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A. J. DINGLEY

METHOD FOR DETERMINING THE APPROACH OF A COMBUSTION FRONT ADJACENT A PRODUCTION WELL

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PRODUCTION FACILITY

INVENTOR

ALAN J. DINGLEY

ATTORNEY
METHOD FOR DETERMINING THE APPROACH OF A COMBUSTION FRONT ADJACENT TO A PRODUCTION WELL

Alan J. Dingley, Calgary, Alberta, Canada, assignor to Mobil Oil Corporation, a corporation of New York

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ABSTRACT OF THE DISCLOSURE

A method to determine the approach of a combustion front through a formation to a point adjacent to a production well. The combustion front is advanced by passing an oxygen-containing gas into the formation from an injection well. Water and oil containing formation fluids enter the production well from the formation. At least two physical properties of the fluids which enter the production well are monitored. These properties relate to the water-to-oil ratio, the hydrogen ion concentration and the salinity of the water, and the specific gravity of oil, in the formation fluids. A signal indicating the close proximity of the combustion front to the production well is provided when the water or oil properties are reached at the same time in any of the two named physical properties of the formation fluids. If desired, upon occurrence of the signal, coolant may be introduced into the production well to prevent its thermal destruction by elevated temperatures from the combustion front.

BACKGROUND OF THE INVENTION

Field of the invention

This invention relates to the recovery of hydrocarbons from a subterranean formation by employing in situ combustion procedures. More particularly, it relates in such procedures to protecting production wells subject to thermal injury by the approach of a combustion front.

Description of the prior art

Thermal recovery techniques, in which hydrocarbons are produced from carbonaceous formations such as oil sands, tar sands, oil shales, and the like, by the application of heat thereto, are becoming increasingly prevalent in the oil industry. Perhaps the most widely used thermal recovery procedure involves in situ combustion or "fire flooding." In a typical fire flood, a combustion front is established in the formation and propagated therethrough by the injection of a combustion supporting gas through a suitable injection well. As the combustion supporting gas is injected, products of combustion, and other heated fluids in the stratum, are forced away from the injection well and toward a production well from which these fluids are removed to the earth's surface.

In fire flooding the failure of downhole well equipment results from the high temperatures which are sometimes reached in the production well. These high temperatures usually are caused by appearance of the combustion front in the production well. Obviously, high temperatures cause thermal deterioration or failure of the well equipment such as the liner, casing, or tubing string. In some instances, high temperatures could cause an explosion within the well.

In order to overcome the destructive effects of such high temperatures, a coolant such as water may be introduced into the production well in order to control downhole temperatures and maintain them at or below a preselected level. The indiscriminate and premature injection of coolant into the well has obvious disadvantages. Therefore, the coolant is introduced usually upon detection of undesirably high bottomhole temperatures. For this purpose, the temperature of the production effluent may be monitored at the wellhead, and water injected into the well when a significant product temperature rise is noted. Techniques such as these are not always as effective as might be desired. For example, a burn-through over a limited vertical section causes very localized high temperatures because of poor heat transfer conditions within the production well by reason of the predominantly gaseous nature of the formation fluids. A temperature measurement carried out in such production well can reveal a wellhead product temperature of about 275° F. At the same time, the bottomhole temperature at 1200 feet can be about 800° F. It has been proposed to position a temperature sensing element in the lower portion of the production tubing string to avoid this problem of high temperature gradients. However, the sensing element suffers early failure in this position by being exposed to the highly abrasive and corrosive action of the fluids within the tubing string.

There will obviously be occasions whenever the temperature rise will be so sudden within the production well that thermal injury can occur to the well equipment before sufficient coolant can be introduced into the well. Thus, effecting temperature control within a production well solely by monitoring the temperatures therein is not always entirely satisfactory.

There will be times during the life of an in situ combustion procedure when the leading edge of the combustion front in the formation approaches a production well. Then, unless remedial action is started promptly, the production well will undergo high temperature destruction of its downhole equipment. In many instances, continued production from this well is not planned. However, it is usually desired to keep the production well in good condition in order to use it as a future injector or as an observation well. Therefore, it is important to know the approach of the combustion front to a production well in conducting an in situ combustion procedure for recovering hydrocarbons from a subterranean formation.

SUMMARY OF THE INVENTION

In accordance with this invention, there is provided a method to determine the approach of a combustion front through a subterranean formation into a close proximity of a production well that coolant will be required therein to prevent its thermal destruction. The combustion front is advanced by injection of an oxygen-containing gas into the formation from an injection well. Water and oil containing formation fluids enter the production well from the formation. At least two physical properties of the formation fluids which enter the production well are monitored. These properties relate to the water-to-oil ratio, the hydrogen ion concentration and the salinity of water, and the specific gravity of liquid hydrocarbons in the formation fluids. A signal indicating the close proximity of the combustion front to the production well is provided when limiting or static values are reached at the same time in any of the named physical properties of the formation fluids entering the production well.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing, the figure is an illustration, partially in section, of a production well installation equipped with suitable apparatus for practicing the present method.

DESCRIPTION OF PREFERRED EMBODIMENTS

In the figure, there is shown a production well 11 extending from the earth's surface 12 into a subterranean carbonaceous formation 13. The formation 13 resides...
beneath an overburden 14 and an oil-barren stratum 15. The formation 13 may be of any geological origin wherein thermal recovery procedures, namely in situ combustion, are applied to recover the hydrocarbons. For example, the formation 13 may be heavy oil sands, tar sands, and like formations in which heat energy can be used for the recovery of hydrocarbons. The well 11 is completed with a casing 16 extending downwardly through the overburden 14 and stratum 15. The casing 16 is sealed at its lower end where it terminates in the formation 13. The casing 16 is sealed by cement sheath 17 to the overburden 14 and stratum 15. Perforations 18 within the casing 16 provide a fluid entry between the interior of the well 11 into the formation 13.

The formation 13 flow through the perforations 18 into the well 11. Then, these formation fluids are withdrawn with a tubing string 19 which passes upwardly from the well 11 through a wellhead 21. The formation fluids can be directed from the tubing string 19 to any surface-disposed facility for utilization.

A coolant usually is introduced into the well 11 to control and maintain downhole temperatures generated by the approach of a combustion front below determined levels. Any system may be employed for the introduction of coolant into the well 11. Usually, a coolant inlet 22 is connected to the casing 16. The coolant is passed through the inlet 22 and flows downwardly through the annulus 23 residing between the tubing string 19 and the casing 16. Thus, the coolant commingles with the formation fluids entering through the perforations 18 and the mixture flows upwardly in the tubing string 19 to the earth's surface 12. The coolant may be of any nature capable of reducing downhole temperatures in the well 11. However, if usual, will be water. The rate of coolant flow into the well 11 is generally controlled so that downhole temperatures are maintained below about 600° F. The coolant inlet 22 is connected to a source of coolant whose flow is regulated by motor valve 24. The motor valve 24 can be opened and closed with an operator 26 which is actuated by a controller 27. The controller 27 may take any form but usually will be an electrical circuit which is energized through conductors 28 and 29. For example, applying proper electrical signals to the conductors 28 and 29 causes the controller 27 to actuate the operator 26 which opens or closes the motor valve 24 in accordance with a preset mode of operation.

Generally, the operation of the motor valve 24 usually has been controlled through the use of a temperature-sensing element disposed within the well 11. In many instances, the combustion front approached the well 11 into a close proximity. Then, the combustion front underwent a sudden "breakthrough" into the well 11 so that a sudden rise in downhole temperatures occurred. In many instances, the temperature rise was so great that before adequate coolant could be introduced through the inlet 22, thermal injury or destruction occurred to the downhole equipment in the well 11. The described arrangement of the well 11, including the coolant system, is provided as an illustration. Many other types of well-completion procedures are known to those skilled in the art, and any of these may be employed with equal facility for the practice of the present method.

The undesired situation created by the combustion front approaching the well 11 is avoided in the following manner by the present invention. At least two physical properties of the formation fluids which enter the well 11 are monitored either continuously or on a periodic basis. These properties relate to the water-to-oil ratio, the hydrocarbon ion concentration, and the salinity of the water, and the specific gravity of the liquid hydrocarbons, in the formation fluids. Any suitable system may be employed for carrying out the monitoring of these properties.

One system for the monitoring of these physical properties is illustrated in the drawing. A sample line 31 is connected to the tubing string 19 to provide a sample of the produced formation fluids. Monitors are connected to the sample line 31 to provide a determination of the named physical properties of the formation fluids. For example, the following monitors may be connected by way of the sample line 31 to detect the monitored physical properties in the formation fluids. More particularly, a BS&W monitor 32, a pH monitor 33, an API gravity monitor 34, and a salinity monitor 36 may be connected to the sample line 31. Obviously, suitable sample line prolongers may also be included between the sample line 31 and these monitors to facilitate conducting the desired monitoring functions.

The BS&W (Basic Sediment and Water) monitor 32 may be of any form which is capable of measuring a property relating to the water-to-oil ratio of the formation fluids. Several commercial instruments are available to provide a direct reading of the water-to-oil ratio of a sample containing water and oil. Usually, a BS&W monitor is employed for the measurement of BS&W to determine whether the hydrocarbons recovered from the formation 13 are acceptable for shipment in a pipeline or for sale. The BS&W monitor 32 may determine the quantity of water present in the formation fluids by measurement between plates of a condenser of the fluid's dielectric constant. Since the dielectric constant is primarily related to water content without being seriously affected by the oil, very accurate results may be obtained. More particularly, when the BS&W monitor 32 may consist of a flow-through capacitance cell connected with the sample line 31. An electronic oscillator, a self-balancing bridge, and a recorder complete the system. Commercial BS&W monitors can provide a determination of the water content in the formation fluids to within 0.1 percent water content and also provide a corresponding millivolt output signal. Alternatively, the BS&W monitor 32 may operate on the differential in pressure which exists between a column of the formation fluids and a column of water-free formation fluids. Thus, the differential in pressure is directly related to the amount of water present. If desired, the BS&W monitor 32 may operate upon the light scattering principle. In this type of monitor, a strong light beam is passed through the formation fluids and a comparison is made between the scattered and transmitted light intensities. The light intensity comparison is directly related to the amount of water present in the formation fluids.

The pH monitor 33 may also be of any construction for obtaining a determination of a property relating to the hydrogen ion concentration of the water in the formation fluids. The monitored property usually is the water's pH. There are many monitors which are available commercially for carrying out a pH determination. Many of these monitors also provide a chart recording of the determined pH value. Several of the commercially available monitors employ standard potentiometric recorders to record automatically the determined pH value and provide correlated millivolt output signals for external use in maintaining a control over the pH of the fluids being monitored.

The API gravity monitor 34 may be of any suitable construction which provides a measurement relating to the specific gravity of the liquid hydrocarbons in the formation fluids. In connection with oil production, the oil's specific gravity is reported as the API gravity. Many monitors of this type are commercially available in which API gravity is determined to an accuracy of between 0.1° and 0.05°. These monitors are used in continuous and intermittent measurement of the API gravity of produced oil since the price of the oil usually depends upon its gravity. The API gravity monitor 34 may operate on the submerged float principle which provides a gravity determination by buoyancy of the formation fluids. If desired, the monitor may operate by the automatic weighing of a known volume of oil. In either mode of operation, the specific gravity or the API gravity is readily determined. These monitors usually are associated with positive dis-
placement meters in automated field production systems. If desired, the monitor 34 may be operated on a differential pressure-type system. Also, gamma ray sources and detectors may be employed to provide instantaneous readings of specific or API gravity of the formation fluids. In any event, where the API gravity is referred to, it will be understood that this is directly correlated to the specific gravity or density of the liquid hydrocarbons in the formation fluids.

The salinity monitor 36 may be of any form for determining a property relating to the salt content, namely sodium chloride, of the water in the formation fluids. Many commercial monitors are available for this determination. These monitors usually operate on the conductivity principle. For this purpose, a flow of electricity is passed through the water interposed between spaced metallic electrodes. The conductivity of the water depends upon the concentration and mobility of the ions of the salt which ions move toward the electrodes. Thus, the conductivity of the water is proportional to the concentration of the sodium chloride which is present in the water from the formation fluids. The salinity monitor 36 may take the form of an A-C Wheatstone bridge with platinitized electrodes normally used to determine the conductivity of aqueous solutions in a conductivity cell. The bridge is used with a voltage source, a null-balance indicator, a rebalancing potentiometer, and a recorder. This type of monitor provides a direct recording of the salinity of the water from the formation fluids and also a related millivolt output signal for controlling external devices. If desired, the salinity monitor 36 may be an A-C electrode dynanometer which measures the conductivity of aqueous solutions. This type of monitor uses crossed-coils as the sensing element in the water being tested. Alternatively, an ohmmeter circuit may also be used for this measurement, if desired. In any of these instruments, the salinity can be obtained from standard charts once the conductivity is known for a water-salt solution. For example, the conductivity (specific) varies from about zero to about 2400 ohms for a salt content (sodium chloride) varying from 0 to 26 weight percent at 25° centigrade.

Although the several monitors may be employed using visual readouts which an operator may watch, it is preferred that they be arranged for automatic operation in accordance with the present invention. For this purpose, the monitors 32, 33, 34 and 36 are provided with differentiators, respectively, and the differentiator is arranged to accept, from its respective monitor, an output signal correlated to the measurement of the determined physical condition. When the output of the monitor indicates that the detected physical condition has reached a static or limiting value, the differentiator provides an output signal or control function. These differentiators may be simple capacitor-resistor networks which have suitable time constants to pass only amplitude-varying signals of a certain duration indicative of a limiting or static value of the measured physical condition. The output signal of the differentiators may be employed to activate a switch for use of relay means.

More particularly as an example, the differentiator 37 receives the output signal of the BS&W monitor 32. Upon the water-to-oil ratio of the formation fluids in the sample line 31 reaching a limiting or static value, a switch 42 is closed. Similarly, the differentiator 38 receives the output signal from the pH monitor 33. Upon the pH of the water in the formation fluids in the sample line 31 reaching a static or limiting value, a switch 43 is closed. The switches 42 and 43 are connected in series in a circuit with a source of electrical power such as an alternator 44. Such a circuit provides a signal light 48, a bell alarm 47, and a signal actuating relay 48. Thus, upon the water-to-oil ratio, and the pH of the water, in the formation fluids reaching limiting values at the same time, the switches 42 and 43 close to provide a visual indication by the signal light 48, an audible indication by the bell 47. Simultaneously, an electrical signal is obtained from the relay 43 to actuating switch contacts 49, and thereby to establish an external control circuit through conductors 51 and 52. The conductors 51 and 52 may be interconnected to a control circuit 53 and a controller 27. Thus, the signal provided in the circuit associated with switches 42 and 43 actuates the control circuit of the controller 27 through the contacts 49 of the relay 48. The motor valve 24 then is operated through functioning of the operator 26 by the controller 27. Thus, a signal may be introduced automatically into the well 11 upon limiting or static values being obtained at the same time in the water-to-oil ratio, and the pH or hydrogen ion concentration in the water, of the formation fluids in the sample line 31.

If desired, the same arrangement of circuitry may be employed using the API gravity monitor 34 and the salinity monitor 36. Additionally, a combination of any two monitors may be employed in the same manner as the monitors 32 and 33. Preferably, the BS&W monitor 32 will always be one of these monitors since it is usually necessary to determine the amount of water present in the formation fluids being sent to a surface facility for utilization.

The determination of combustion front arrival adjacent the well 11 by the aforesaid steps of the present method are believed to reside for operability in the following relationship associated with in situ combustion procedures. The movement of a combustion front through the formation 13 results in the creation of several distinctive zones which move successively to the well 11. The combustion front traversing the formation 13 produces a burned zone which is hot and completely void of liquids. The combustion front is at a temperature generally greater than about 700° F, so that downstream formation fluids are almost completely vaporized to leave behind only a residue of coke. This coke provides the fuel for moving the combustion front through the burned zone.

There is complete miscibility between the injected oxidant or air and the vaporized formation fluids immediately downstream of the combustion front. Thus, nearly 100 percent displacement efficiency of formation fluids occurs in the formation 13 swept by the combustion front. Heat is transmitted downstream of the combustion front by conduction through the solid matrix of the formation 13, and also by convection of the displaced combustion gases, vaporized oil and steam.

Downstream of the heat front a water-saturation front is a region where the temperature has decreased to about 200–400° F. A steam flood zone is formed in this region, where steam displacement of fluids through the formation 13 occurs. Downstream of the steam flood zone, hydrocarbons and steam condense and thereby produce a hot-waterflood zone which includes a liquid bank of light hydrocarbons. Downstream of the hot-waterflood zone, a cold waterfront occurs upon a suitable reduction in temperature, and in this zone is formed an oil bank. The oil bank contains the oil in-place and also that oil displaced from all the zones.

The arrival of the cold waterfront zone at the well 11 results in increased hydrocarbon or oil production due to the increased oil saturation from the oil bank carried with this zone. However, as the hot waterflood zone and the steamflood zone reach the well 11, the water-to-oil ratio increases. This is the result obtained by the higher water saturation existing in the hot waterflood and steamflood zones.

After these zones, the burned zone with the combustion front at its leading edge reaches the well 11 and thermal destruction of unprotected well equipment will quickly occur.

The relative amounts of oil and water, and their nature, in the formation fluids which enter the well 11 are dependent upon the three-phase relative permeability relationship, fluid viscosities, and fluid saturation distributions, all of which conditions are functions of temperatures.
Generally, the data to define these functions are not available. However, in accordance with the present method, knowledge of these particular functions is not essential. The parameter of greatest interest is the water-to-oil ratio of the formation fluids which move into the well immediately ahead of the combustion front. If sufficient data were available, the water-to-oil ratio of the formation fluids would give notice of the combustion front arrival at the well. An estimate of the displaced water-to-oil ratio of these formation fluids (which occurs just before breakthrough of the combustion front into the well) can be made by considering their relative displacement rates before the burned zone. The water includes both the connate water of the formation, and the water formed chemically by the in situ combustion process. The displaced water-to-oil ratio, WOR, is given by:

\[
\text{WOR} = \frac{18(W_0)}{\left(\frac{S_a}{B_o} - \frac{S_i}{B_i}\right)} \left(1 - \frac{(CO + CO_2)(H/12)}{7758 \phi}ight)
\]

in which
- \(\phi\) = fractional formation porosity
- \(S_a\) = fractional formation water saturation in the steamflood zone
- \(B_o\) = formation-water, formation-volume factor, RB/STB
- \(W_o\) = moles of water of combustion formed per mole of combustion gas generated
- \(S_i\) = fluid deposit, STB/acre-ft.
- \(CO\) = moles of carbon dioxide formed per mole of combustion gas generated
- \(CO_2\) = moles of carbon monoxide formed per mole of combustion gas generated
- \(H/12\) = atomic hydrogen to carbon ratio in the fuel consumed
- \(S_o\) = fractional oil saturation in the steamflood zone
- \(B_i\) = oil formation volume factor, RB/STB
- \(RB\) = reservoir barrels
- \(STB\) = stock tank barrels

The above equation defines the displaced water-to-oil ratio in the formation fluids which enter the well immediately before the breakthrough of the combustion front. Additionally, this same water-to-oil ratio could be observed shortly after the arrival of the hot water flood zone at the well. Then, the time of arrival of the combustion front at the well can be estimated from the volumetric rate of advance of the combustion front, and the knowledge of the relative fluid volumes of the burned zone and combined steam and hot water flood zones. Whatever the exact numerical value of this displaced water-to-oil ratio, the water-to-oil ratio should gradually increase to a limiting value closely approaching the numerical value immediately before the combustion front breaks through into the well.

Thus, the salinity of the water contained in the formation fluids entering the well will decrease to a static or limiting value when the hot water flood zone arrives at the well. If both the water-to-oil ratio, and the salinity of the water, in the formation fluids reach their static or limiting values at the same time, the combustion front can be expected shortly thereafter to break through into the well.

The pH, or hydrogen ion concentration, of the produced water in the formation fluids is also used to determine the approach of the combustion front to the well. More particularly, the pH of formation fluids entering the well should gradually decrease until a static value is reached. This behavior is due to the fact that large quantities of combustion gases have passed through this water and it becomes saturated with the dioxides of carbon and sulfur. As a result, the pH of the water in the formation fluids is estimated to decrease ultimately to a value of about 4. When the pH of the produced water in the formation fluids has reached a static or limiting value, and this event occurs at a time when the water-to-oil ratio also reaches its limiting value, then the combustion front is about to break through into the well.

The gravity of the produced liquid hydrocarbons, or oil, also may be employed for determining the approach of the combustion front to the well. The removal of heavy ends of the hydrocarbons as coke for fuel, from the formation fluids, causes the liquid hydrocarbons in the hot water flood zone to become richer in light hydrocarbon fractions than the original oil in-place. Thus, a trend to a higher API gravity (lower specific gravity) of the produced oil can be expected during the movement of this zone to the well just before arrival thereat of the combustion front. Thus, whenever the API gravity of the produced liquid hydrocarbons has reached a high API gravity of a static or limited value, at a time when the water-to-oil ratio has also reached its static or limiting value, then the combustion front has approached into close proximity to the well.

In summary, the combustion front traversing the formation can be detected in its approach into a close proximity to the well by the steps of the present method. At this time, remedial steps, through the introduction of coolant into the well, can be taken to prevent thermal destruction of the downhole well equipment by break-through of the combustion front into the well. The detection of approach to the combustion front is obtained whenever at least two physical properties related to the water-to-oil ratio, the hydrocarbon ion concentration and salinity of water, and the specific gravity of the liquid hydrocarbons, in the formation fluids have reached limiting values at the same time. By correlation of the limiting values of at least two physical properties of the formation fluids, the approach of the combustion front to the well may be readily determined without undertaking to collect sufficient data to make detailed calculations of the relative displacement fluid volumes in the various zones moving through the formation, the rate of combustion front advance, and the time of its arrival at the well.

From the foregoing it will be apparent that there has been provided a method well suited for determining the approach of a combustion front into close proximity to a production well. Additionally, this method provides steps for protecting such production well by the introduction of coolant whenever the combustion front has arrived adjacent the production well. It will be apparent that various changes may be made by those skilled in the art to the steps of the present method without departing from the spirit of this invention. It is intended that such changes and alterations be included within the scope of the appended claims.

What is claimed is:

1. A method to determine the approach of a combustion front through a subterranean carbonaceous formation into a close proximity of a production well that a
9 coolant will be required therein to prevent thermal injury thereto, where in said method, said combustion front is advanced by injection of an oxygen-containing gas into said formation from an injection well, and water- and oil-containing formation fluids enter said production well from said formation, comprising the steps of:

(a) monitoring the water-to-oil ratio of the formation fluids which enter said production well;

(b) monitoring at least one or other physical properties of the formation fluids which enter said production well, said properties relate to the hydrogen ion concentration and the salinity of water, and the gravity of liquid hydrocarbons, in said formation fluids; and

(c) providing a signal representing the close proximity of said combustion front to said production well when the water-to-oil ratio has reached a static value at a time when a static value has also been reached in any one of the other monitored physical properties of said formation fluids.

5. The method of claim 4 wherein said signal initiates the introduction of coolant into said production well.

6. The method of claim 4 wherein said signal initiates the introduction of coolant into said production well.

7. The method of claim 6 wherein the coolant is water.

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STEPHEN J. NOVOSAD, Primary Examiner
U.S. Cl. X.R.

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