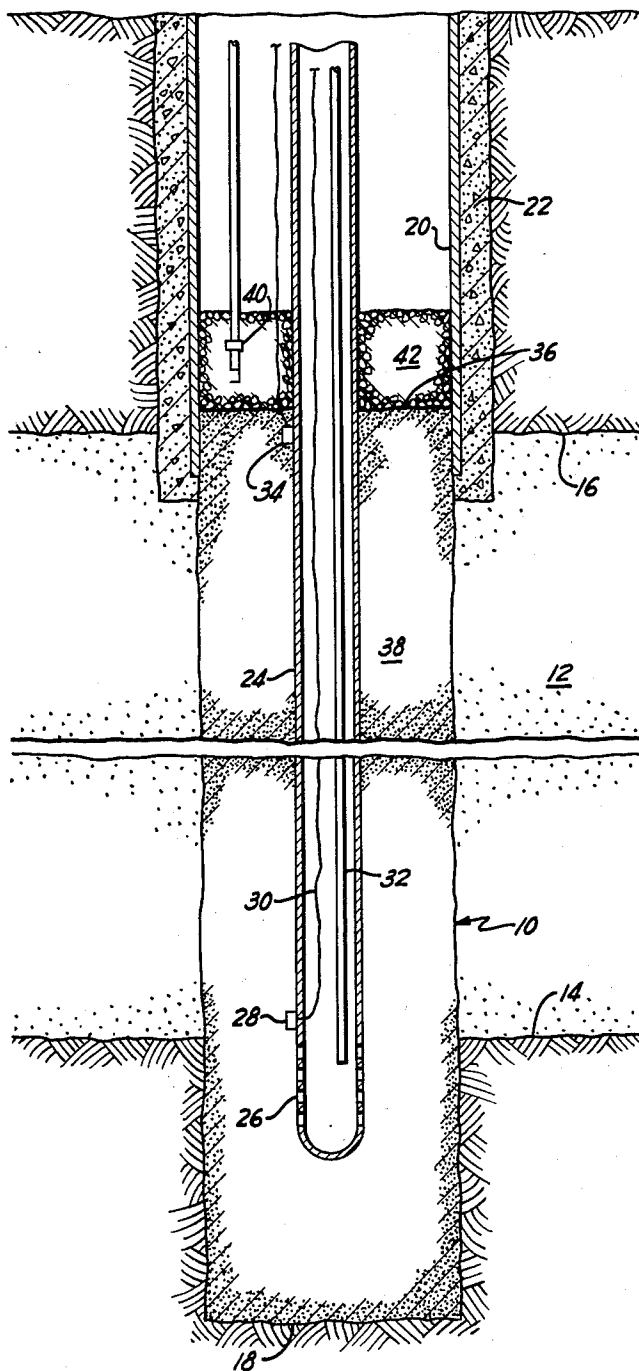


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THE BOREHOLE OF A WELL
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METHOD OF HEATING UNDERGROUND FORMATIONS AROUND THE BOREHOLE OF A WELL

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This invention relates to a method of heating a well bore and is particularly useful in uniformly heating the formation around the borehole of a well to consolidate loose and unconsolidated formations, dehydrate clays and sands or initiate in-situ combustion in a formation penetrated by the borehole of a well.

It is frequently desirable to consolidate sands around the borehole of a well to prevent sand migration into the well. One method of consolidating the sands is by heating the sands which cokes oil in place in the sands to form a bond between sand particles to form a structure of increased stability around the borehole of the well. If clays are present in the formation, it is desirable to heat them to a temperature sufficiently high to cause an irreversible dehydration of the clays which will prevent the clays swelling if they should subsequently be contacted with water.

One method that has been suggested for well bore heating is to use an electric heater. If the interval which is to be heated is large, a heater extending through the full interval is very expensive. Additional expense is incurred as a result of the heavy lead lines and connections required to support the heater in the borehole and supply electric current to it. Another method of heating a borehole that has been suggested is to pack the borehole with a solid fuel or with a solid fuel mixed with a granular refractory material and then introduce an oxygen-containing gas to burn the solid fuel in place in the borehole. This process has the disadvantage that the amount of heat available for heating the formation is limited by the amount of fuel that is originally packed in the borehole.

It has also been suggested to inject a gaseous fuel and air into a well and burn the fuel at gas burners supported in the borehole adjacent the formation to be heated. The gas burners cause uneven heating and often cause heating to excessive temperatures which may cause sloughing of the borehole wall.

This invention resides in a method of heating the borehole of a well in which the borehole is packed with a refractory material such as sand through the interval of the borehole to be heated and a fuel-air mixture is injected into the sand near one end of that interval. The fuel-air mixture is ignited at the opposite end of the interval to be heated and the fuel burned in the borehole by a reverse combustion process in which the combustion front moves from the point of ignition towards the point of injection of the fuel-air mixture into the sand pack. The characteristics of the fuel-air mixture are controlled to control the rate of movement of the combustion front. When the combustion front nears the point of injection of the fuel-air mixture into the sand pack, the direction of burning may be reversed to cause the combustion front to move in the opposite direction. Any desired number of reversals of the direction of burning can be used to supply the desired quantity of heat to the formation surrounding the borehole.

The single FIGURE of the drawings is a diagrammatic illustration, partially in vertical section, of apparatus in the lower end of a borehole for heating a formation in accordance with the process of this invention. In the embodiment illustrated, an open borehole extends through the formation to be heated.

By this invention the formation adjacent the borehole

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of a well can be uniformly heated to the desired temperature and the amount of heat transferred to the formation surrounding the borehole can be controlled to cause heating of the formation for the desired radial distance around the borehole. The combustion of the fuel in the process of this invention is designated as reverse combustion. By that term is meant combustion in which the direction of movement of the combustion front through a permeable medium is opposite the direction of movement of the fuel-air mixture and the products of combustion.

Referring to the drawing, a borehole indicated generally by reference numeral 10 is drilled through a pay zone 12 which lies between a basement rock 14 and cap rock 16. The borehole 10 extends to a total depth 18 in the basement rock 14. In the embodiment illustrated in the drawing, casing 20 is set for a short distance into the pay zone 12 and is cemented in place by conventional techniques forming a cement sheath 22 around the casing.

A tubing string 24 is suspended in the borehole and provided with a suitable screen 26 at its lower end at the bottom of the pay zone 12. Tubing 24 extends upwardly to the well head, not shown, and is connected there with an air supply line, also not shown. Secured to the lower end of the tubing 24 adjacent screen 26 is a thermocouple 28 connected to suitable electric leads 30 which extend to the well head for connection to a device for indicating the temperature of the thermocouple. A fuel supply line 32 is run through the tubing and opens at its lower end adjacent the screen 26. The fuel supply line 32 is connected at the well head with a source of fuel. An upper thermocouple 34 is mounted on the side of tubing 24 at approximately the level of the bottom of the cap rock 16. Conventional well head closures and connections to the tubing, fuel lines, electrical leads, etc. are used but are not shown in the drawings because they are not critical to this invention and their omission allows the use of a larger scale in illustrating the apparatus at the lower part of the borehole.

The borehole 10 is then filled with sand from its bottom to a level 36 preferably slightly above the bottom of the cap rock 16 to form a permeable sand pack 38 in the annular space in the borehole around the tubing 24. The size of the sand particles will influence the rate at which the combustion rate can be made to move through the sand pack. It is preferred to use 4 to 8 mesh sand in packing the borehole. An igniter 40 is then run into the borehole to a position slightly above the upper level 36 of the sand pack 38. It is preferred to form a layer of gravel, for example of about 1/4 inch mesh, on the top of the sand pack to prevent the sand from being entrained by gases discharged from the sand pack. In the drawings, a layer of gravel 42 is shown on the upper surface of the sand pack 38. The layer of gravel extends to a position above the igniter 40.

Heating the formation around the borehole is accomplished in this invention by injecting fuel through fuel supply line 32 and air through the annular space between the tubing 24 and fuel supply line 32, through screen 26 and into the lower end of the sand pack 38. The ratio of flow of the fuel and air are controlled to avoid an excess of fuel which would cause formation of carbon particles which might plug the formation. A fuel-air ratio only slightly less than the stoichiometric ratio is ordinarily preferred, but any ratio above about 35% of the stoichiometric ratio is adequate to maintain reverse burning. Hydrocarbon gaseous fuels such as natural gas and lease gas, bottled gases such as propane and butane and the slightly less volatile hydrocarbons such as pentane and hexane are preferred. The hydrocarbon fuels gaseous at the conditions in the borehole have the advantage of mixing readily with the air to form combustible mixtures and not forming coke deposits in the sand pack 38. The mixture

of fuel and air moves upwardly through the sand pack 38 and is ignited by igniter 40 in the gravel layer 42 resting on the upper surface of the sand pack. Once the combustion is started and the gravel layer 42 and upper portion of the sand pack 38 are heated, the combustion front moves downwardly by reverse combustion through the sand pack toward the perforations 26. Thermocouple 28 will indicate when the combustion front approaches it. If a single pass of the combustion front through the sand pack is sufficient to heat the formation to the desired temperature, the injection of fuel through feed line 32 and air through the tubing 24 is stopped.

Ordinarily, more than one pass of the combustion front through the sand pack is required to heat the formation to the desired temperature. The combustion front is then made to travel upwardly through the sand pack by reducing the fuel to air ratio to a range which causes the combustion in the sand pack to be converted to forward burning. A fuel-air ratio below about 25% of the stoichiometric ratio will cause forward burning. The forward burning is continued until the combustion front reaches the vicinity of the upper thermocouple 34.

The process of reversing the direction of burning can be repeated as often as desirable to accomplish the desired consolidation and dehydration of the formation surrounding the borehole. During the burning, the combustion products flow through the casing 20 to the well head and are discharged. It is desirable to inject water through the annulus between tubing 24 and fuel supply line 32 during the well bore heating process to prevent those gases being heated to a temperature at which they will ignite as they mix adjacent screen 26.

An alternative procedure for reversing the direction of movement of the combustion front in the sand pack is to run a second string of air supply tubing and a second fuel supply line to open into the top of the sand pack. When the combustion front reaches the vicinity of the thermocouple 28, the flow of air and gas through lines 24 and 32, respectively, is stopped and the fuel and air injected through the second tubing and supply line into the top of the sand pack. The fuel-air mixture is forced downwardly through the sand pack where it is ignited as it reaches the vicinity of the combustion front. Products of combustion are discharged through line 24. If this alternative arrangement is employed to reverse the direction of burning, a stream of air flowing downwardly through the annulus into the gravel layer 42 should be maintained at all times during the upward burning to avoid the formation of an explosive mixture in the well above the gravel layer.

A temperature of at least about 800° F. is desired to cause hydrocarbons in the formation to coke in a reasonable time. With some oils, a temperature as low as 500° F. may be sufficient to cause coking but a longer period will be required for coking at that temperature. In order to accomplish the desired coking of oil in the formation for a sufficient radial distance into the formation to provide effective consolidation within a reasonable time, it is desired to control the temperature at the combustion front in the sand pack in the range of about 1000° to 1600° F. Temperatures in the upper part of the range, for example 1400° to 1600° F. are preferred to speed the rate of heat transfer to the surrounding formation. However, temperatures above about 1600° F. are to be avoided to avoid damage to the equipment. If a temperature of 1700° F. is attained for an extended period, steel equipment in the borehole usually is damaged. The time required for the consolidation will depend greatly upon the maximum temperature reached in the sand pack. If a temperature of 1100° F. is maintained for a 24 hour heating period, a surrounding coke thickness of three inches can be obtained. The loss of heat from the formation around the borehole is slow and if the formation is heated to a temperature above the incipient coking temperature, coking will continue after the supply of heat is cut off.

The selection of the fuel used provides a method of controlling the temperature reached in the sand pack. If methane is used as the fuel, a temperature of at least about 1500° F. is required to ignite it. Heavier hydrocarbons are ignited at lower temperatures. For example, pentane will ignite at a temperature of about 900° F. Control of the pressure on the well bore also provides a method of controlling the temperature attained. It is desirable to maintain a rate of advance of the combustion front of about ½ to 1 foot per hour. This rate can be obtained by supplying heat at a rate of about 70,000 B.t.u.'s per hour.

The process of this invention has been described for consolidating the formation around an open borehole. It can also be used to consolidate the formation around a cased hole. When heating an interval of a cased hole, the heating can be accomplished either before or after the casing has been perforated. After consolidation of the formation has been completed, the sand pack can be removed from the borehole by circulating air at a high rate through the tubing to entrain the sand upwardly to the well head through the annulus between the casing and tubing.

In an example of the process of this invention, a borehole is drilled to a total depth of 3790 feet. The formation to be heated occupies the interval of 3760 to 3780 feet. Casing is set to the total depth of the borehole. A 1½ inch air supply line having its lower end closed and provided at its lower end with 32¼" x 2" slots in four rows is suspended in the borehole with its lower end just off bottom. The borehole is then packed with 4 to 8 mesh sand through the interval occupied by the pay zone to be heated. A ¼" fuel line is run through the tubing and opens at its lower end adjacent the slots in the lower end of the tubing. Hexane is injected through the fuel line at a rate of one gallon per hour and air is injected through the annular space in the tubing surrounding the fuel line at a rate stoichiometrically equivalent to the hexane. The mixture of hexane and air travels upwardly through the sand pack and is ignited by an electric igniter. Water is injected with the hexane at a rate of 0.2 to 1.0 gallon per hour. A temperature is attained at the combustion front in the range of 1400° to 1600° F., as measured by thermocouples spaced along the wall of the tubing. The rate of movement of the combustion front varied in the range of ½ to 1 foot per hour, as indicated by thermocouples positioned in the sand pack.

An important advantage of the process of this invention is the absence of any limit on the amount of heat that can be transferred to the formation surrounding the borehole. The combustion front can be made to pass back and forth through the sand pack any desired number of times until the desired temperature of the surrounding formation has been attained.

I claim:

1. A method of heating a well bore and an underground formation surrounding the well bore comprising packing the well bore adjacent said underground formation with particles of a solid refractory material to form a permeable mass in the well bore, introducing a gaseous fuel-air mixture having a fuel to air ratio between about 35 and 100 percent of the stoichiometric ratio into the permeable mass at one area, withdrawing gaseous products from the permeable mass at an area spaced from the area of introduction of the mixture into the permeable mass, igniting the fuel-air mixture in the well bore at an area spaced from the area of introduction of the mixture into the permeable mass and between the area of introducing the fuel-air mixture and the area of withdrawal of the gaseous products, continuing the introduction of the fuel-air mixture and burning the fuel in the permeable mass to cause the combustion front to move by reverse combustion to the area of introduc-

tion of the fuel-air mixture from the area of ignition of the fuel-air mixture.

2. A process as set forth in claim 1 in which the fuel is a hydrocarbon which is gaseous at the conditions of temperature and partial pressure in the fuel-air mixture injected into the permeable mass.

3. A process as set forth in claim 1 in which the concentration of the fuel in the fuel-air mixture is controlled to produce a temperature in the range of 1000° to 1600° F. at the combustion front.

4. A process as set forth in claim 1 in which a diluent is introduced into the fuel-air mixture to control the temperature at the combustion front in the range of 1000° to 1600° F.

5. A process as set forth in claim 1 in which water is added to the fuel-air mixture to control the temperature at the combustion front in the range of 1000° to 1600° F.

6. A process for heating the borehole of a well and a subsurface formation surrounding the well comprising packing the borehole adjacent said subsurface formation with particles of a solid refractory material to form a permeable mass in the borehole, injecting a gaseous fuel-air mixture into the permeable mass at one area and displacing the fuel-air mixture through the permeable mass, the fuel to air ratio in said mixture being between about 35 and 100 percent of the stoichiometric ratio, igniting the fuel-air mixture at an area downstream from the area of injection of the fuel-air mixture and remote therefrom, continuing the injection of the fuel-air mixture to cause reverse combustion to proceed from the point of ignition toward the point of injection of the fuel-air mixture, and then reducing the fuel to air ratio of the mixture to less than about 25 percent of the stoichiometric ratio whereby the direction of movement of the combustion front is reversed.

7. A process for heating an interval of the borehole of a well comprising packing the interval of the borehole with particles of a solid refractory material to form a permeable mass in the borehole, introducing a fuel-air mixture into the permeable mass adjacent the lower end of the interval of the borehole to be heated, the fuel being a hydrocarbon gaseous at the temperature and partial pressure in the fuel-air mixture introduced into the permeable mass and the fuel to air ratio of the mixture being between about 35 and 100 percent of the stoichiometric ratio, igniting the fuel-air mixture in the permeable mass adjacent the upper end of the interval to be heated, continuing the introduction of the fuel-air mixture into the permeable mass to cause reverse combustion to proceed from the point of ignition to adjacent the point of injection and discharging products of combustion from the upper end of the permeable mass, discontinuing the introduction of said mixture into the lower end of the borehole, then introducing a gaseous fuel-air mixture having a fuel to air ratio between about 35 and 100 percent of the stoichiometric ratio, into the permeable mass at the upper end of the interval to be heated, igniting the fuel-air mixture in the permeable mass adjacent the lower end of the interval to be heated, continuing injection of the fuel-air mixture into the upper end of the permeable mass to cause reverse combustion to proceed from the lower end of the interval to be heated towards the upper end, and withdrawing products of combustion from the lower end of the permeable mass.

8. A method of heating a well bore, and a subsurface formation surrounding the well comprising packing the well bore adjacent said subsurface formation with finely

divided particles of a solid refractory material to form a permeable mass in the well bore, introducing a gaseous fuel-air mixture into the permeable mass at one area, said mixture having a fuel to air ratio between about 35 and 100 percent of the stoichiometric ratio, igniting the fuel-air mixture in the well bore at an area spaced from the area of introduction of the mixture into the permeable mass, continuing the introduction of the fuel-air mixture, burning the fuel in the permeable mass to cause the combustion front to move by reverse combustion from the area of introduction to the area of ignition of the fuel-air mixture, discontinuing the introduction of the fuel-air mixture and then injecting a gas into the lower end of the permeable mass at a high velocity to remove the refractory material from the borehole.

9. A process as set forth in claim 1 in which the refractory material is sand in which the size of the particles is principally in the range of 4 to 8 mesh.

10. A method of heating a well bore, and a subsurface formation surrounding the well comprising packing the well bore adjacent said subsurface formation with solid refractory particles to form a permeable mass in the well bore, introducing a gaseous hydrocarbon fuel-air mixture in which the fuel to air ratio is in excess of about 35 percent of the stoichiometric fuel to air ratio but less than the stoichiometric fuel to air ratio into the permeable mass at one area, igniting the fuel-air mixture in the permeable mass at an area spaced from the area of injection of the fuel-air mixture, reverse burning the mixture whereby the combustion front moves through the permeable mass towards the area of injection of the fuel-air mixture, and then reducing the fuel-air ratio to less than 25 percent of the stoichiometric fuel to air ratio to cause the combustion front to move towards the area of ignition of the fuel-air mixture.

11. A method of heating a formation surrounding the borehole of a well to stabilize the formation comprising packing the borehole with finely divided solid refractory particles to form a permeable mass extending through the borehole for the interval adjacent the formation to be stabilized, introducing a gaseous hydrocarbon fuel-air mixture into the lower end of the permeable mass and displacing the mixture upwardly through the permeable mass, the fuel to air ratio in said mixture being between about 35 and 100 percent of the stoichiometric fuel to air ratio igniting the fuel-air mixture at the upper end of the permeable mass, continuing the injection of the fuel-air mixture into the lower end of the permeable mass whereby the combustion front moves from the upper end of the permeable mass to the lower end thereof; injecting a diluent into the fuel-air mixture and controlling the fuel-air ratio at a level between about 35 and 100 percent of the stoichiometric ratio to control the temperature of the combustion front within the range of about 1000° to 1600° F. whereby the formation surrounding the borehole is heated to a temperature at which the formation is stabilized.

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