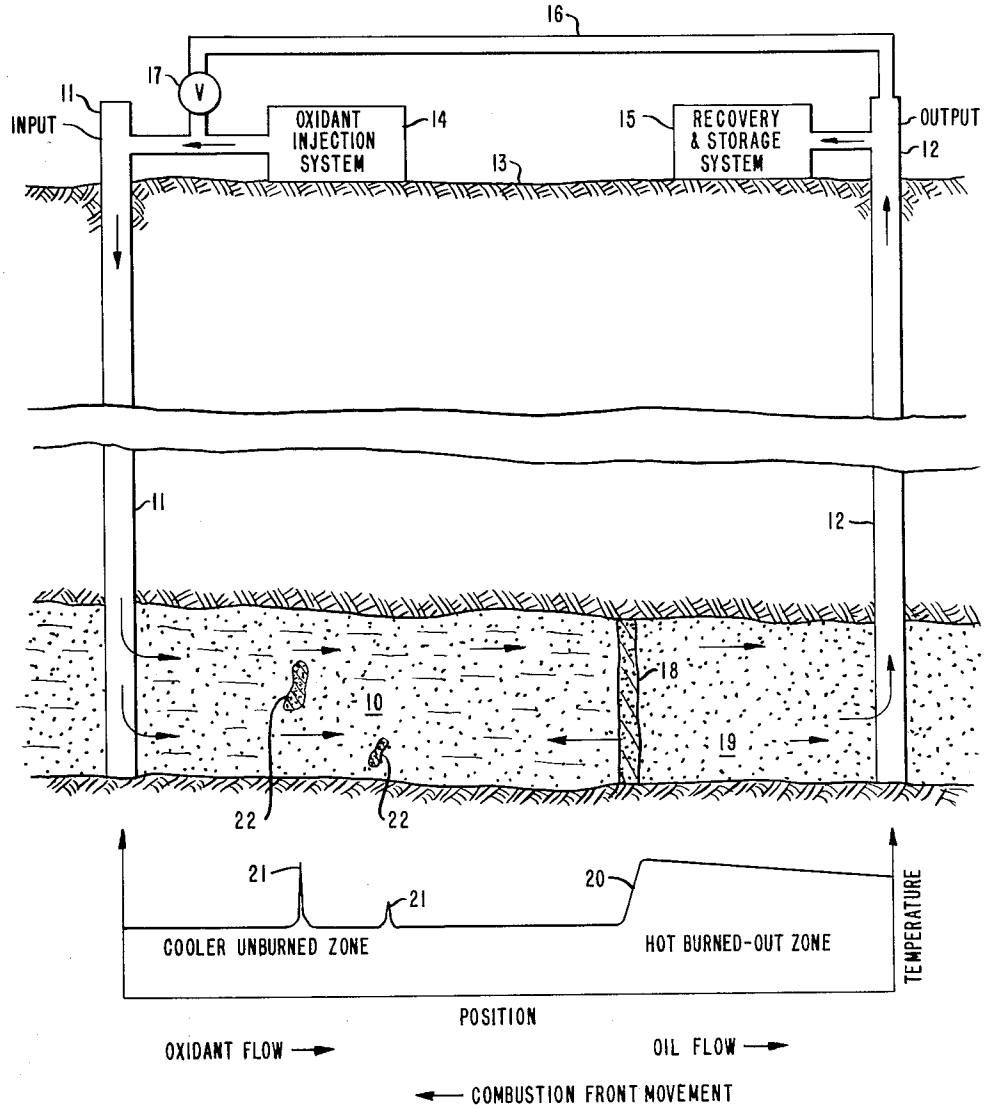
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UNDERGROUND COMBUSTION CONTROL

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UNDERGROUND COMBUSTION CONTROL

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2 Claims. (Cl. 166—11)

This application is a division of my earlier application entitled "Underground Combustion Control," Serial No. 275,515, filed April 25, 1963.

The present invention relates to the secondary recovery of hydrocarbons from hydrocarbon oil-bearing formations. More particularly, the invention is directed to an improved method of utilizing the reverse in-situ combustion process for recovering viscous hydrocarbons from hydrocarbon oil-bearing formations. The reverse combustion process referred to herein is identical to that sometimes referred to as the "inverse" or "countercurrent" combustion process.

In-situ combustion is commonly used to facilitate production of viscous hydrocarbons which are not readily produced by conventional production procedures. Typically, an in-situ combustion arrangement may include an input or injection well for the introduction of an oxygen containing combustion supporting fluid, such as air, and an output well for the removal of the desired hydrocarbons. Each of these wells extend from the surface of the earth into the formation desired to be produced. In the more conventional forward or direct in-situ combustion process, a combustion front is initiated in the formation desired to be produced around the input well and combustion-supporting fluid is continually fed into the formation and to this front through said input well. The combustion front provides a radially expanding source of heat and functions to distill and reduce the viscosity of hydrocarbons in the formation. In the latter state, the hydrocarbons are capable of more freely moving through the formation to the output well where they may be recovered by conventional production means. In addition to creating the expanding source of heat, the combustion-supporting fluid is converted to hot combustion products that move away from the input well toward the output well while transporting reservoir hydrocarbons.

When used in formations containing very viscous hydrocarbons, the forward or direct combustion process often proves unsuccessful because of the building up of a relatively immobile bank of viscous liquid hydrocarbons in the formation beyond the combustion front. This bank functions to seal the formation around the combustion front and thus impedes, or restricts completely, the flow of combustion-supporting fluid from the input well and through the formation. As a result, the combustion front dies and the recovery process becomes completely ineffective. In order to avoid the viscous hydrocarbon build-up problem encountered in the forward combustion process, the aforementioned reverse combustion process has been developed. The reverse combustion process is similar to the forward combustion process in that it utilizes input and output wells extending from the surface of the earth into the formation desired to be produced and also utilizes a combustion front in the formation to decrease the viscosity of hydrocarbons therein. The reverse combustion process differs from the forward combustion process primarily in that the combustion zone is initiated around the output well rather than the input well.

Typically, in application of the reverse combustion process, combustion is initiated around the output well by heating the formation and injecting an oxygen-containing combustion supporting fluid, such as air, into the heated area. Initially, the combustion-supporting fluid may be injected through either the input or output well. After combustion is initiated, however, the injection through the output well is terminated and combustion-supporting fluid is introduced into the formation through only the input well. In order to increase the rate of movement of the combustion front and decrease the combustion temperature, it is sometimes found desirable to introduce a fuel, generally having a low ignition point, such as carbon disulfide, into the formation concurrently with the combustion-supporting fluid. When the process is in operation the combustion zone moves radially outward from the output well while being supplied with combustion-supporting fluid, and possibly fuel, from the input well. From the latter relationship, the process derives the name of reverse, inverse, or countercurrent combustion, since the combustion front moves in a reverse direction to that in the forward combustion process and in a direction countercurrent to the direction in which the combustion-supporting fluid moves. It is noted that in the aforedescribed forward combustion process, both the combustion front and the combustion-supporting fluid move in the same direction.

The combustion-supporting fluid introduced through the input well in the reverse combustion process functions to drive hydrocarbons toward the output well, as well as to maintain the combustion zone. Concurrently with the introduction of combustion-supporting fluid through the input well, hydrocarbons are removed from the output well. As in the forward combustion process, hydrocarbons removed from the output well will have a low viscosity, since the heat generated in the combustion zone functions to lower the viscosity of hydrocarbons within the formation. However, contrary to the situation in the forward combustion process, the flow of gas and hydrocarbons is not impeded by the formation of a heavy bank of viscous hydrocarbons near the combustion front, since hydrocarbons upstream from the combustion front remain relatively cool and those downstream from the front are maintained at a low viscosity by the preheated formations around the output well. A more detailed discussion of the reverse combustion process and the advantages thereof may be found in U.S. Patent No. 2,793,696 to Richard A. Morse.

The application of the reverse combustion process, however, presents a spontaneous ignition problem that is not encountered in a forward combustion process. Specifically, in the reverse combustion process it has been discovered that spontaneous ignition will take place in portions of the formation upstream from the advancing combustion front. Spontaneous ignition results from the slow oxidation of organic matter (in this case the crude within the formation being produced) by the oxygen-containing combustion supporting fluid as it flows through the formation from the injection well to the combustion front. This slow oxidation generates heat that increases the temperature of the formation. As the temperature increases, the rate at which the oxidation occurs increases until the temperature is sufficiently high that all, or nearly all, of the oxygen in the combustion-supporting fluid is consumed before it reaches the combustion front. When this occurs, there is little or no oxygen available to support the desired reverse combustion front, and as a result this front dies out. At or near this time, the portions of the formation remote from the output well, and generally near the injection well, reach a temperature sufficient to support spontaneous ignition and, thus a new and undesired combustion front is created. Typically, this front will form around the injection well and create, in effect, a direct combustion process.

The time required for spontaneous ignition within a

formation is affected by such things as the character of the crude, the oxygen content of the injected gas, the rate of gas injection and the reservoir pressure. The most controlling factor, however, is the ambient temperature of the reservoir. For nearly all reservoirs, but the most shallow (i.e. less than 500 feet from the surface), the ambient reservoir temperature will be sufficiently high (i.e. 85° F. or above) to promote spontaneous ignition near the injection well within a relatively short time, for example, in the order of three months.

Therefore, since reverse combustion operations are usually planed to last for periods ranging in years, it can be seen that spontaneous combustion in areas of the formation remote from the desired reverse combustion zone is likely to occur. With this occurrence, the combustion zone around the output well will die out and a new combustion zone will form around and spread radially from the input well, thus creating a direct combustion process. This direct combustion process will, in turn, be accompanied by the aforediscussed problems encountered in conventional direct combustion processes. Thus, in reverse combustion processes, it has now been found to be highly desirable to control the rate of oxidation in the formations upstream from the combustion zone to prevent spontaneous ignition within those portions of the producing formations.

It is therefore, a primary object of the present invention to provide an improved reversed combustion process wherein the problems of spontaneous ignition may be alleviated.

Another and related object of the invention is to provide a method of preventing slow oxidation in reverse combustion processes from yielding temperatures so high as to result in spontaneous ignition.

A particularly preferred specific object of the invention is to provide a method of inhibiting the relatively low temperature oil oxidation reactions of the combustion-supporting fluid used in a reverse combustion process.

A more specific object of the invention is to provide a method of withdrawing heat from a producing hydrocarbon formation during the production thereof.

Briefly, the present invention provides a method of recovering hydrocarbons from hydrocarbon oil-bearing formations which are penetrated by substantially spaced output and input means, such as wells. The method includes initiating combustion in the portion of the formation surrounding the output means and introducing a combustion-supporting fluid, such as air, through the input means. The rate of oxidative heating by the fluid that is introduced through the input means is restricted to prevent spontaneous ignition in the formation upstream from the zone of combustion surrounding the output means. In the method, hydrocarbons are removed from the output means.

This problem can be better understood by referring to the single accompanying drawing which is a diagrammatic view of a reverse combustion process in a subterranean reservoir formation together with a temperature profile. In the drawing, an oil producing stratum **10** is shown penetrated by two spaced wells **11** and **12**. Well **11** is the input well and well **12** is the output well from which effluents can be removed from the reservoir formation. At the ground surface **13**, an oxidant injection system **14** for injecting combustion-supporting fluids is connected to the wellhead of input well **11** and provides for the injection of the combustion-supporting fluid. In this inventon an agent can be blended in the oxidant injection system to control the rate of oxidative heating between the input well **11** and the combustion front. This prevents spontaneous ignition in the stratum **10** prior to the oxidant reaching the combustion front.

A recovery and storage system **15** is connected to output well **12** and is equipped with a separator so that the effluent from output well **12** can be separated into liquids and hot gases, the latter of which may be mixed with the

combustion-supporting fluid being injected through the oxidant injection system **14** by passing through pipe **16** and valve **17**.

Generally, combustion-supporting fluid from the injection system **14** passes down input well **11** and into the permeable stratum **10** adjacent to the input well as indicated by the arrows. Since no combustion is normally taking place in this cooler unburned portion of stratum **10**, the combustion-supporting fluid moves through the permeable stratum to combustion front **18** where ignition is actually taking place. In such a reverse combustion process, the product of combustion from the combustion front **18** and heated petroleum move through the burned out zone **19** and into output wells from which the effluents can be recovered.

Looking at the temperature profile representing positions across the bottom of the reservoir stratum **10**, it can be seen that the burned out zone **19** is much warmer than the unburned portion of stratum **10** as a result of the passage of the combustion front **18**. This combustion front causes a sharp rise in formation temperature, the increase represented by line **20**, as the combustion front moves toward the input wall. Temperature peaks **21** on the temperature profile represent areas **22** in the stratum **10** where unwanted spontaneous combustion has occurred as a result of uncontrolled oxidative heating in the cool, unburned zone of the reservoir. Such unwanted, upstream spontaneous ignition is detrimental to the recovery of petroleum when employing a reverse combustion process and should be avoided.

The method of the invention and the enumerated objects will be more fully understood when viewed in light of the following detailed description.

The control of oxidative heating in a formation from which hydrocarbons are being produced by the reverse combustion process can be accomplished as either a continuous process, or as an intermittent process applied only when necessary. In either case, however, it is desirable to determine the rate at which the hydrocarbons are oxidatively heated by the combustion-supporting fluid. Stated more specifically, it is desirable to know the rate at which the temperature of the oil in the reservoir is raised to a temperature at which its spontaneous ignition becomes imminent. As was set forth previously, this rate is affected by such things as the character of the oil in the formation, the oxygen content of the combustion-supporting fluid being introduced through the injection well, the rate of the combustion-supporting fluid injection, the reservoir pressure and the ambient reservoir temperature. In addition, the rate at which the producing formation raises in temperature due to oxidative heating is affected to some extent by heat losses in the formation, the permeability of the formation, and the oil saturation of the formation. As a practical matter, however, the initial ambient temperature of the formation has proved to be the most significant and controlling factor in determining the time required for a producing formation to reach the spontaneous ignition temperature of the oil therein. The partial pressure of the oxygen injected into the formation also affects the heating rate to a noticeable, although not controlling, degree. All of the other enumerated factors may generally be neglected in estimating the rate at which the formation will reach spontaneous ignition temperature due to oxidative heating. The latter conclusion has been determined experimentally.

It is possible to estimate the time required to reach the point of spontaneous ignition during the reverse combustion production of a reservoir formation by knowing only the initial reservoir temperature in addition to the porosity and fluid content properties that are ordinarily available from core samples and logs of reservoirs for which thermal recovery processes are contemplated. Although such estimates may not be absolutely accurate, due to the many variable factors encountered in each well, they are sufficient, when used conservatively, to facilitate the control

of oxidative heating in a producing formation, as will be developed subsequently.

At this point it is noted that the present invention is directed to the concept of controlling oxidative heating in the reverse combustion process of recovering hydrocarbons. The control is accomplished by restricting the rate of oxidative heating by the combustion-supporting fluid introduced into the reservoir formation during a reverse combustion process. Although the subsequent disclosure will develop alternative ways of controlling this capacity it is not intended that the invention be limited to these specific alternatives.

In application of the invention, the reverse combustion process is commenced in a conventional manner, as was developed previously, with the oil-bearing formation desired to be produced being penetrated by spaced output and input wells. Combustion is first initiated in the portion of the formation surrounding the output well by means of an ignition process, e.g. the process described in United States Patent No. 2,863,510 to Harco J. Tadema et al. After combustion has been so initiated, a combustion-supporting fluid, such as air, or any mixture of gases containing sufficient oxygen to support the combustion, and possibly a fuel is injected into the input well to effect a reverse combustion production process. During the injection of the combustion-supporting fluid, the oxidative heating within the formation is controlled by restricting the rate of oxidative heating by the combustion-supporting fluid being introduced through the input well, and hydrocarbons are removed from the output well.

The rate of oxidative heating by the combustion-supporting fluid that is introduced into the reservoir formation during the reverse combustion process is preferably restricted by dispersing an oxidation inhibitor in the combustion-supporting fluid. It can also be further restricted, or alternatively restricted, by causing the combustion-supporting fluid to flow through portions of the reservoir formation that have a relatively low temperature.

The rate of oxidative heating by the combustion-supporting fluid injected into a producing formation is restricted by continuously or intermittently incorporating substantially any organic oxidation inhibitor or antioxidant therewith. Suitable antioxidants include phenols, e.g. hydroquinone, pyrocatechol; amines, a.g. p-aminophenol, ethanolamine, methyl amine, the sugar amines; sulfur compounds, e.g. theaurea; and the like antioxidant materials. The water soluble antioxidants such as ethanolamine, are advantageous in being adapted for use in a solvent which has a high specific heat and the gaseous or relatively volatile antioxidants such as methyl amine are particularly advantageous in being dispersible in the form of a vapor. When such antioxidants pass from these relatively cool upstream zones to the hot region of the combustion zone, they become thermally decomposed and, as a result, become fuel for the desired combustion at the combustion front.

As indicated above, the antioxidants may be introduced either intermittently or continuously. In intermittent introduction, the inhibitor would be introduced as a slug in the combustion-supporting fluid. In the continuous introduction, the inhibitor would be introduced as a dispersion in the combustion-supporting fluid. Where desirable the antioxidant may be diluted with a diluent, such as water, prior to its introduction. In general, the inhibitor should be present in less than about 100 parts per million concentration in the combustion-supporting fluid, with the exact concentration being determined experimentally to achieve the optimum economic advantage.

In the varying flow pattern method of restricting oxidative heating, the production well is surrounded by a plurality of spaced injection wells and each of the injection wells is provided with a valve or other control means to selectively control the introduction of combustion-supporting fluid therethrough. Oxidative heating within the producing formation is controlled by initiating flow through a first zone of the formation through one or more of the injection wells and moving the point of injection and/or the pattern of flow to cause a flow through other zones when the first and subsequent zones of the formation approach the temperature of spontaneous ignition. The point of injection is moved by discontinuing injection at the first or subsequent points through the injection wells communicating therewith and commencing injection at other points by means of an alternative injection well or a plurality of alternative injection wells. Injection is controlled by means of the valves on the injection wells. In this way, the zones of the producing formation around the alternative injection wells are allowed to cool before they reach the temperature of spontaneous ignition. If sufficient spaced injection points are provided, the points may be alernatively used over a considerable period of time and the process may be recycled wherein the first and subsequently used injection points are reused after the surrounding zones have been allowed to cool to a temperature substantially below the spontaneous ignition temperature.

The time intervals at which injection points should be switched may be determined by estimating the time required for oxidative heating to raise an injection zone to a temperature at which a rapid attainment of the temperature of spontaneous ignition is impending, as described previously. In the case of recycling, where the injection points are reused after a period of cooling, estimates for the cooling time required may be similarly made. If necessary, more accurate estimations can be made wherein heat losses and temperature distribution within the formation are considered. Such estimations are well within the province of those skilled in the thermal secondary recovery art.

EXAMPLE I

Varying flow pattern method

In producing oil from the reservoir formation described in Example I, the pattern of the injection and production wells is arranged to include alternative injection wells that are spaced from the production wells by about 140 feet and spaced from each other by about 200 feet. The injection of air is continued through the first used injection wells only for a time sufficient to oxidatively heat the reservoir formation to an ambient temperature which is less than the temperature at which the attainment of spontaneous ignition becomes imminent. At this time, e.g. several weeks less than the 100 days predicted by the laboratory tests described above, the air is injected only through the alternative injection wells. The production through the output wells is continued and the injection flow pattern is again varied, if necessary, to keep the combustion-supporting fluid flowing through only those portions of the reservoir formation that have ambient temperatures below the temperature at which the attainment of spontaneous combustion becomes imminent.

The rate of oxidative heating by the combustion-supporting, injected fluid can also be controlled by withdrawing heat from the region of the formation where it is being generated. Heat may be withdrawn by injecting a heat absorbing material, such as water, either simultaneously or intermittently with the combustion-supporting injection fluid. In any specific case, calculations may be made in order to determine the cooling effect of the absorbent on the formation temperature and the spontaneous ignition time. As with the aforediscussed estimated times required for spontaneous ignition, these calculations would be experimental in nature.

The above oxidative heating control methods, namely; the varying injection flow pattern method, the heat withdrawal method and the antioxidant method, may be used either alternatively or additionally. For example, the flow pattern of the injection could be selectively varied while introducing the combustion-supporting fluid having a heat

absorbent and/or an antioxidant incorporated therein. Furthermore, with a single injection well, both the heat absorbent and an antioxidant could be used to control the oxidative heating capability of the combustion-supporting fluid supplied to the formation.

I claim as my invention:

1. A method of recovering hydrocarbon from a hydrocarbon oil-bearing formation which is penetrated by substantially spaced output and input means comprising:

(a) initiating the combustion front in the portion of the formation immediately surrounding the output means;

(b) maintaining the combustion front by introducing a combustion supporting fluid through the input means;

(c) controlling the rate of oxidating heating by said combustion supporting fluid that is introduced through said input means to prevent spontaneous ignition of the formation upstream from said combustion front by selectively varying the region of the hydrocarbon oil-bearing formation into which said combustion supporting fluid is introduced through said input means; and

(d) removing hydrocarbons from the formation through said output means.

2. A method according to claim 1 wherein the input means takes the form of a plurality of spaced wells located around the output means and wherein the combustion-supporting fluid is selectively introduced into varying regions of the oil-bearing formation by alternatively introducing the combustion-supporting fluid through said input wells.

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