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METHOD FOR PRODUCING OIL BY IN SITU COMBUSTION WITH OPTIMUM STEAM INJECTION

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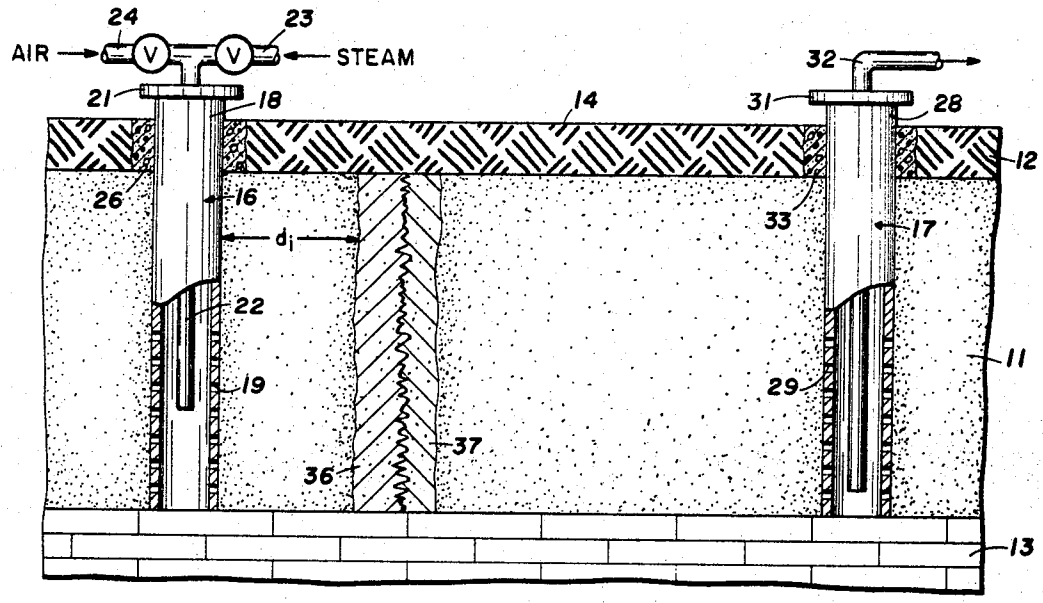


FIG. 1

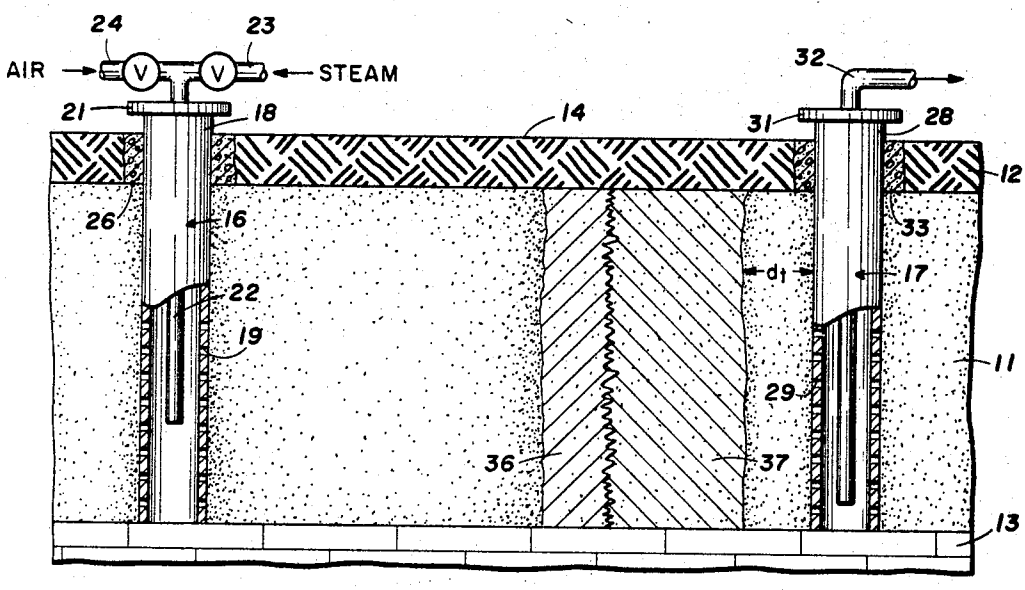


FIG. 3

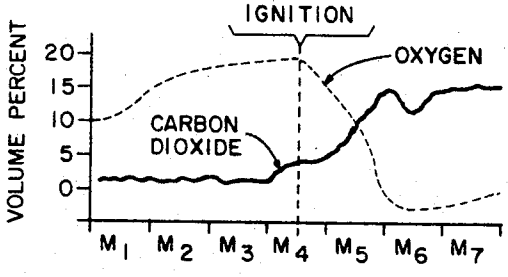


FIG. 2

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# METHOD FOR PRODUCING OIL BY IN SITU COMBUSTION WITH OPTIMUM STEAM INJECTION

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## ABSTRACT OF THE DISCLOSURE

A method for producing oil from a subterranean formation by forward in situ combustion combined with optimum steam injection. A forward in situ combustion front is passed by a flow of air through a formation between input and output wells. Oil is produced from the output well. Injection of steam with the air is begun when the combustion front is stabilized, and before the front-traversed formation is sufficiently cooled that the injected steam is condensed into a liquid bank of water. About 240 barrels of water converted into steam are used for each one million standard cubic feet of air concurrently injected into the formation. Steam injection ends when steam is produced with the displaced oil through the output well.

## BACKGROUND OF THE INVENTION

### (1) *Field of the invention*

The present invention relates to producing oil from a subterranean formation. More particularly, it relates to a method for producing oil from a subterranean formation employing in situ combustion with, in a certain interval, concurrent steam injection.

### (2) *Description of prior art*

Forward in situ combustion procedures have been found to be of good utility for producing oil from subterranean formations. However, the formation traversed by the forward-movement combustion front remains at elevated temperatures to provide large amounts of recoverable heat energy. Various methods have been proposed for employing this residual heat energy to improve the efficiency of forward in situ combustion procedures in producing oil.

It is apparent that heat must be transferred downstream of the forward-movement combustion front to thin the oil to be displaced. This oil must be heated sufficiently to be displaced readily towards an output well from which such oil is produced. Therefore, the efficiency of the forward in situ combustion procedures depends directly upon the carrying of heat downstream from the combustion front for heating the oil to be displaced. The region in the formation in which the oil is heated may be termed a heated condensation zone. It is in this zone that the condensable products of hot gases from the combustion front become liquids while effecting heating of the oil.

It has been proposed to inject water, as a liquid, into the burned-out formation for generating steam in situ. This steam "picks up" heat energy while moving through the burned-out formation and the combustion front. As a desired result, the transfer of heat energy to the condensation zone is increased. As an undesired result of such in situ steam generation, a liquid bank of water forms in the formation about the water-input well. This liquid bank of water must reach a 60 percent fluid saturation in the formation before the water can be displaced into adjacent portions of the formation where sufficient heat exists that more of the water can be converted into steam. Obviously, such a liquid bank of water will impede the flow of fluids passing from the input well towards the combustion front. Any gain to improve the efficiency of the procedure by injecting liquid water as a heat transfer agent is offset by the undesired effects of the resulting bank of water.



It has been proposed to inject steam with the oxidant for moving the combustion front through the formation to overcome the above problems with injecting liquid water. Obviously, difficulties arise in such process as to when to begin the steam injection. The injection of steam is critical during the time when the combustion front is being initiated. Injecting steam at this time can prevent the initiation of, or the continuation of, the combustion front. Likewise, there is a problem of when to terminate the injection of steam. For example, the continued injection of steam will be wasteful after the combustion front has arrived adjacent the output well. Additionally, the amount of steam injected during movement of the combustion front directly concerns the efficiency of the procedure. The steam can include uses as a heat transfer agency, as a primary energy agency, or a blend of both agencies, for the production of oil from the formation.

The present invention provides for the injection of steam for a select period during the movement of a forward in situ combustion front through a formation for producing oil. Also, the steam is used in a certain amount to serve as the most effective heat transfer agent for moving heat through the combustion front to heat oil downstream thereof without becoming the primary source of heat energy for producing oil.

### *Summary of the invention*

The present invention provides a method for producing oil from a subterranean formation which is penetrated by spaced input and output wells in fluid communication with the formation. The formation adjacent the input well is heated to the ignition temperature of resident combustible materials. Air is passed from the input well through the heated formation to the output well. As a result, an in situ combustion front is moved through the formation from the input well toward the output well. Steam is injected concurrently with the air, over a certain period of time, from the input well into the formation for carrying heat energy to the downstream side of the combustion front in the formation. The injection of steam is begun after the combustion front is stabilized at a first distance from the input well. Also, the injection of steam is begun before the combustion front has passed to a second distance from the input well at which distance the injection of the air would have cooled the formation adjacent the input well sufficiently below the temperature of the injected steam that a liquid bank of water is formed. This liquid bank of water would impede the flow of air through the formation. The amount of injected steam is adjusted to an amount equal to about 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation. Steam injection is terminated when the heated condensation zone ahead of the combustion front has moved to within a certain distance of the output well at which time the intervening formation is heated to such a temperature that steam is produced with the oil ahead of the combustion front into the output well. Oil is produced from the output well into which it is displaced by the combustion front moving from the input well toward the output well.

In another embodiment of the present invention, steam may be introduced at least during one interval at a rate greater than the above stated amount. When the formation between the input well and the combustion front is

cooled to about the steam temperature, the rate of steam is reduced to an amount such that the total amount of injected steam averages about an amount equal to about 240 barrels of water converted to steam for each one million standard cubic feet of air concurrently injected into the formation.

In yet another embodiment, the injection of steam is begun when the combustion front moved by the injected air becomes stabilized as reflected by the gases produced with the oil from the output well reaching equilibrium conditions in concentrations of oxygen and carbon dioxide.

*Description of the drawings*

The drawings illustrate, in FIGURES 1 and 3, a vertical section taken through the earth of a formation provided with suitable apparatus for carrying out the steps of the present method. FIGURES 1 and 3 illustrate, respectively, the condition of the formation during the practice of initial and terminal steps of the present method. In these figures, like structures and features will be identified with like numerals and terminology. FIGURE 2 is a graph illustrating the concentrations of oxygen and carbon dioxide in the produced gases at the output well when the combustion front, shown in FIGURES 1 and 3, becomes stabilized in the formation.

*Description of specific embodiments*

Prior to a detailed description of the steps of the present method, structures employable for practicing these steps will be described. In FIGURES 1 and 3, there is shown a formation **11** which contains oil to be produced by the present method. The formation **11** may be of any origin. For example, the formation **11** can be the heavy oil sands located in California. The formation **11** resides beneath an overburden **12** and rests upon strata **13**. For purposes of this description, the overburden **12** and strata **13** have insufficient carbonaceous materials to support combustion. However, they serve as vertical barriers to fluid flows which occur in the formation **11**.

In order to carry out the steps of the present method, fluid communication between the earth's surface **14** and the formation **11** is provided, and may take the form of input well **16** and output well **17** having a suitable construction for this purpose.

For example, the input well **16** includes a casing **18** which extends from the earth's surface **14** into the formation **11**. Perforations **19** in the lower portion of the casing **18** provide fluid communication between the input well **16** and the surrounding formation **11**. The perforations **19** preferably extend over a substantial part of the input well **16** which traverses the formation **11**. The casing **18** carries a wellhead **21** through which is passed tubing **22**. The tubing **22** is connected at its upper end to conduits **23** and **24** which carry suitable valve means for regulating the flow of fluids therethrough. The input well **16** is sealed to the overburden **12** by cement sheath **26** to provent the escape of fluids from the formation **11** to the earth's surface **14**. With this arrangement of the input well **16**, several fluids may be passed in regulated amounts from the conduits **23** and **24** through the tubing **22**, thence via perforations **19**, into the formation **11**.

For example, the output well **17** includes a casing **28** which extends into the formation **11**. Perforations **29** in the casing **28** provided fluid communication between the output well **17** and the surrounding formation **1**. Preferably, the perforations **29** extend substantially along the vertical extent of the casing **28** in the formation **11**. The casing **28** carries a wellhead **31** at its upper end. Tubing **32** extends through the wellhead **31** into the well **17** for conveying fluids from the output well **17** to the earth's surface **14**. These fluids include the oil and gases produced from the formation **11**. A cement sheath **33** about the output well **17**, at the overburden **12**, prevents the escape of fluids from the formation **11** to the earth's surface **14**.

Referring particularly now to FIGURE 1, the steps of the present invention will be described. An in situ combustion front **36** which is moved through the formation **11** from the input well **16** to the output well **17** is obtained in any suitable manner. In this regard, the formation **11** adjacent the input well **16** is heated, by suitable heating means, to the ignition temperature of the resident combustible materials. For example, such heating may be obtained by placing an electric heater (not shown) in the input well **16** adjacent the perforations **19**. Air is passed through the conduit **24** into the tubing **21** to flow, via the perforations **19**, through the formation **11**, and via the perforations **29**, into the output well **17**.

In many instances, the flow of air causes heating, by auto-oxidation of combustible materials in the formation **11** to a sufficient degree that spontaneous combustion creates the combustion front **36**. Supplemental heating may be employed to effect the ignition of combustible materials in the formation **11** where spontaneous combustion does not produce the combustion front **36**. The continued passage of air through the formation **11** then moves the combustion front **36** toward the production well **17**.

The air may be provided from any suitable source. For example, an air compressor can provide a flow of air, at suitable injection pressure, into the conduit **24** for its introduction from the input well **16** into the formation **11**. The term "air," as used herein, refers to the oxidant which has the atmosphere as its origin. The term "air" also includes any oxidant which provides the function of air in promoting combustion. Moreover, the air used in the present invention may include additional oxidant or fuel. References given herein to amounts of steam used per certain volume of air to be injected into the formation are based upon air taken directly from the atmosphere with approximately a 20 percent by volume concentration of oxygen. Whenever the air is admixed with additional materials, or sources of air-equivalent oxidant are used in carrying out this invention, the amounts of steam relative to a stated volume of air should be corrected upon a directly proportionate basis of the actual oxygen content to the normal oxygen content of air taken from the atmosphere.

A condensation zone **37** is formed in the formation **11** downstream of the combustion front **36**. The passage of air into the combustion front **36** moves the heated products of combustion into the condensation zone **37**. Condensing of at least a portion of these heated fluids heats the oil in the formation **11** within the condensation zone **37**. The heated oil is then displaced toward the output well **17** from which it may be recovered by means of the tubing **32**.

It will be apparent that during initiation of the combustion front **36** adjacent the input well **16**, the conditions controlling combustion have not reached an equilibrium. Any substantial change in these conditions may cause extinguishment, in part or in whole, of the combustion front **36**. However, when the combustion front **36** has been moved a distance $d_i$ from the input well **16**, the combustion front **36** becomes stabilized. At this time, these conditions may be changed appreciably without extinguishing the combustion front **36**. These changes produce only a change in the rate of movement of the combustion front **36**.

Reference may be taken briefly to FIGURE 2 for an explanation of one mode for determining when the combustion front **36** is stabilized. The produced gases flowing from the output well **17** through the tubing **32** are examined for their contents of oxygen and carbon dioxide. The data obtained from such examination is presented graphically with the oxygen and carbon dioxide contents of the gases, displayed as volume percentages, and compared to time increments $M_1$ to $M_7$ which may be days, weeks, or months. At the beginning of air injection, some oxygen is consumed in the auto-oxidation of combustible materials which reside in the formation **11** immediately adjacent the input well **16**. Since the oxygen is principally being consumed in such auto-oxidation, only small

amounts of carbon dioxide are being produced from the output well **17**. This condition exists throughout interval $M_1$. However, as the supply of air continues, its radial diffusion through the formation **11** causes increased volumes of unreacted air to reach the output well **17**. However, the amount of carbon dioxide in the produced gases remains small. This condition exists throughout intervals $M_2$ and $M_3$. Ignition of the combustible materials in the formation **11** adjacent the input well **16** produces the combustion front **36** during interval $M_4$. A rapid decline in the amount of oxygen, and a rapid increase in the amount of carbon dioxide, occur in the gases produced from the output well **17** during the interval $M_5$. Some fluctuation of the oxygen and carbon dioxide contents in the produced gases occurs during stabilization of the combustion front **36** during the interval $M_6$. However, an equilibrium condition is reached in the concentrations of oxygen and carbon dioxide produced from the output well **17** during the interval $M_7$. This condition indicates stabilization of the combustion front **36** for a constant set of operating conditions existing in the formation **11**. If desired, other means for obtaining knowledge of when the combustion front **36** becomes stabilized may be employed for carrying out the present method.

Steam is injected concurrently with the air through the input well **16** into the formation **11** after the combustion front **32** becomes stabilized. The steam is introduced into the input well **16** through the conduit **23** for this purpose. Any supply source for the steam may be utilized. Preferably, the steam is of high quality so that only relatively small amounts of water, in the liquid phase, are present. The quality of the steam is given as the percentage of liquid water converted into steam in the resulting steam-water fluid mixture. It has been determined that 80 percent quality steam may be employed with good results in the present invention. One reason for this result is that the heat content of the steam is sufficiently large to vaporize the small amount of water present upon the resulting pressure decline which occurs in the steam passing through the formation **11**. However, the steam should not contain such large amounts of liquid water that a liquid bank of water is created in the formation **11** adjacent the input well **16** in carrying out the steps of this invention.

The injection of steam also begins before the combustion front **36** has passed a second distance, greater than $d_i$, from the input well **16** at which distance the flow of injected air would have cooled the formation **11** adjacent the input well **16** sufficiently below the temperature of the injected steam that a liquid bank of water is formed. This liquid bank would impede the flow of air through the formation **11**.

The steam injected concurrently with the air adsorbs heat energy from that portion of the formation **11** through which the combustion front **36** has passed. Then, the adsorbed heat energy is carried by the steam through the combustion front **36** into the condensation zone **37** which becomes further heated. As a result, the heated condensation zone **37** begins to expand downstream. This expansion fosters the heating of greater amounts of oil in the formation **11** to a thinned condition for ready displacement into the output well **17**.

The amount of steam is adjusted to an amount equal to about 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation **11**. A standard cubic foot of air, as used herein, is a volume of one cubic foot of air measured at a pressure of 760 mm. of mercury and at a temperature of 60° F. It has been found that this amount of steam provides for the optimum transfer of heat remaining in the formation **11** upstream of the combustion front **36** into the condensation zone **37**. Under these conditions, the steam serves only as a carrier of the residue heat remaining in the formation **11** after passage therethrough of the combustion front **36**. Although it is preferred to employ as near the stated amount of steam as possible on an average basis, the amount of steam may be varied by approximately 20 percent from this amount in normal operations without detracting substantially from the desired optimum result. Lesser amounts of steam do not provide the greatest transfer of residue heat downstream of the combustion front **36** into the condensation zone **37**. Greater amounts of steam likewise are undesirable since the steam then is a primary source of heat energy.

In another mode of operation, the steam may be introduced at least during one interval at a rate greater than an amount equal to 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation **11**. This interval of steam injection continues until the formation **11** between the input well **16** and the combustion front **36** is cooled to about the steam temperature. At this time, the steam injection rate is reduced to such an amount that the total amount of injected steam averages an amount equal to about 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation **11**.

When steam is concurrently injected with the air through the formation **11** from the input well **16** towards the output well **17**, heat is transferred effectively from the formation **11** upstream of the combustion front **36**. The adsorbed heat in the steam then is moved downstream into the heated condensation zone **37**. The results of such heat transfer are readily appreciated by viewing FIGURE 3. The transfer of heat in accordance with the present method causes a preheating of the air entering the combustion front **36**. This causes the combustion front **36** to expand slightly upstream into the flow of air. The transfer of heat into the heated condensation zone **37** causes it to expand horizontally because of the increased heat content of the steam which passes through the combustion front **36**. Additionally, the higher temperatures of the air and heated steam which flow into the combustion front **36** cause a greater efficiency in burning of the carbonaceous residue which remains in the formation **11** behind the condensation zone **37**. By employment of the stated particular amounts of steam, and its selective concurrent injection with air during the interval herein stated, an effective recovery of heat from the burned-out portion of the formation **11** into the heated condensation zone **37** is obtained. Under these conditions, forward in situ combustion is the primary source of thermal energy for promoting the recovery of oil from the formation **11**. These steps of the present method also provide for the most efficient transfer of heat generated in the combustion front **36** downstream into the heated condensation zone **37**.

It will be apparent that by injecting steam in the stated amounts, the optimum combination of steam injection with in situ combustion is obtained. The sources of air and steam accordingly can be made smaller, for the same oil production, than if either air or steam were used alone.

The injection of steam is terminated when the heated condensation zone **37** has moved to a distance $d_t$ from the output well **17**. At this occurrence, the intervening formation **11** is heated to such a temperature that steam is produced with the oil displaced ahead of the combustion front **36** into the output well **17**. Continued introduction of steam at this time is undesirable and wasteful, and it would cause a premature breakthrough of the combustion front **36** into the output well **17**. Although the injection of steam might be terminated at an earlier time, the optimum benefits obtained by the concurrent injection of steam with air would not be obtained.

Oil is produced into the output well **17**, via the perforations **29**, from the formation **11**. This oil is displaced by the combustion front **36** as it moves from the input well **16** toward the output well **17**. The produced oil, and other fluid products of combustion, are removed to the

earth's surface **14** through the tubing **32** for suitable utilization.

From the foregoing it will be apparent that there has been provided a method employing forward in situ combustion with an interval of concurrent steam injection for the optimum production of oil from a subterranean reservoir. Various changes and adaptations may be made to the present method by a person skilled in the art without departing from the spirit of this invention. It is intended that the foregoing description be considered as illustrative of the present invention whose scope is defined by the appended claims.

What is claimed is:

**1.** A method for producing oil from a subterranean formation penetrated by spaced input and output wells in fluid communication therewith, comprising the steps of:

(a) heating the formation adjacent said input well to the ignition temperature of resident combustible materials, and passing air from said input well through the heated formation to said output well whereby an in situ combustion front is moved from said input well through the formation toward said output well;

(b) injecting steam concurrently with the air from said input well into the formation so that said steam carries heat energy from that portion of the formation through which said combustion front has passed into that portion of the formation downstream of said combustion front for forming a heated condensation zone ahead of said combustion front, said steam injection beginning after said combustion front becomes stabilized at a first distance from said input well and before said combustion front has passed to a second distance from said input well in the formation that injection of said air has cooled the formation adjacent said input well sufficiently below the temperature of the injected steam that a liquid bank of water is formed which impedes the flow of air therethrough;

(c) adjusting the amount of steam injected to an amount equal to about 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into said formation;

(d) terminating the injection of steam when the heated condensation zone ahead of said combustion front has moved to within such a distance of said output well that the intervening formation is heated to such a temperature that steam is produced with the oil displaced ahead of said combustion front into said output well; and

(e) producing oil from said output well into which it is displaced by said combustion front moving from said input well toward said output well.

**2.** The method of claim **1** wherein the steam is introduced at least during one interval at a rate greater than an amount equal to 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation until the formation between said input well and said combustion front is cooled to about the steam temperature, and then reducing such steam injection rate to such an amount that the total amount of injected steam averages about an amount equal to about 240 barrels of water converted into steam for each one million standard cubic feet of air concurrently injected into the formation.

**3.** The method of claim **1** wherein the steam injection begins when said combustion front moved by injected air becomes stabilized as reflected by the gases produced from said output well with the oil reaching equilibrium conditions in concentrations of oxygen and carbon dioxide.

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