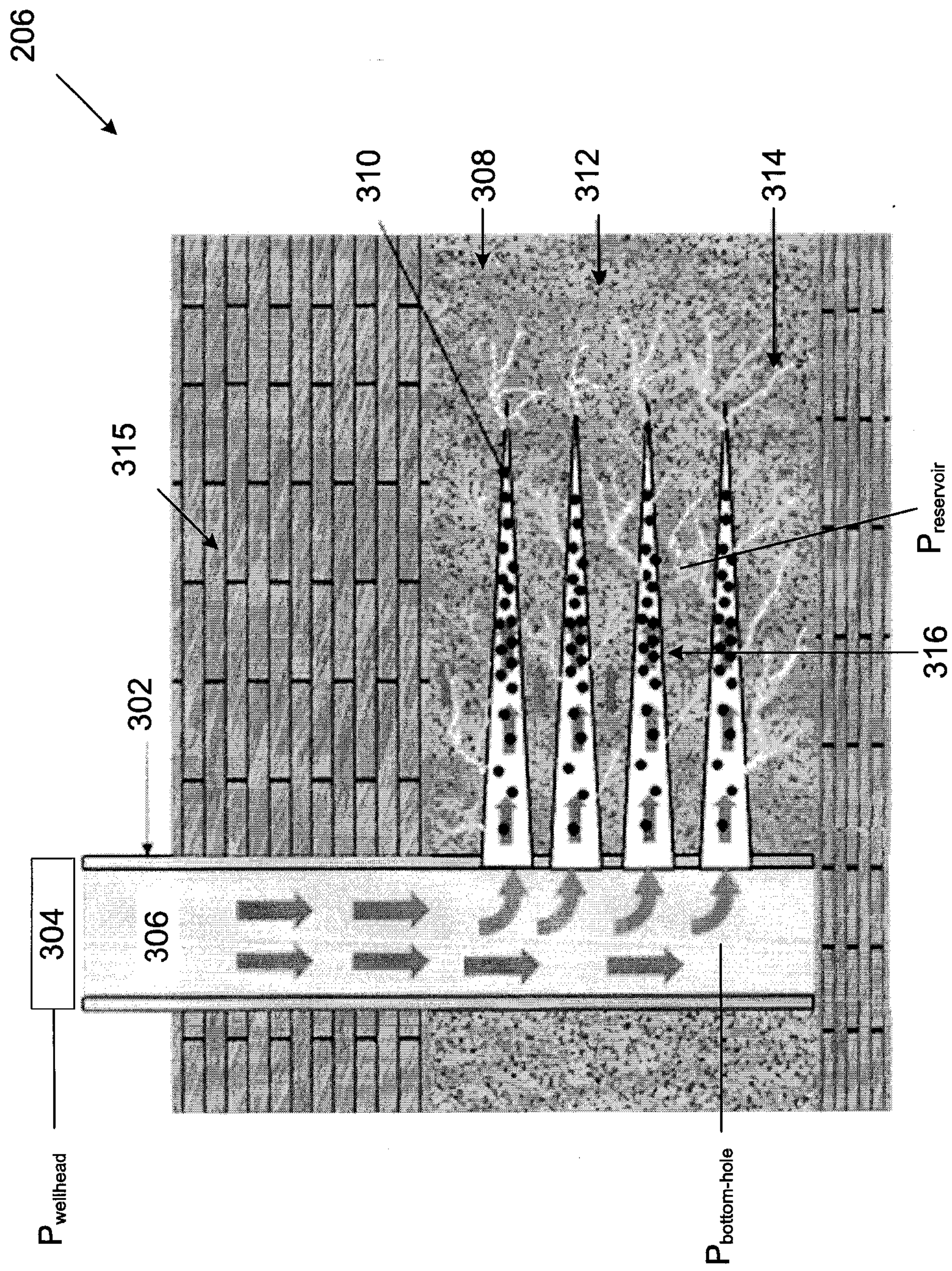


FIG. 5

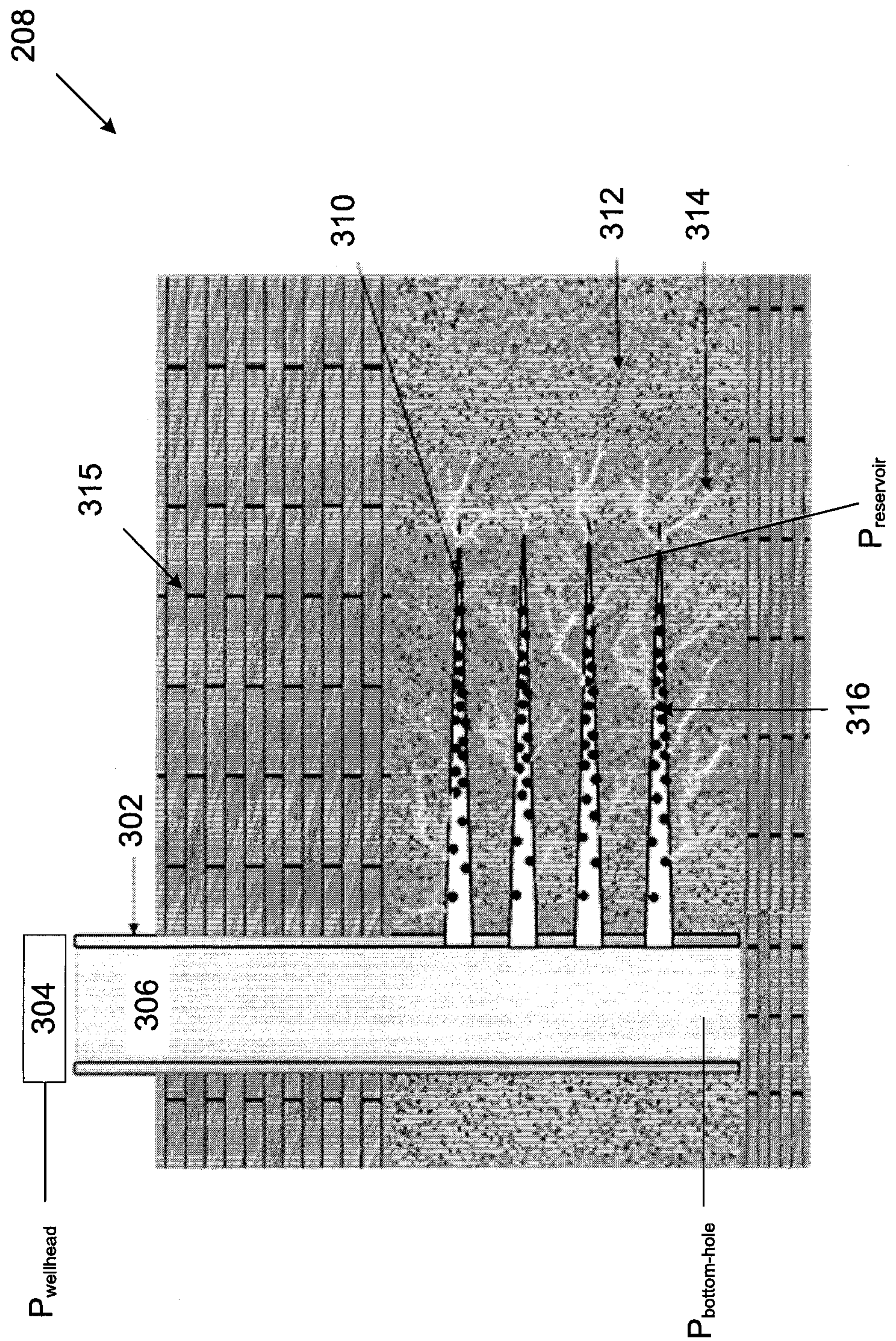


FIG. 6

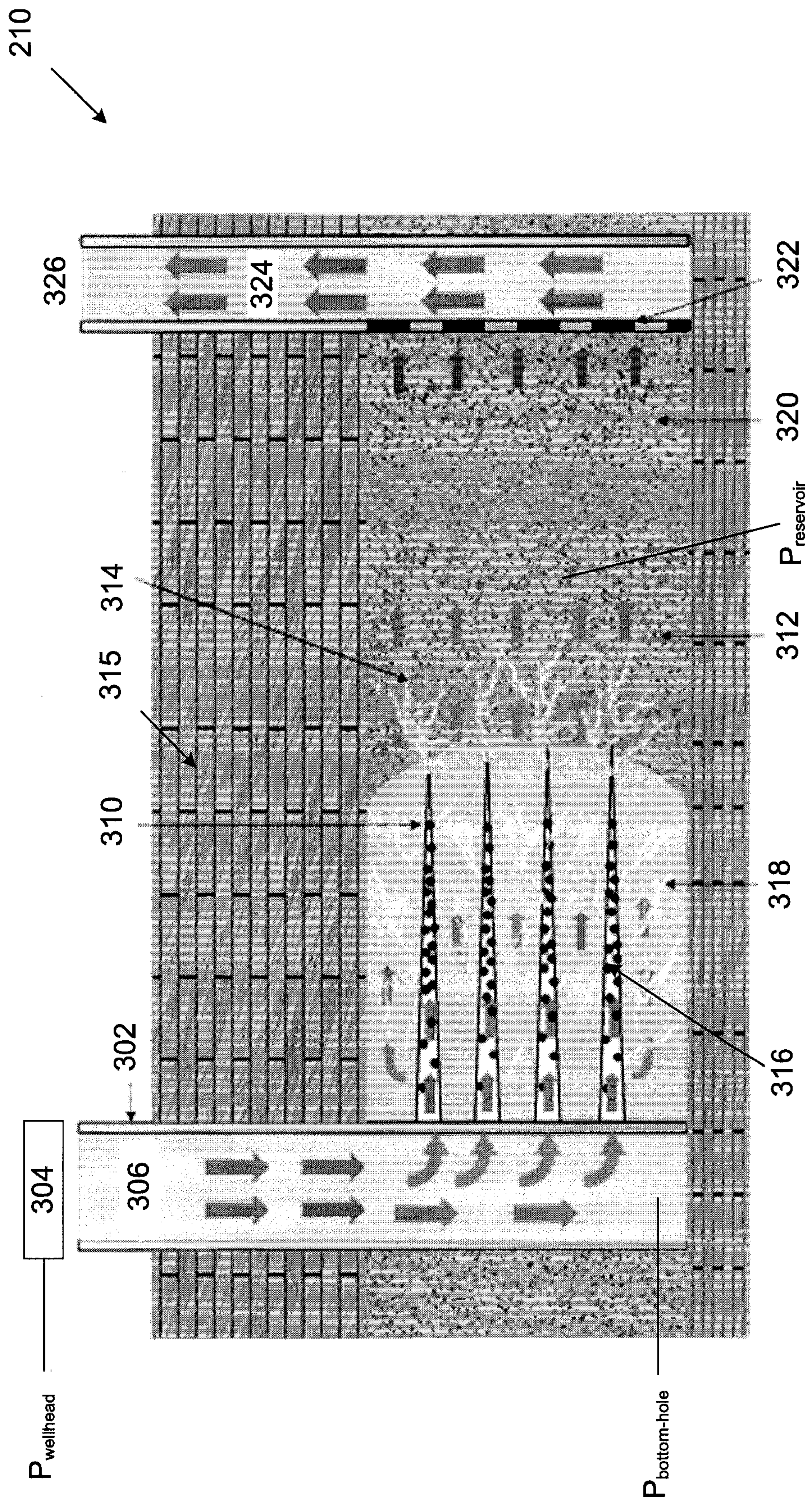


FIG. 7

