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(54) **Title**: APPARATUS AND METHOD FOR DETERMINATION OF FORMATION BUBBLE POINT IN DOWNHOLE TOOL

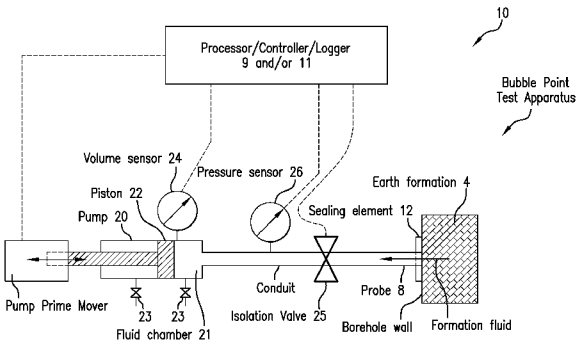


FIG.2

(57) **Abstract**: An apparatus for estimating a bubble point of a fluid in an earth formation penetrated by a borehole includes: a pump configured to pump fluid from the earth formation through an extendable probe into a volume; and a processor. The processor is configured to perform a pressure-volume test on the fluid sample. The test includes: increasing the pressure of the fluid sample above formation pressure and logging the pressure and volume of the fluid sample; calculating a reference compressibility of the fluid sample; decreasing the pressure of the fluid sample and logging the pressure and volume; calculating a compressibility of the fluid sample using the logged pressure and volume obtained from during the decreasing; comparing the calculated compressibility to a threshold; and estimating the bubble point as the current fluid sample pressure when the calculated compressibility first meets or exceeds the threshold factor.

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APPARATUS AND METHOD FOR DETERMINATION OF FORMATION BUBBLE POINT IN DOWNHOLE TOOL

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Application No. 13/666282, filed on November 1, 2012, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] A borehole is generally drilled into an earth formation in order to extract hydrocarbons from a reservoir. The hydrocarbons may be in the form of oil and/or gas. The hydrocarbons are produced by lowering the pressure in the borehole so that the hydrocarbons, which are under higher pressure, flow into the borehole and to the surface of the earth.

[0003] If the hydrocarbons in the formation are in the form of oil and gas, it is important to know the bubble pressure of the oil. The bubble pressure relates to the highest pressure at which a chemical constituent in a liquid turns to vapor and forms bubbles. Thus, if only oil is desired to be extracted and the pressure in the borehole is lowered below the bubble point, mostly or only gas will flow out because the hydrocarbon gas has a lower viscosity than oil. Hence, in order to extract oil, it is important to extract the oil at a pressure above the bubble point. Keeping the pressure in the borehole above the bubble point but close to the bubble point will improve the rate of production since the lower the pressure the higher the rate of oil production will be. Therefore, it would be well received in the drilling industry if a downhole tool were available to accurately measure the bubble pressure of oil.

BRIEF SUMMARY

[0004] Disclosed is an apparatus for estimating a bubble point of a fluid in an earth formation penetrated by a borehole. The apparatus includes: a carrier configured to be conveyed through the borehole; a probe disposed at the carrier and configured to extend from the carrier and seal to a wall of the borehole; a pump in fluid communication with the probe, the pump having a variable volume configured to pump fluid from the earth formation into the volume within the pump; a volume sensor configured to sense the volume within the pump; a pressure sensor in pressure communication with the fluid in the volume of the pump and configured to sense the pressure of the fluid in the volume in the pump; an isolation valve coupled to the probe and configured to isolate a sample of the fluid pumped through the probe; and a processor coupled to the volume sensor, the pressure sensor, and a prime mover

configured to operate the pump to change the variable volume. The processor is configured to perform a pressure-volume test on the fluid sample. The test includes: increasing the pressure of the fluid sample above formation pressure by decreasing the volume within the pump and logging the pressure and volume of the fluid sample using the pressure sensor and the volume sensor during the decrease in volume of the pump; calculating a reference compressibility of the fluid sample; decreasing the pressure of the fluid sample and logging the pressure and volume using the pressure sensor and the volume sensor; calculating a compressibility of the fluid sample using the logged pressure and volume obtained from during the decreasing; comparing the calculated compressibility to a threshold; and estimating the bubble point as the current fluid sample pressure when the calculated compressibility first meets or exceeds the threshold factor.

[0005] Also disclosed is a method for estimating a bubble point of a fluid in an earth formation penetrated by a borehole. The method includes: conveying a carrier through the borehole; extracting a sample of fluid from the formation using a probe extending from the carrier to the formation; closing an isolation valve in fluid communication with the probe in order to isolate the fluid sample from the formation; increasing the pressure of the fluid sample above formation pressure by decreasing a volume within a pump in fluid communication with the probe and logging the pressure and volume of the fluid sample using a pressure sensor and a volume sensor during the decreasing of the volume within the pump; calculating a reference compressibility of the fluid sample using a processor; decreasing the pressure of the fluid sample by increasing the volume within the pump and logging the pressure and volume measured by the pressure sensor and the volume sensor; calculating a compressibility of the fluid sample using the logged pressure and volume obtained from during the decreasing, the calculating being performed by the processor; comparing the calculated compressibility to a threshold using the processor; and estimating the bubble point as the current fluid sample pressure when the calculated compressibility first meets or exceeds the threshold.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike:

[0007] FIG. 1 illustrates an exemplary embodiment of a downhole tool for measuring bubble pressure disposed in a borehole penetrating the earth;

[0008] FIG. 2 depicts aspects of the downhole tool;

[0009] FIG. 3 illustrates one example of response curve for a pressure-volume test;

[0010] FIG. 4 is a flow chart for a method for estimating a bubble point of a liquid in an earth formation;

[0011] FIG. 5 illustrates one example of compressibility versus volume being calculated using a small data segment size;

[0012] FIG. 6 illustrates one example of compressibility versus volume being calculated using a large data segment size that is larger than the small data segment size;

[0013] FIG. 7 illustrates one example of compressibility versus volume with a pump stalled without reaching the bubble point; and

[0014] FIG. 8 illustrates one example of compressibility versus volume for a gas.

DETAILED DESCRIPTION

[0015] A detailed description of one or more embodiments of the disclosed apparatus and method presented herein by way of exemplification and not limitation with reference to the Figures.

[0016] Disclosed are method and apparatus for estimating or determining a bubble point of a liquid disposed in an earth formation by performing a pressure-volume test. In general, as related to oil production, the bubble point is only applicable to volatile or non-volatile oil.

[0017] FIG. 1 illustrates a cross-sectional view of an exemplary embodiment of a downhole tool 10 disposed in a borehole 2 penetrating the earth 3, which includes an earth formation 4. The formation 4 represents any subsurface material of interest such as formation fluid. The downhole tool 10 is conveyed through the borehole 2 by a carrier 5. In the embodiment of FIG. 1, the carrier 5 is an armored wireline 6. Besides supporting the downhole tool 10 in the borehole 2, the wireline can also provide communications between the downhole tool and a computer processing system 11 disposed at the surface of the earth 3. Communications can include sending measurement data uphole to the computer processing system 11 or commands downhole to the tool 10. In logging-while-drilling (LWD) or measurement-while-drilling (MWD) embodiments, the carrier 5 can be a drill tubular such as a drill string. In order to operate the downhole tool 10, process measurement data, and/or provide a communications interface with the surface computer processing system 11, the downhole tool 10 includes downhole electronics 9. The operating and processing functions of the disclosure may be performed by the downhole electronics 9, the computer processing system 11, or a combination thereof.

[0018] Still referring to FIG. 1, the downhole tool 10 is configured to perform a measurement of the bubble point of a fluid (i.e., formation fluid) extracted from the formation 4. In order to extract the formation fluid, the downhole tool 10 includes a probe 8 configured to extend from the tool 10 and seal to a wall of the borehole 2. The probe 8 may include a pliable pad 12 to provide sealing to an uneven surface of the borehole wall. An extendable brace 13 may be included to hold or brace the probe 8 against the borehole wall while the fluid is being extracted from the formation 4.

[0019] FIG. 2 is a cross-sectional view depicting aspects of the downhole tool 10 in further detail. The downhole tool 10 includes a positive displacement pump 20, which is configured to receive formation fluid extracted via the probe 8. The pump 20 includes a fluid chamber 21 and a piston 22, which is configured to traverse the fluid chamber 21 to pump fluid. The pump 20 also includes remotely-isolatable discharge valves 23, which may be used to flush the pump of borehole fluid or mud infiltrate. A volume sensor 24 is configured to measure a volume in the fluid chamber 21 with the piston 22 forming one boundary of the fluid chamber 21 as shown in FIG. 2. The volume sensor 24 provides a measurement of the volume throughout the sequence of the pressure-volume test. In one or more embodiments, the volume sensor 24 is configured to measure the position of the piston 22, such as magnetically for example, in order to measure the volume of the fluid chamber 21 based on piston position. A remotely-operated isolation valve 25 is disposed in a conduit leading from the probe 8 to the fluid chamber 21. The isolation valve 25 is configured to isolate a volume that may be varied by varying the position of the pump piston 22. Hence, the volume sensed by the volume sensor 24 may include the volume of the conduit between the pump 20 and the isolation valve 25. It can be appreciated that the pressure of the fluid sample within the isolated volume may be increased by decreasing the volume of the fluid chamber 21 (for example by moving the piston 22) and, conversely, the pressure of the fluid sample may be decreased by increasing the volume of the fluid chamber 21. A pressure sensor 26 is in pressure communication with the isolated volume and is configured to sense the pressure of the fluid in the isolated volume. The volume sensor 24 and the pressure sensor 26 are configured to send measurement information to the downhole electronics 9 and/or the computer processing system 11. The pump 20, the remotely-operated discharge valves 23, and the remotely-operated isolation valve 25 are configured to receive commands from the downhole electronics 9 and/or the computer processing system 11 for operating the downhole tool 10 in accordance with the disclosure herein.

[0020] FIG. 3 illustrates one example of a response curve for a pressure-volume test. The dashed arrow indicates a change of the shape of the curve during the test. This change happens when the pressure is low enough for a fluid component to change into a gaseous state. The fluid thus changes from single-phase to multi-phase. The bubble point is defined as the pressure at which the first gas bubbles appear. In one or more embodiments, the bubble point is determined where the magnitude of the negative slope on the left part of the curve first starts to decrease (i.e., curve from the straight line). It is noted that the bubble point cannot be measured if the fluid is already in a gaseous state or supercritical state (i.e., condensate, wet gas or dry gas). A fluid in such a state does not show a bubble point when it is being expanded, but it might reach a dew point when the pressure is decreased. The bubble point might not also be measured if the bubble point is too low for the pump to reach (i.e., if the pump stalls at its rated maximum differential pressure before the bubble point is reached).

[0021] FIG. 4 is a flow chart for a method 40 for estimating a bubble point of a fluid in an earth formation. Block 41 calls for conveying a carrier through a borehole penetrating the earth formation. Block 42 calls for extracting a sample of the fluid through a probe extended from the carrier. Block 43 calls for closing an isolation valve to isolate a volume containing the sample. Block 44 calls for increasing a pressure of the isolated fluid above formation pressure by decreasing the isolated volume using a pump. The formation pressure may be determined by the pressure sensor after the sample is extracted, but before the isolation valve is closed (i.e., with the sample pressure in equilibrium with the formation pressure). A piston in the pump may be moved at a predetermined speed to decrease the volume while pressure and volume are logged (i.e., recorded). Block 45 calls for stopping the pump when a limit has been reached (e.g., pressure limit above formation pressure, a percentage above formation pressure, volume limit of the pump, time limit for decreasing the volume, or maximum differential rating of the pump). In one or more embodiments, the pump is stopped when the sample pressure is 20 bar above the formation pressure. Block 46 calls for calculating fluid compressibility using the logged pressure and volume data. The calculated compressibility is used as a reference compressibility. Compressibility is defined as $\beta = -\frac{1}{V}\frac{\partial V}{\partial p}$ where V represents fluid volume and p represents fluid pressure.

[0022] In one or more embodiments, the partial differential is determined in an isothermal process (i.e., at constant temperature). Accordingly, in Block 44 the pressure can be increased slowly so that the compression is an isothermal process.

[0023] Block 47 calls for determining if the reference compressibility is higher than a threshold compressibility. If the reference compressibility is higher than the threshold, then the bubble point cannot be determined because there is already gas in the fluid. If the reference compressibility is less than or equal to the threshold, then proceed with determining the bubble point.

[0024] Block 48 calls for calculating a volume expansion rate (i.e., change in volume over time) for a pressure-volume (P-V) test. In one or more embodiments, the volume expansion rate is the pump rate for pumping. The volume expansion rate in combination with the reference compressibility leads to a pressure decrease rate, assuming constant compressibility of the fluid. Block 49 calls for applying a maximum limit and a minimum limit to the calculated volume expansion rate. Different factors, such as equipment ratings and time constraints, may dictate these limits. For example, the minimum limit might be determined by the minimum speed of the pump or time available for conducting the P-V test. The maximum limit might be determined by available pump stroke, time available for conducting the P-V test, or maximum possible pump differential pressure.

[0025] Block 50 calls for decreasing the pressure of the fluid sample by increasing the isolated volume at the calculated volume expansion rate and logging pressure and volume during this P-V test. Block 51 calls for calculating compressibility of the fluid sample after a time duration X, such as X milliseconds, using the logged pressure and volume data obtained during the time duration X. Calculating the fluid sample compressibility may be performed every X milliseconds using the logged pressure and volume data obtained during the previous X milliseconds. Once the fluid sample compressibility is calculated, it is compared to the reference compressibility. If the calculated compressibility is a factor Y higher than the reference compressibility (i.e., a reference threshold), then the current fluid sample pressure is the estimated bubble point (Block 52).

[0026] A detailed explanation of the method 40 and possible variations are discussed next. Gases and liquids have large differences in compressibility at equal temperature and pressure. Hence, the gas bubbles which appear when the bubble point is reached alter the fluid compressibility rapidly and provide an indication of the bubble point.

[0027] Decreasing the pressure of the fluid sample from the formation pressure might lead to non-reversible changes to the phase state of the fluid sample. However, increasing the fluid sample pressure above the formation pressure does not change the phase state of the fluid sample. It is important to keep the fluid sample in its original phase state when

performing the pressure-volume test so that the determined bubble point is applicable to the fluid in the formation

[0028] So increasing the pressure before performing the actual PV-test does not alter the phase of the fluid, but gives additional compressibility information and a starting pressure more away from the bubble point. This leads to a longer linear shape of the pressure curve at the beginning of the P-V test thus providing a more accurate reference curve from which to determine the bubble point.

[0029] A variable or adaptive pump rate may be used to optimize the usage of available test time and the pump stroke by setting a predetermined pressure decrease rate instead of a predetermined pump rate.

[0030] The segment size or time duration for logging pressure and volume data for the compressibility calculation ("X milliseconds") influences the smoothness of the resulting compressibility and also the response time of the bubble point detection. A large segment size leads to smooth data, but delays the time until the bubble point can be detected (and lead to underestimating the bubble point pressure). FIG. 5 illustrates one example of compressibility versus volume being calculated using a small data segment size, while FIG. 6 illustrates one example of compressibility versus volume being calculated using a large data segment size that is larger than the small data segment size. The curve in FIG. 6 was derived from the same raw data used derive the curve in FIG. 5, thus enabling the two curves to be directly compared.

[0031] The reference compressibility is the compressibility of the fluid at the beginning of the P-V test. One way is to determine the reference compressibility is to use the compressibility calculated in block 46 of the method 40 as the reference compressibility. Other variations are possible, such as using compressibility calculated in the first segment(s) of the PV-test, while the fluid sample pressure is still above formation pressure.

[0032] The bubble point is detected when the actual compressibility is significantly larger than the reference compressibility. The "significantly larger" is determined by setting a threshold that is scaled to the reference compressibility. A factor Y near 1.5 times the reference compressibility has shown to yield good results with the data presented herein. The horizontal dashed line in FIG. 6 illustrates a possible threshold based on a factor of Y = 1.5 times the reference compressibility.

[0033] The choice of Y may depend on the noise level of the compressibility data. It should be as small as possible to detect the earliest change in compressibility, but must be

high enough not to trigger bubble point detection due to noise. Since noise level is influenced by the choice of X, both parameters may not be independent of each other.

[0034] In one or more embodiments, Y may be dynamically derived from the first seconds of the P-V test, when the actual pressure is still above formation pressure. The data acquired during this time shows a certain noise level. Using this noise level and a desired significance level, a threshold for bubble point detection can be calculated. For example, the threshold can be set a certain amount above the noise level or spikes in the noise level to help prevent false bubble point detection.

[0035] In one or more embodiments, X may be adjusted dynamically instead of Y to adjust the noise level to a given threshold since X and Y may not be independent of each other.

[0036] In one or more embodiments, several results (i.e., bubble point pressure determinations) can be determined using different Y significance values. From the several bubble point determinations, outlying values from an expected trend can be excluded to determine the most accurate or most likely bubble point.

[0037] FIG. 7 illustrates a compressibility curve of a test where the bubble point has not been reached. The compressibility stays nearly constant and the curve never crosses the dashed-line threshold. This data and method indicate that there is no bubble point. In this example, the compressibility curve is derived from a P-V test where the bubble point has not been reached because the pump stalled before reaching the bubble point.

[0038] FIG. 8 illustrates another compressibility curve without detecting a bubble point because the medium being decompressed is already a gas. Hence, data of the type illustrated in FIG. 8, where the compressibility exceeds a gas detection set point, may be used to detect gas in the formation. The gas detection set point may be predetermined or it may be derived from compressibility calculation data such when "spikes" in the calculated compressibility meet or exceed a certain percentage above an average of the data in one or more embodiments.

[0039] The reference compressibility can be used to decide if the fluid already contains a gas phase and thus no bubble point should be determined (see block 47 of the method 40). Compressibility of gas and supercritical fluids depends on pressure and temperature.

[0040] Using pressure and temperature measurements and maybe additional information about the expected fluid composition, a heuristic compressibility threshold for

the reference compressibility can be chosen. If the reference compressibility is already higher than the threshold, no bubble point will be determined.

[0041] The order of magnitude of gas compressibility is 1 / P where P is the pressure of the gas (isothermal bulk modulus of ideal gas equals its pressure). This value can be used as a starting point to derive a compressibility threshold.

[0042] The horizontal dashed line in FIG. 8 illustrates a simple example threshold of 0.5 * 1 / P, where P is starting pressure of the test.

[0043] In one or more embodiments, the bubble point is always determined or detected, but the gas detecting threshold is used to calculate a quality indicator indicative of the quality of the result. Higher reference compressibility (above threshold) leads to a lower quality indicator.

[0044] It can be appreciated that the apparatus and method disclosed herein offer several advantages over traditional apparatuses and methods for determining the bubble point of formation fluids. For example, traditional analysis of the curvature of a pressure-volume test for local maxima always leads to a determination of a bubble point, even if there is no bubble point in the data. Traditional apparatuses and methods perform a pressure-volume test starting at or below formation pressure. If the bubble point is near formation pressure, the first linear part of the curve might be very short, so the onset of high curvature is hard to determine. Further, traditional apparatuses and methods use a predefined pump speed (i.e., not a variable or adaptive pump speed).

[0045] In support of the teachings herein, various analysis components may be used, including a digital and/or an analog system. For example, the downhole electronics 9 or the computer processing system 11 may include the digital and/or analog system. The system may have components such as a processor, storage media, memory, input, output, communications link (wired, wireless, pulsed mud, optical or other), user interfaces, software programs, signal processors (digital or analog) and other such components (such as resistors, capacitors, inductors and others) to provide for operation and analyses of the apparatus and methods disclosed herein in any of several manners well-appreciated in the art. It is considered that these teachings may be, but need not be, implemented in conjunction with a set of computer executable instructions stored on a non-transitory computer readable medium, including memory (ROMs, RAMs), optical (CD-ROMs), or magnetic (disks, hard drives), or any other type that when executed causes a computer to implement the method of the present invention. These instructions may provide for equipment operation, control, data

collection and analysis and other functions deemed relevant by a system designer, owner, user or other such personnel, in addition to the functions described in this disclosure.

[0046] Further, various other components may be included and called upon for providing for aspects of the teachings herein. For example, a power supply (e.g., at least one of a generator, a remote supply and a battery), cooling component, heating component, magnet, electromagnet, sensor, electrode, transmitter, receiver, transceiver, antenna, controller, optical unit, electrical unit or electromechanical unit may be included in support of the various aspects discussed herein or in support of other functions beyond this disclosure.

[0047] The term "carrier" as used herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. Other exemplary non-limiting carriers include drill strings of the coiled tube type, of the jointed pipe type and any combination or portion thereof. Other carrier examples include casing pipes, wirelines, wireline sondes, slickline sondes, drop shots, bottom-hole-assemblies, drill string inserts, modules, internal housings and substrate portions thereof.

[0048] Elements of the embodiments have been introduced with either the articles "a" or "an." The articles are intended to mean that there are one or more of the elements. The terms "including" and "having" are intended to be inclusive such that there may be additional elements other than the elements listed. The conjunction "or" when used with a list of at least two terms is intended to mean any term or combination of terms. The terms "first" and "second" are used to distinguish elements and are not used to denote a particular order. The term "couple" relates to coupling a first component to a second component either directly or indirectly through an intermediate component.

[0049] The flow diagram depicted herein is just an example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order, or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

[0050] It will be recognized that the various components or technologies may provide certain necessary or beneficial functionality or features. Accordingly, these functions and features as may be needed in support of the appended claims and variations thereof, are recognized as being inherently included as a part of the teachings herein and a part of the invention disclosed.

[0051] While the invention has been described with reference to exemplary embodiments, it will be understood that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications will be appreciated to adapt a particular instrument, situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

CLAIMS

What is claimed is:

1. An apparatus for estimating a bubble point of a fluid in an earth formation penetrated by a borehole, the apparatus comprising:

a carrier configured to be conveyed through the borehole;

a probe disposed at the carrier and configured to extend from the carrier and seal to a wall of the borehole;

a pump in fluid communication with the probe, the pump having a variable volume configured to pump fluid from the earth formation into the volume within the pump;

a volume sensor configured to sense the volume within the pump;

a pressure sensor in pressure communication with the fluid in the volume of the pump and configured to sense the pressure of the fluid in the volume in the pump;

an isolation valve coupled to the probe and configured to isolate a sample of the fluid pumped through the probe; and

a processor coupled to the volume sensor, the pressure sensor, and a prime mover configured to operate the pump to change the variable volume, the processor being configured to perform a pressure-volume test on the fluid sample, the test comprising:

increasing the pressure of the fluid sample above formation pressure by decreasing the volume within the pump and logging the pressure and volume of the fluid sample using the pressure sensor and the volume sensor during the decrease in volume of the pump;

calculating a reference compressibility of the fluid sample;

decreasing the pressure of the fluid sample and logging the pressure and volume using the pressure sensor and the volume sensor;

calculating a compressibility of the fluid sample using the logged pressure and volume obtained from during the decreasing;

comparing the calculated compressibility to a threshold; and

estimating the bubble point as the current fluid sample pressure when the calculated compressibility first meets or exceeds the threshold factor.

2. The apparatus according to claim 1, wherein the pump is a positive displacement pump comprising a moveable piston coupled to the prime mover, and wherein a position of the piston defines the volume within the pump.

3. The apparatus according to claim 2, wherein the prime mover is configured to move the piston at a rate corresponding to a selected volume expansion rate in order to decrease the pressure of the fluid sample.

4. The apparatus according to claim 1, further comprising calculating a volume expansion rate using the reference compressibility for decreasing the pressure in order to meet a selected pressure decrease rate.

5. The apparatus according to claim 1, wherein the processor is coupled to the isolation valve and is further configured to close the isolation valve after the fluid sample is obtained.

6. The apparatus according to claim 1, wherein the processor is further configured to determine a formation pressure using the pressure sensor while the isolation valve is open.

7. The apparatus according to claim 5, wherein the processor is further configured to perform the decreasing the pressure, the calculating a compressibility, the comparing, and the estimating while the pressure of the fluid sample is above the formation pressure.

8. The apparatus according to claim 1, wherein the processor is further configured to calculate the compressibility of the fluid after receiving ***X*** milliseconds of measurements from the pressure sensor and the volume sensor.

9. The apparatus according to claim 8, wherein the processor is further configured to calculate the compressibility after receiving the next ***X*** milliseconds of measurements from the pressure sensor and the volume sensor.

10. The apparatus according to claim 1, wherein the processor is further configured to calculate the reference compressibility using measurements obtained from the pressure sensor and the volume sensor during the increasing of the pressure of the fluid sample.

11. The apparatus according to claim 1, wherein the logged pressure for calculating a reference compressibility of the fluid sample is above the formation pressure.

12. The apparatus according to claim 1, wherein the processor is further configured to detect that the fluid sample contains a gas component when the calculated compressibility meets or exceeds a gas detection set point.

13. The apparatus according to claim 1, wherein the carrier comprises a wireline or a drill tubular.

14. A method for estimating a bubble point of a fluid in an earth formation penetrated by a borehole, the method comprising:

conveying a carrier through the borehole;

extracting a sample of fluid from the formation using a probe extending from the carrier to the formation;

closing an isolation valve in fluid communication with the probe in order to isolate the fluid sample from the formation;

increasing the pressure of the fluid sample above formation pressure by decreasing a volume within a pump in fluid communication with the probe and logging the pressure and volume of the fluid sample using a pressure sensor and a volume sensor during the decreasing of the volume within the pump;

calculating a reference compressibility of the fluid sample using a processor;

decreasing the pressure of the fluid sample by increasing the volume within the pump and logging the pressure and volume measured by the pressure sensor and the volume sensor;

calculating a compressibility of the fluid sample using the logged pressure and volume obtained from during the decreasing, the calculating being performed by the processor;

comparing the calculated compressibility to a threshold using the processor; and

estimating the bubble point as the current fluid sample pressure when the calculated compressibility first meets or exceeds the threshold.

15. The method according to claim 14, wherein the logged pressure for calculating a reference compressibility of the fluid sample is above the formation pressure.

16. The method according to claim 14, further wherein the decreasing the pressure is according to a volume expansion rate calculated using the reference compressibility.

17. The method according to claim 16, further comprising applying a maximum limit and a minimum limit to the volume expansion rate, wherein the volume expansion rate is not to exceed the maximum limit and the minimum limit.

18. The method according to claim 14, wherein the compressibility is calculated after logging pressure and volume measurements for a time duration of ***X*** milliseconds.

19. The method according to claim 18, wherein the compressibility is calculated again after the next ***X*** milliseconds.

20. The method according to claim 18, further comprising adjusting the time duration to achieve a selected noise level in the calculated compressibility.

21. The method according to claim 18, wherein the threshold is a scale factor of a compressibility curve derived from each calculated compressibility after one or more time durations.

22. The method according to claim 14, wherein the pump is a positive displacement pump comprising a piston, a position of the piston determining the volume within the pump, and the method further comprises stopping movement of the piston during the increasing the pressure of the fluid sample when an upper pressure limit is reached.

23. The method according to claim 14, wherein in the increasing the pressure of the fluid sample is done slow enough so that the compression of the fluid sample is isothermal.

24. The method according to claim 14, further comprising detecting that a gas is present in the fluid sample when the calculated compressibility meets or exceeds a gas detection set point.

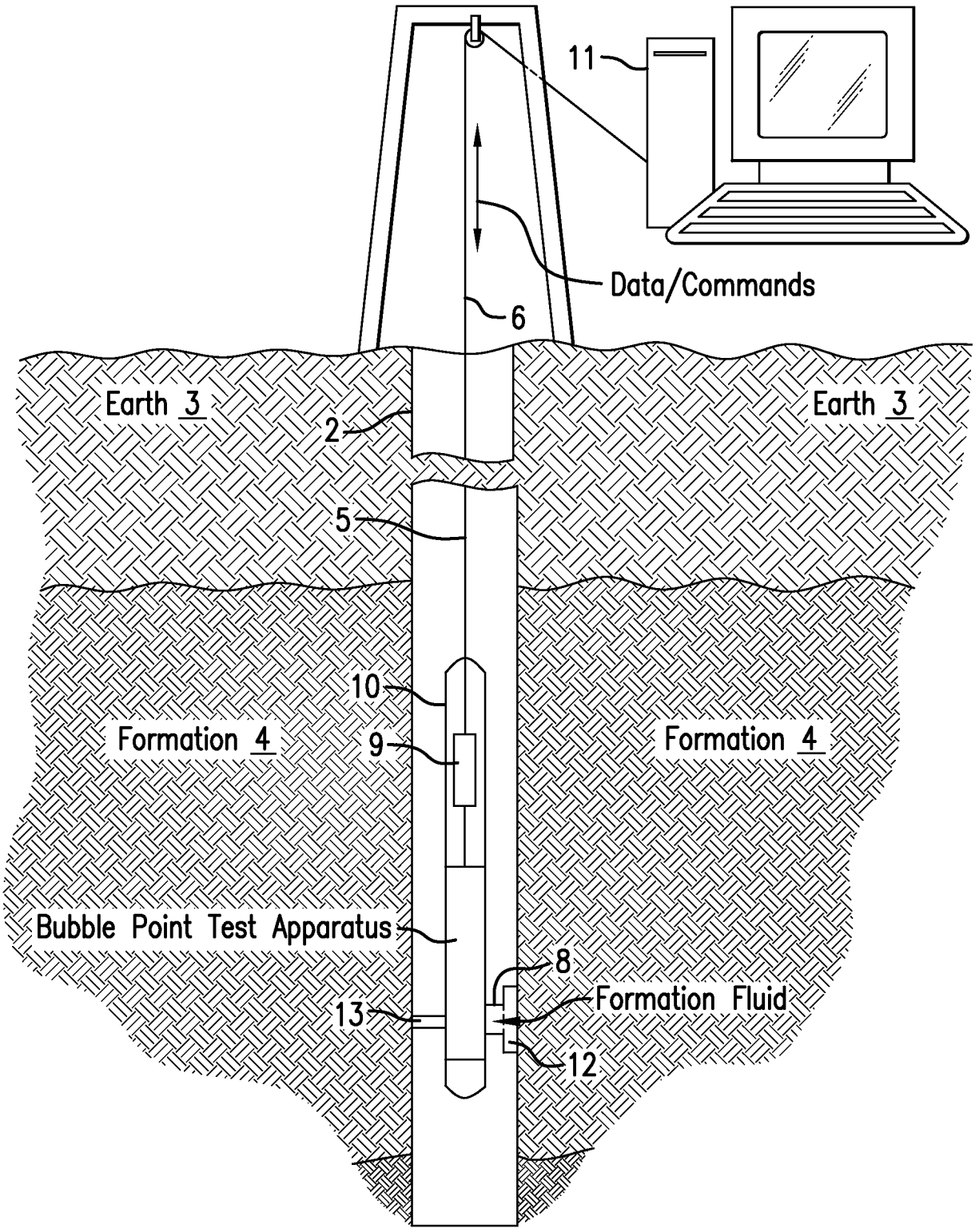

11
Data/Commands
6
Earth 3
2
Earth 3
5
10
Formation 4
9
Formation 4
Bubble Point Test Apparatus
8
Formation Fluid
13
12

FIG. 1

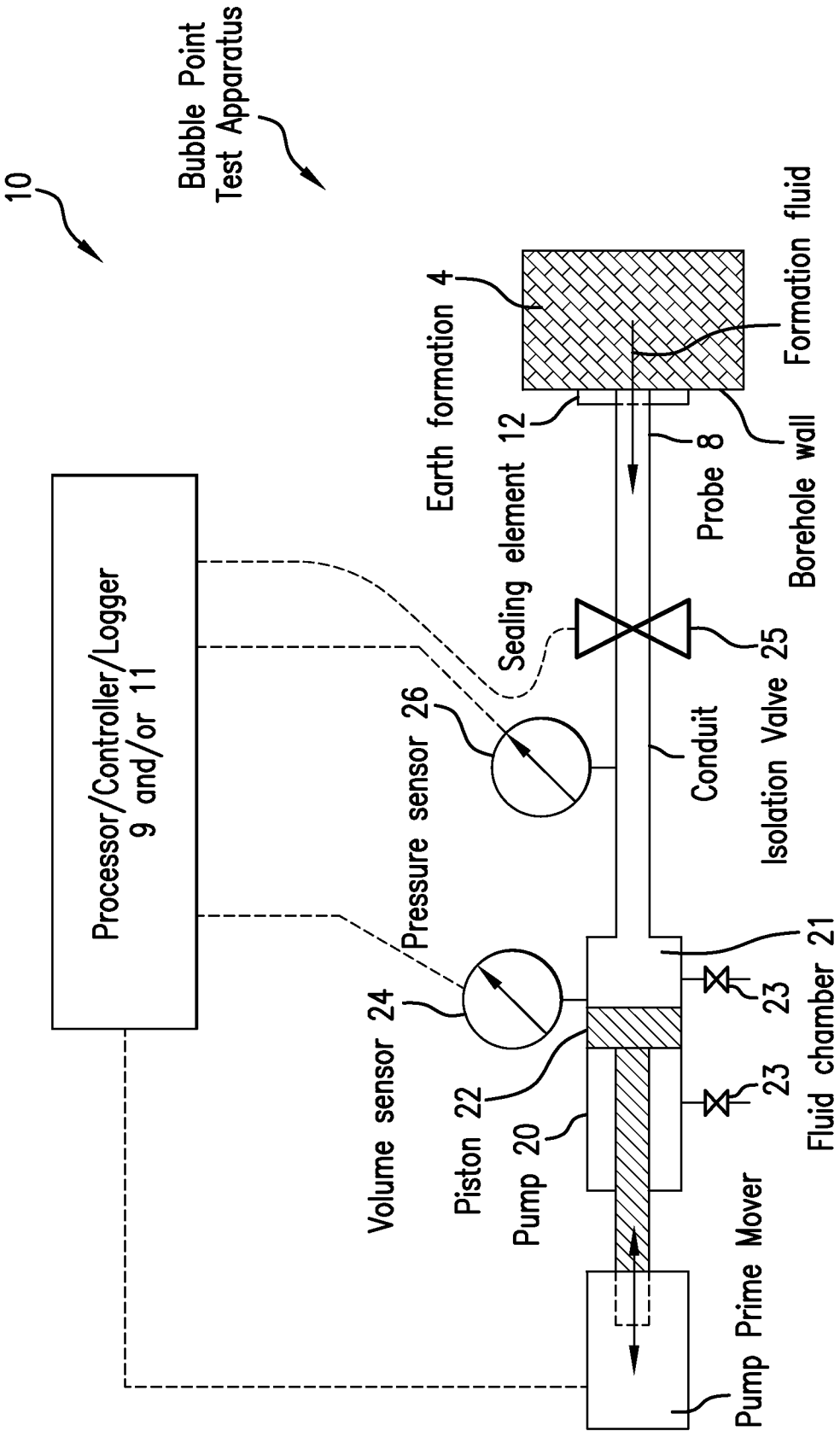

10
Bubble Point
Test Apparatus
Processor/Controller/Logger
9 and/or 11
Earth formation 4
Formation fluid
Sealing element 12
Probe 8
Borehole wall
Pressure sensor 26
Conduit
Isolation Valve 25
Volume sensor 24
Piston 22
Pump 20
23
23
Fluid chamber 21
Pump Prime Mover

FIG.2

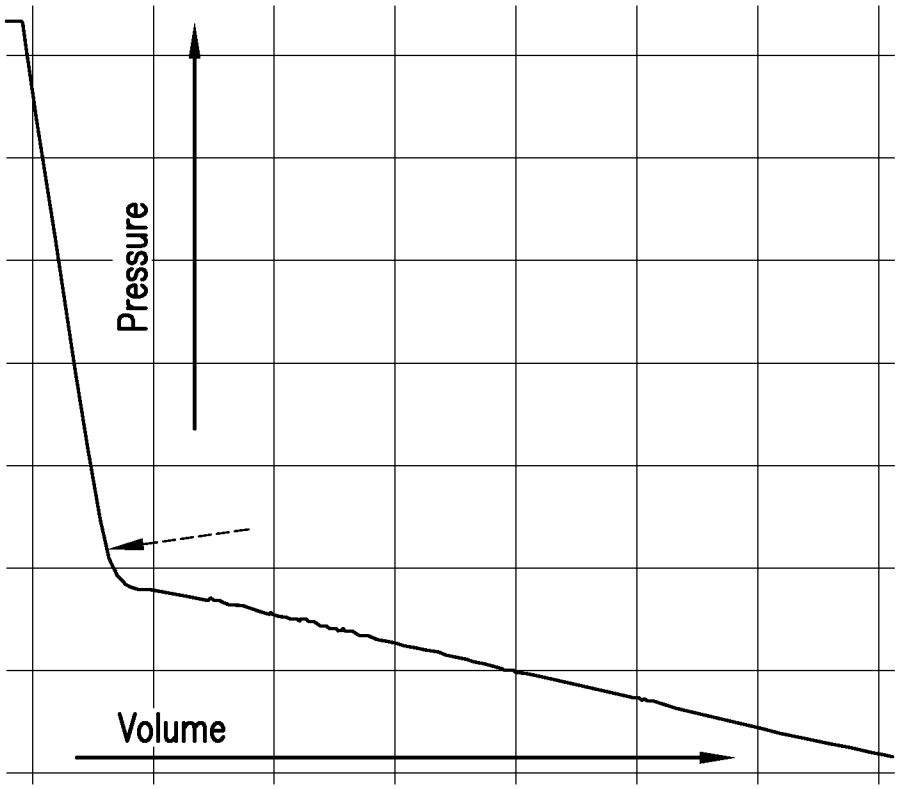


FIG.3

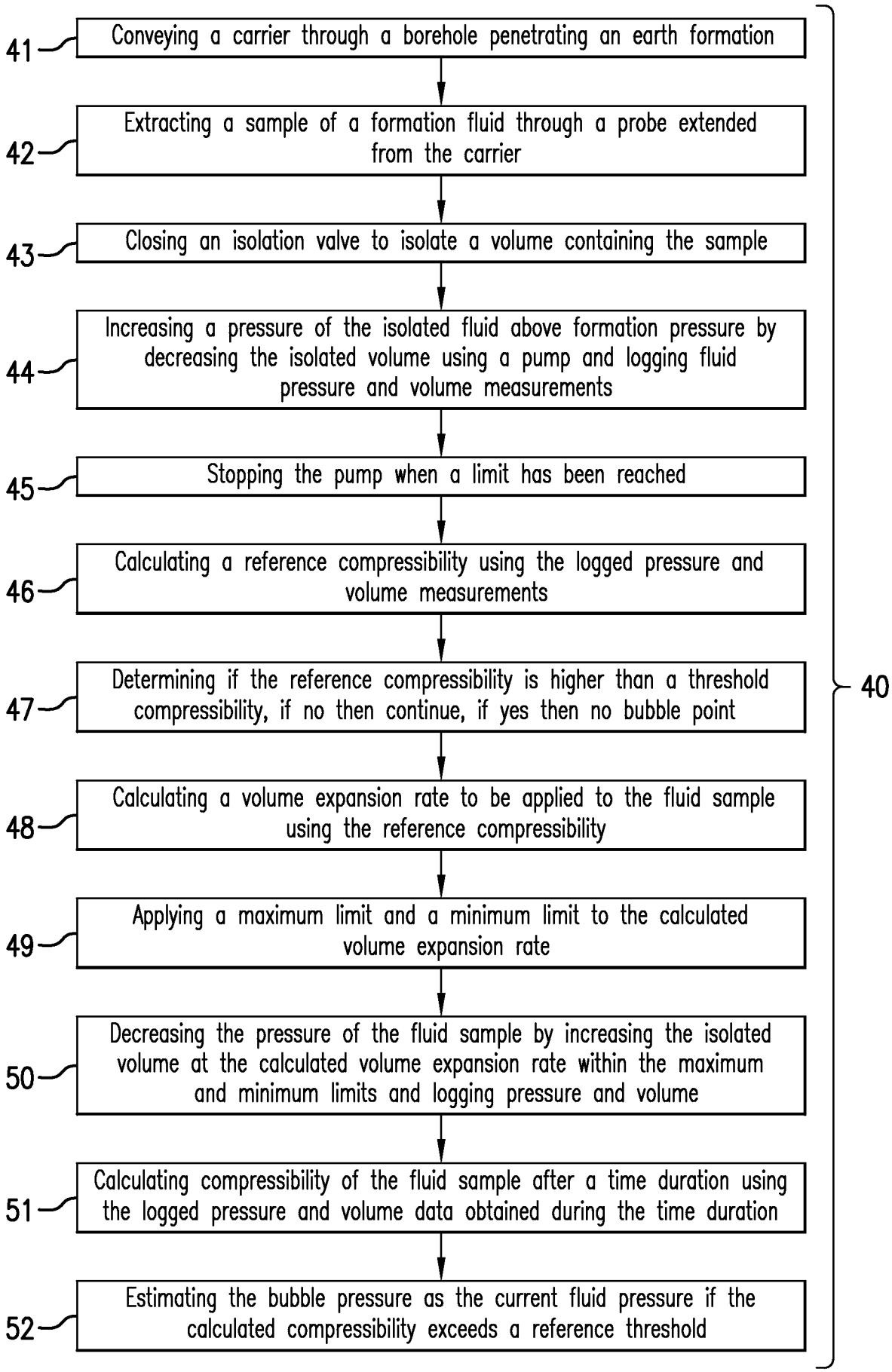

41
Conveying a carrier through a borehole penetrating an earth formation
42
Extracting a sample of a formation fluid through a probe extended from the carrier
43
Closing an isolation valve to isolate a volume containing the sample
44
Increasing a pressure of the isolated fluid above formation pressure by decreasing the isolated volume using a pump and logging fluid pressure and volume measurements
45
Stopping the pump when a limit has been reached
46
Calculating a reference compressibility using the logged pressure and volume measurements
47
Determining if the reference compressibility is higher than a threshold compressibility, if no then continue, if yes then no bubble point
48
Calculating a volume expansion rate to be applied to the fluid sample using the reference compressibility
49
Applying a maximum limit and a minimum limit to the calculated volume expansion rate
50
Decreasing the pressure of the fluid sample by increasing the isolated volume at the calculated volume expansion rate within the maximum and minimum limits and logging pressure and volume
51
Calculating compressibility of the fluid sample after a time duration using the logged pressure and volume data obtained during the time duration
52
Estimating the bubble pressure as the current fluid pressure if the calculated compressibility exceeds a reference threshold
40

FIG.4

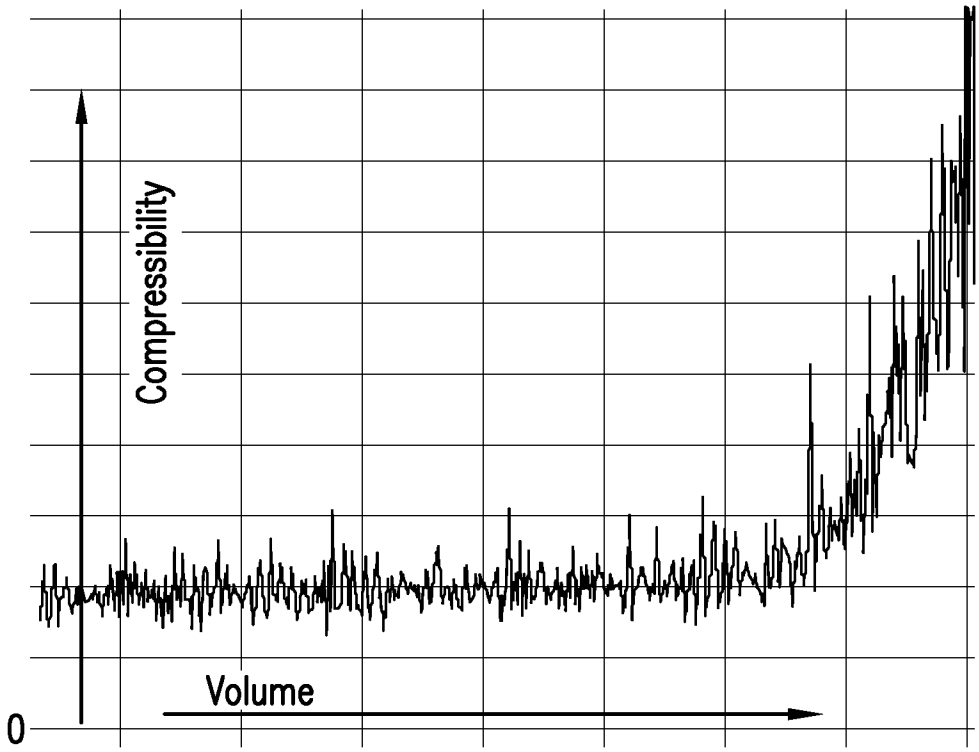


FIG.5

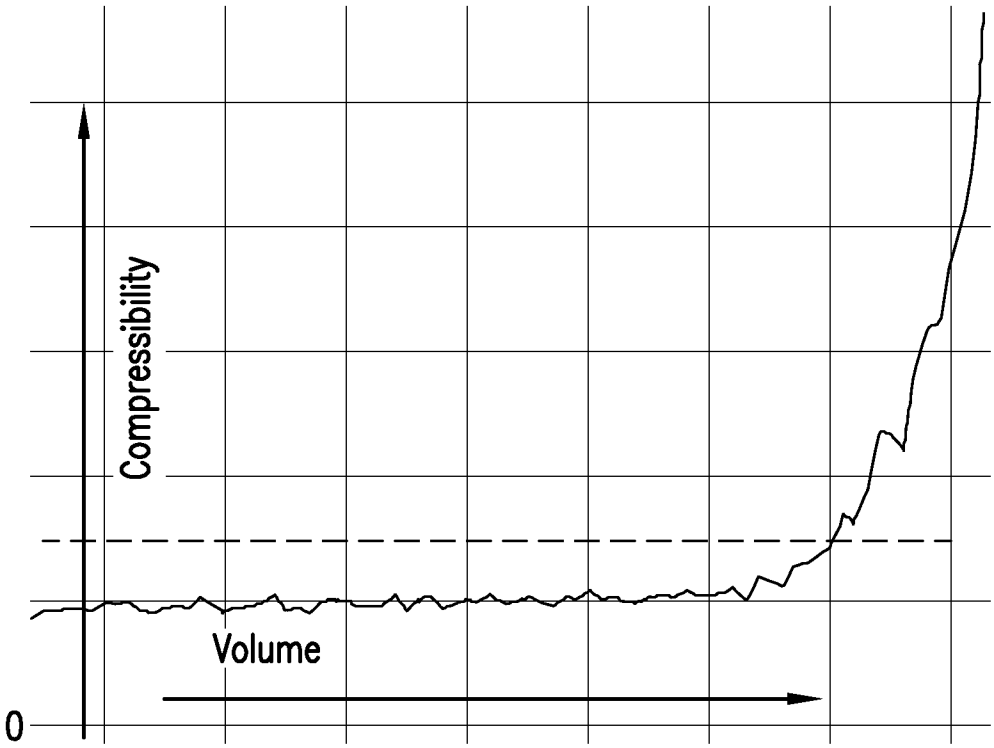


FIG.6

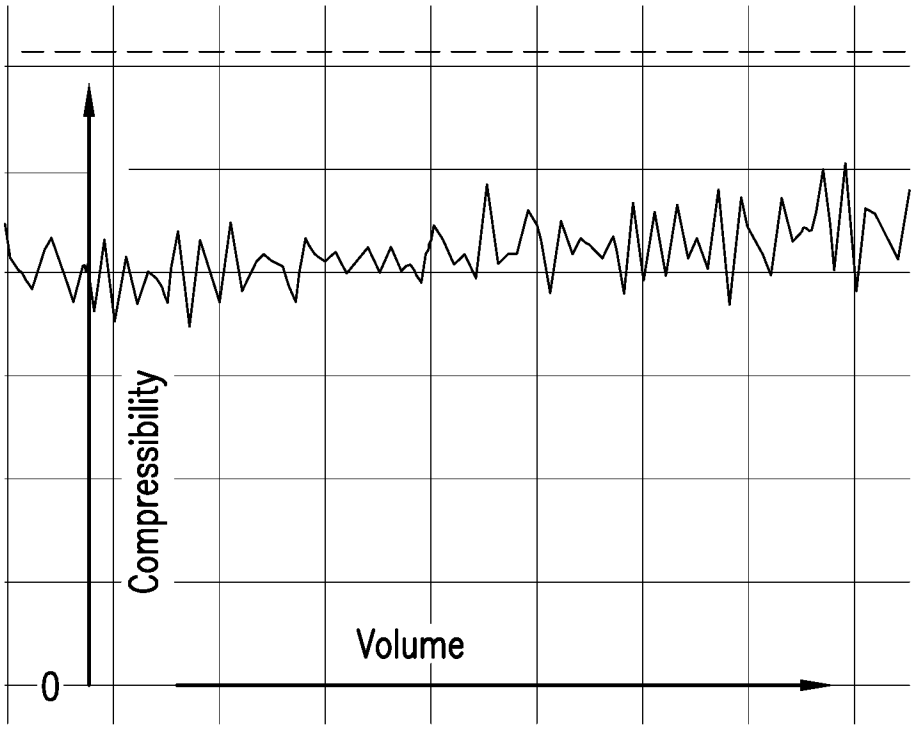


FIG.7

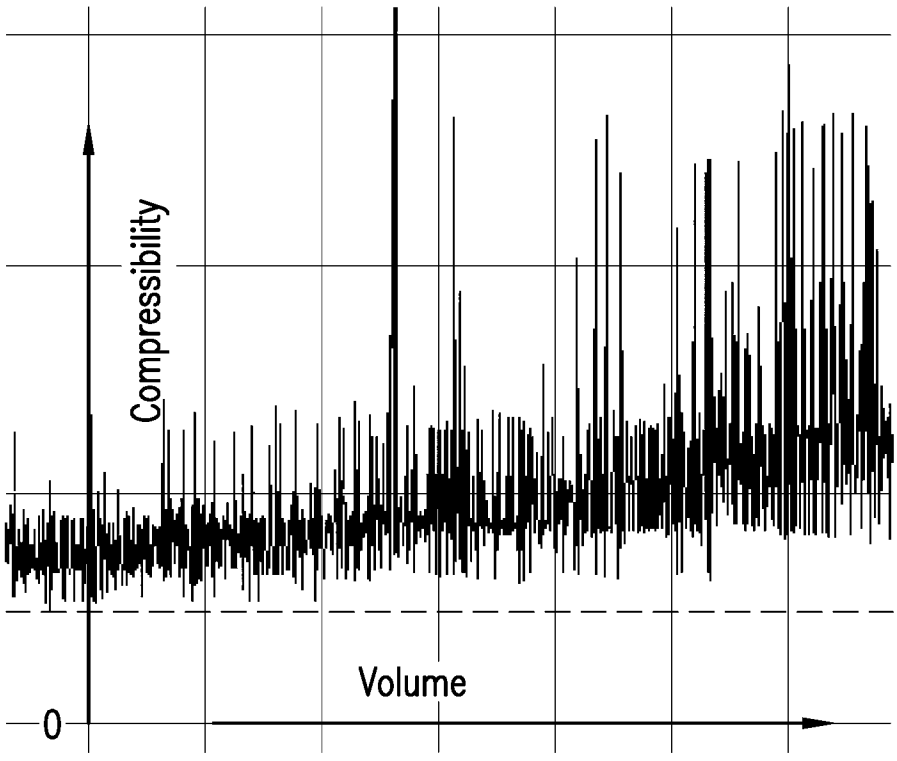


FIG.8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/067250

A. CLASSIFICATION OF SUBJECT MATTER

E21B 49/08(2006.01)i, E21B 49/10(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B 49/08; E21B 49/10; E21B 47/08; E21B 34/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: probe, pump, sensor, pressure, valve, compressibility and dew point

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010-0313647 A1 (TERABAYASHI et al.) 16 December 2010 See paragraphs [0037]-[0046],[0052]-[0073],[0090]-[0098]; figures 1,4-5.	1-24
A	US 7,665,354 B2 (SHAMMAI, MICHAEL) 23 February 2010 See column 5, line 14 - column 6, line 47; figure 5.	1-24
A	US 7,234,521 B2 (SHAMMAI et al.) 26 June 2007 See column 5, line 21 - column 7, line 46, column 18, lines 4-30; figure 13.	1-24
A	US 2009-0187346 A1 (LI, BAOYAN) 23 July 2009 See paragraphs [0007]-[0010]; figures 3-6.	1-24
A	US 2012-0018152 A1 (ZUILEKOM et al.) 26 January 2012 See paragraphs [0007]-[0012]; figures 3,6.	1-24

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

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 February 2014 (14.02.2014)	**17 February 2014 (17.02.2014)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2013/067250

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010-0313647 A1	16/12/2010	CA 2639577 A1	20/03/2009
		GB 0817272 D0	29/10/2008
		GB 2453051 A	25/03/2009
		GB 2453051 B	18/01/2012
		NO 20083975 A	23/03/2009
		US 2009-0078036 A1	26/03/2009
		US 7788972 B2	07/09/2010
		US 8256283 B2	04/09/2012
US 7665354 B2	23/02/2010	BR PI0410776 A	27/06/2006
		CN 1823210 A	23/08/2006
		EP 1629177 A1	01/03/2006
		EP 1629177 B1	18/04/2007
		NO 20055733 A	12/01/2006
		NO 20055733 D0	05/12/2005
		RU 2005139713 A	10/08/2006
		RU 2352776 C2	20/04/2009
		US 2004-0231408 A1	25/11/2004
		US 2007-0214877 A1	20/09/2007
		US 7222524 B2	29/05/2007
		WO 2004-104374 A1	02/12/2004
US 7234521 B2	26/06/2007	AU 2001-77087 A1	05/02/2002
		AU 2001-77087 B2	06/01/2005
		AU 2001-82928 A1	05/02/2002
		AU 2001-82928 B2	07/10/2004
		AU 2001-82928 C	05/02/2002
		AU 777211 C	07/09/2006
		BR PI0408193 A	04/04/2006
		CA 2385376 A1	31/01/2002
		CA 2385376 C	05/04/2005
		CA 2385385 A1	31/01/2002
		CA 2385385 C	10/10/2006
		CA 2556427 A1	01/09/2005
		CA 2556427 C	15/05/2012
		CN 1759229 A	12/04/2006
		CN 1759229 B	05/05/2010
		CN 1759229 C	05/05/2010
		EP 1301688 A1	16/04/2003
		EP 1381755 A2	21/01/2004
		EP 1381755 B1	26/12/2007
		EP 1601858 A2	07/12/2005
		EP 1623090 A1	08/02/2006
		EP 1623090 B1	13/06/2007
		EP 1676976 A1	05/07/2006
		EP 1676976 B1	19/11/2008
		EP 1716314 A1	02/11/2006
		EP 1716314 B1	16/01/2008
		GB 2370882 A	10/07/2002

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2013/067250

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
		GB 2373060 A	11/09/2002
		NO 20054033 A	06/10/2005
		NO 20054033 D0	31/08/2005
		RU 2005131170 A	10/09/2006
		RU 2349751 C2	20/03/2009
		US 2002-0060094 A1	23/05/2002
		US 2002-0112854 A1	22/08/2002
		US 2002-0185313 A1	12/12/2002
		US 2004-0026125 A1	12/02/2004
		US 2004-0055745 A1	25/03/2004
		US 2004-0099443 A1	27/05/2004
		US 2004-0119471 A1	24/06/2004
		US 2004-0231841 A1	25/11/2004
		US 2004-0231842 A1	25/11/2004
		US 2006-0192554 A1	31/08/2006
		US 2007-0182408 A1	09/08/2007
		US 6478096 B1	12/11/2002
		US 6568487 B2	27/05/2003
		US 6609568 B2	26/08/2003
		US 6640908 B2	04/11/2003
		US 6871713 B2	29/03/2005
		US 7011155 B2	14/03/2006
		US 7032661 B2	25/04/2006
		US 7126332 B2	24/10/2006
		US 7205762 B2	17/04/2007
		US 7368909 B2	06/05/2008
		US 7395703 B2	08/07/2008
		WO 02-08570 A1	31/01/2002
		WO 02-08571 A1	31/01/2002
		WO 2004-081344 A2	23/09/2004
		WO 2004-081344 A3	04/11/2004
		WO 2004-097176 A1	11/11/2004
		WO 2005-045474 A1	19/05/2005
		WO 2005-080752 A1	01/09/2005
US 2009-0187346 A1	23/07/2009	GB 201012801 D0	15/09/2010
		GB 2469597 A	20/10/2010
		GB 2469597 B	18/01/2012
		NO 20101040 A	24/09/2010
		US 7774141 B2	10/08/2010
		WO 2009-102526 A2	20/08/2009
		WO 2009-102526 A3	12/11/2009
US 2012-0018152 A1	26/01/2012	BR PI1005568 A2	02/04/2013
		MX 2011004746 A	23/01/2012