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INTERMITTENT DIRECT IN SITU BURNING METHOD

Lloyd K. Strange, Grand Prairie, and Dean P. Nichols, Dallas, Tex., assignors to Socony Mobil Oil Company, Inc., a corporation of New York

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This invention relates to the recovery of hydrocarbons from subterranean oil-bearing formations by in situ combustion. More particularly, it relates to an improved method for oil recovery by intermittent in situ combustion.

Methods of recovering oil from subterranean oil-bearing formations by intermittent in situ burning or combustion are known. For example, the United States Letters Patent 3,047,064, discloses one such method. Generally, these methods include the steps of passing a plurality of direct thermal drives through the oil-bearing formation. The thermal drives are provided by passing successive combustion fronts from an input well to a production well with extended intervals of time between each combustion front to permit the heat in the combustion zone swept by each of the combustion fronts to warm the unburned oil-bearing formation adjacent to the combustion zone. The combined effects of the combustion fronts traversing the formation and the warming of the unburned formation result in oil production at the production well. The combustion fronts are continued successively until substantially all of the oil-containing formation is burned.

These known intermittent in situ combustion methods for recovering oil from oil-bearing formations are an improvement over conventional direct and reverse in situ combustion methods using a continuous thermal drive. However, there are a number of problems involved in these methods which result in reducing their commercial desirability. One undesired result arises from the fact that the combustion fronts are propagated at rather high velocities which causes them to pass preferentially through the more permeable areas of the formation and by-pass any less permeable areas. Thus, there will be some unburned areas within the oil-bearing formation from which no oil is recovered. Another undesired result arises from the tendency of the oxygen-containing fluid driving each of the successive combustion fronts to channel through the combustion zone of the previous combustion front rather than through the unburned oil-bearing formation. Thus, there is an excessive requirement of the oxygen-containing fluid. Also, there is a reduction in the oil recovery efficiency of the intermittent in situ combustion method with the increasing numbers of repeated thermal drives required to extend the combustion zone the full thickness of the oil-containing formation.

In the known intermittent in situ combustion methods, light-bodied oils with a low viscosity are more easily recovered than heavy-bodied oils with high viscosity, such as tars. Thus, in these methods the number of thermal drives and the total amount of oil recovered are somewhat dependent upon the physical characteristics of the oil. One reason for this result is that a light-bodied oil requires less natural solution gas drive to flow readily to the production well than the heavy-bodied oil, which may be relatively fluid at elevated temperatures to flow under similar conditions to the same well.

After the passage of a combustion front through the formation, some oil migrates under a small pressure gradient a short vertical distance into the combustion zone along the boundary between the combustion zone and the unburned oil-bearing formation. This small

amount of migrated oil tends to contribute little to the operation of the known intermittent in situ combustion methods. One reason for this, in addition to a small pressure drive, is that substantially all the heat passing from the combustion zone to the unburned oil-bearing formation is by conduction. As a result, the unburned formation is heated to a distance of only several feet from the combustion zone and oil can migrate to the combustion zone only from this relatively small heated area in the unburned formation. Further, only a small amount of such migrated oil will flow into the production well.

It is therefore an object of the present invention to provide an improved method of intermittent in situ combustion for recovering hydrocarbons from subterranean oil-bearing formations. Another object of this invention is to use such improved method to recover substantially all of the oil from a given subterranean oil-bearing formation and ultimately use a lesser number of successive thermal drives than in heretofore known similar processes. Another object of this invention is to use such improved method in an oil-bearing formation without leaving some areas unstripped of oil as a result of such areas having lower permeability. Another object of this invention is to use such improved method for the recovering of oil from oil-bearing formations with equal facility for all oils independent of their natural characteristics. Another object of this invention is to provide an improved in situ combustion method for recovering oil wherein a relatively constant ratio of the quantity of the oxygen-containing fluid injected into the formation to the amount of oil produced is maintained for each of the successive combustion fronts. These and other objects will be more apparent from the following description of one illustrative embodiment of the present invention and the appended claims.

Generally, the known intermittent in situ combustion methods utilize an input well and an adjacent production well which wells penetrate the subterranean oil-bearing formation. A combustion zone is initiated by conventional means through the input well in a portion of the oil-bearing formation adjacent the input well. An oxygen-containing fluid is injected into the combustion zone to drive a combustion front with a very small vertical sweep rapidly through the more permeable areas of the oil-bearing formation to the production well. A heat-soaking period is obtained by terminating the injection of the oxygen-containing fluid into the formation when the production well is heated to about well-destructive temperatures. During the heat-soaking period the heat is conducted from the combustion zone into the adjacent unburned oil-bearing formations. Preferably, the heat-soaking period extends for an interval of time sufficient for the formation adjacent the production well to cool to a temperature at which the formation oil is too viscous to be produced in significant amounts. The steps of igniting and driving a combustion front through the formation and terminating the injection of the oxygen-containing fluid to provide the heat-soaking period are repeated to provide successive intermittent thermal drives to recover as much of the oil from the mentioned formation as possible or desired.

In accordance with the present invention there are provided additional steps to be taken in conjunction with the known intermittent in situ combustion methods. These steps greatly improve such methods whereby substantially all of the oil contained in a given subterranean oil-containing formation can be recovered with greater efficiency. Briefly, the present invention comprises at least one of the following steps to be practiced in conjunction with the steps of known intermittent in situ combustion meth-

ods. In the heat-soaking period, after a combustion front has traversed the formation, a hydrocarbon-soluble gas is injected through the input well to increase the gas-to-oil ratio of the oil-bearing formation. After the gas-to-oil ratio of the oil bearing formation is increased, the pressure in the production well is reduced to increase the flow of oil through the formation. Subsequent to reducing the pressure in the production well, and prior to the initiation of a subsequent combustion front, a viscous combustible fluid is injected through the input well into the combustoin zone to reduce the permeability of the combustion zone. The steps may be repeated until all of the oil in the oil-bearing formation is recovered.

Proceeding now with a more detailed description of the present invention, the relationship of the above steps separately to, and in combination with, the steps of the known methods of intermittent in situ combustion to recover oil from subterranean formations will become apparent.

The step of injecting a hydrocarbon-soluble gas through the input well produces an increase in the gas-to-oil ratio in both the unburned portion of the oil-bearing formation and in the combustion zone. The hydrocarbon-soluble gas may be any gas that is soluble in the oil of the formation. The gas may be combustible but should contain insufficient oxygen to support combustion. The hydrocarbon-soluble gas preferably is a hydrocarbon which is normally gaseous at the conditions present within the formation. Natural gas or enriched natural gas containing C_3 or C_4 hydrocarbons may be used. The hydrocarbon-soluble gas may also be a gas such as carbon dioxide or other gas soluble in oil. Effluent residual gases from the production well may also be used. The amount of the hydrocarbon-soluble gas injected into the formation through the input well is not critical. However, the gas should be injected in an amount to reduce the viscosity of the oil sufficiently that it will flow at temperatures of about 200° F. above formation temperature. Thus, the oil will flow through the formation into the production well and from the unburned oil-bearing formation into the combustion zone so as to resaturate it at least partially. The injection pressure generally will not exceed the pressure at which the oxygen-containing fluid is injected into the combustion zone. Thus, the wellhead gas compressing means employed for injecting the oxygen-containing fluid are more fully utilized. However, the exact magnitude of pressure is not critical and injection pressures other than those of the oxygen-containing fluid may be used as long as the pressure is not less than that existing at the production well. The hydrocarbon-soluble gas is injected through the input well during the interval of time during which the injection of the oxygen-contained fluid remains terminated. The hydrocarbon-soluble gas may be injected for all or any part of such interval of time as is found to produce best results.

Increasing the gas-to-oil ratio of the oil-bearing formation by at least partially saturating the oil contained therein increases the efficiency of known intermittent in situ combustion methods. For example, injecting the hydrocarbon-soluble gas provides a heat convection means which reduces the time required for distributing the heat from the combustion zone to the unburned oil-bearing formation. Further, the viscosity of the oil in the unburned oil-bearing formation is reduced proportionately to the increase in the gas-to-oil ratio and the temperature increase. Thus, the oil is more readily driven from the capillaries and pores of the formation to flow to the production well and through the combustion zone. This flow reduces the time of the heat-soaking period.

The previously burned area or combustion zone is at least partially resaturated with oil as a result of the above gas injection, and the permeability to gas of the unbured formation is increased due to the decreased liquid

saturation. For these reasons, the oxygen-containing fluid will not channel as readily through the previous combustion zone upon passage of a subsequent combustion front. The oil-producing efficiency of a subsequent combustion front thereby is improved by an increase in the vertical sweep of such combustion front because the oxygen-containing fluid will flow in greater amounts through the unburned oil-bearing formation. This is of particular significance when the vertical dimension of the combustion zone is large and is especially important when the oil in the formation has a high viscosity.

The injection of the gas provides a further result with respect to the recovery of oil. Thus, injecting the hydrocarbon-soluble gas provides a pressure gradient between the input and the production wells during the "heat-soaking period" to move the oil in the formation from the high pressure area adjacent the input well to the lower pressure area adjacent the production well. This is particularly so when used with one or both of the following steps.

The step of reducing the pressure in the production well may be used separately or in combination with the preceding step. The pressure is reduced to a point at which significant solution gas drive occurs in the unburned oil-bearing formation and combustion zone adjacent the production well. The pressure in the production well is reduced at a time subsequent to terminating the injection of the oxygen-containing fluid into the formation and prior to a subsequent combustion front being driven through the oil-bearing formation to adjacent the production well. If the step of injecting the hydrocarbon-soluble gas is utilized, the pressure reducing step should preferably occur after the desired increase in the gas-to-oil ratio is obtained in the formation. However, this step is useful in improving the efficiency of the known in situ combustion methods without injection of the hydrocarbon-soluble gas. More particularly, it is useful when the oil in the formation has any significant vapor pressure at the conditions present in the heated portions of the formation. The pressure in the production well is reduced in an amount sufficient to produce significant solution gas drive in the oil contained in the heated formation adjacent the combustion zone. For example, assume the injection pressure of the oxygen-containing fluid or the hydrocarbon-soluble gas, as the case may be, to be about 500 pounds per square inch gauge (hereinafter abbreviated as "p.s.i.g."). The pressure in the production well may be reduced conveniently, for example, to about 15 p.s.i.g. Thus, a reduction in pressure of 485 pounds can be effected. Such pressure reduction can create significant solution gas drives in even tarlike oils having only a moderate gas-to-oil ratio. This reduction in pressure causes the oil to flow from the interstices of the unburned oil-containing formation and into the combustion zone to resaturate same. Also, the oil flows from the formation into the production well. The flow of oil accelerates the cooling of the formation adjacent the production well by convection to reduce the period of heat soaking. Moreover, the combustion zone is resaturated for a relatively great radial distance from the production well as a result of the rather high permeability of the combustion zone. This step is of great advantage when used separately or in combination with the other steps of this invention. This step results in an increase in the amount of oil recovery at the production well due to solution gas drive during the heat-soaking period of intermittent in situ combustion. Also, this step results in partially blocking the combustion zone adjacent the production well during passage of a subsequent combustion front to reduce the tendency of the injected oxygen-containing fluid to channel through the previous combustion zone rather than passing through the unburned oil-bearing formation. This, of course, greatly increases the efficiency of the subsequent thermal drives.

Upon passage of the combustion front through the oil-containing formation in conventional methods, the pressure between the input well and the output well rapidly becomes equalized when the flow of the oxygen-containing fluid or other fluids into the formation is terminated. This is because the combustion zone is a rather highly permeable zone through which fluids can freely flow from the input well to the production well. Oil production will be slight under these circumstances since only a slight pressure gradient may exist between the input and production wells. Thus, increasing the gas-to-oil ratio by the preceding step produces significant increases in oil production in combination with the step of reducing the pressure in the production well.

The step of injecting a viscous combustible fluid through the input well into the combustion zone may be used separately or in combination with the preceding steps. This viscous fluid may be of any type that can be burned in the formation upon the injection of an oxygen-containing fluid in a similar manner as the interstitial oil. Further, the viscosity of the injected fluid at the temperature in the combustion zone should be about as great as the viscosity of the formation or reservoir oil at the temperature in the unburned formation. Most commonly, it is a heavy crude oil. Other viscous hydrocarbons may also be used. The amount of the combustible fluid injected through the input well into the combustion zone is not critical. An amount of fluid injected to penetrate the combustion zone from the input well to the production well would produce maximum results. However, injecting sufficient fluid to penetrate the combustion zone to a small radial distance from the input well is sufficient. Such small radial distances may be between about 3 to about 15 feet. The combustible fluid is injected through the input well at a time prior to the initiation of a subsequent combustion front and injecting an oxygen-containing fluid into the input well.

This step may be used separately with the known intermittent in situ combustion methods. However, it has especial utility when used in conjunction with one or both of the preceding steps. By resaturating the combustion zone adjacent the input well, a subsequent combustion front can be initiated having a much greater vertical sweep adjacent the input well than the preceding combustion front that has passed through the oil-containing formation. Thus, the number of successive intermittent thermal drives required to strip the oil from the formation is greatly reduced. This, of course, increases the efficiency of the method in recovering oil. By using this step in conjunction with the step of injecting a hydrocarbon-soluble gas, the increased vertical sweep of each successive combustion front will be maintained substantially throughout its passage through the formation. One factor maintaining such increased vertical sweep is the lower viscosity of the gas-saturated oil in the unburned oil-bearing formation which provides a greater flow of the oil towards the production well and into the combustion zone. A similar result is obtained as a result of the pressure reduction step at the production well. The reduced pressure in the production well provides an oil "plug" in the combustion zone adjacent such well. As a result, a substantially equal and uniform pressure gradient exists in both the unburned oil-bearing formation and the combustion zone adjacent the production well. Thus, injecting the viscous combustible fluid into the combustion zone reduces the permeability of the combustion zone to about the permeability of the unburned oil-bearing formation, especially adjacent the input well to maintain the initial vertical sweep efficiency of combustion front. Additionally, this step reduces the possibility of the oxygen-containing fluid being injected into the input well to by-pass or channel through the previous combustion zone to the production well. The steps of reducing the pressure at the production well and injecting the hydrocarbon-soluble gas maintain the vertical sweep efficiency throughout the travel of the subsequent combustion front. The combination of all of the above steps minimizes the amounts of oxygen-containing fluid required to produce a desired degree of oil recovery. This is for the reason that the ratio of the amount of oxygen-containing fluid to the amount of oil recovered in each successive sweep remains relatively constant throughout the method of the present invention.

In summary, the preceding steps may be used individually and in combination with the steps of the known methods of intermittent in situ combustion for recovering oil from subterranean oil-bearing formations with great advantage.

From the foregoing it will be apparent that there has been herein disclosed a novel improved method of intermittent in situ combustion for efficiently and completely recovering oil in accordance with the stated objects of this invention. Various combinations and subcombinations of the disclosed steps of this invention may be made with the steps of the known methods of the type described as is apparent to one skilled in the art. It is intended that these combinations and the subcombinations of such steps are to be included in the disclosed invention and encompassed within the scope of the following appended claims.

What is claimed is:

1. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating the recited steps, the improvement which comprises the steps of:

(*a*) injecting a hydrocarbon-soluble gas through the input well to increase the gas-to-oil ratio of the unburned oil-bearing formation and the combustion zone between the input and production wells for the interval of time when the injection of the oxygen-containing fluid remains terminated,

(*b*) reducing the pressure in the production well to a pressure at which significant solution gas drive occurs in the unburned oil-bearing formation adjacent to the production well at a time subsequent to terminating the injection of the oxygen-containing fluid into the formation and prior to a subsequent combustion front being driven through the oil-bearing formation to adjacent the production well, and

(*c*) injecting a viscous combustible fluid through the input well into the combustion zone in an amount to substantially reduce the permeability of the combustion zone adjacent the input well at a time prior to the initiating of a subsequent combustion front.

2. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid

into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating the recited steps, the improvement which comprises:

(*a*) injecting a hydrocarbon-soluble gas through the input well to increase the gas-to-oil ratio of the unburned oil-bearing formation and the combustion zone between the input and production wells for the interval of time when the injection of the oxygen-containing fluid remains terminated, and

(*b*) reducing the pressure in the production well to a pressure at which significant solution gas drive occurs in the unburned oil-bearing formation adjacent to the production well at a time subsequent to terminating the injection of the oxygen-containing fluid into the formation and prior to a subsequent combustion front being driven through the oil- bearing formation to adjacent the production well.

3. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts thereafter repeating the recited steps, the improvement which comprises:

(*a*) injecting a hydrocarbon-soluble gas through the input well to increase the gas-to-oil ratio of the unburned oil-bearing formation and the combustion zone between the input and production wells for the interval of time when the injection of the oxygen-containing fluid remains terminated, and

(*b*) injecting a viscous combustible fluid through the input well into the combustion zone in an amount to substantially reduce the permeability of the combustion zone adjacent the input well at a time prior to the initiating of a subsequent combustion front.

4. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating the recited steps, the improvement which comprises:

(*a*) reducing the pressure in the production well to a pressure at which significant solution gas drive occurs in the unburned oil-bearing formation adjacent to the production well at a time subsequent to terminating the injection of the oxygen-containing fluid into the formation and prior to a subsequent combustion front being driven through the oil-bearing formation to adjacent the production well, and

(*b*) injecting a viscous combustible fluid through the input well into the combustion zone in an amount to substantially reduce the permeability of the combustion zone adjacent the input well at a time prior to the initiating of a subsequent combustion front.

5. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating the recited steps, the improvement which comprises injecting a hydrocarbon-soluble gas through the input well to increase the gas-to-oil ratio of the unburned oil-bearing formation and the combustion zone between the input and production wells for the interval of time when the injection of the oxygen-containing fluid is terminated whereby the heat from the combustion zone is distributed to the unburned oil-bearing formation and the viscosity of the oil in such formation is reduced.

6. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating the recited steps, the improvement which comprises reducing the pressure in the production well to a pressure at which significant solution gas drive occurs in the unburned oil-bearing formation adjacent to the production well, and said step of reducing the pressure occurring at a time subsequent to terminating the injection of the oxygen-containing fluid into the formation and prior to a subsequent combustion front being driven through the oil-bearing formation to adjacent the production well whereby the amount of oil produced into the production well is increased and sufficient oil is driven from the unburned oil-bearing formation into the combustion zone to reduce its permeability.

7. In a method of recovering hydrocarbons by intermittent in situ combustion from a subterranean oil-bearing formation which has been penetrated by an input well and an adjacent production well and includes the steps of initiating a combustion zone in a portion of the oil-bearing formation adjacent the input well and injecting an oxygen-containing fluid into the combustion zone to drive a combustion front through the more permeable areas of the oil-bearing formation to the production well, recovering hydrocarbons from the production well, terminating the injection of the oxygen-containing fluid into the formation upon the production well being heated to about well-destructive temperatures for an interval of time until the formation adjacent the production well cools to a temperature at which the formation oil is too viscous to be produced in significant amounts and thereafter repeating

the recited steps, the improvement which comprises injecting a viscous combustible fluid through the input well into the combustion zone in an amount to substantially reduce the permeability of the combustion zone adjacent the input well, and the step of injecting such fluid occurring prior to the initiating of a succeeding combustion front and injecting an oxygen-containing fluid into the input well whereby the vertical sweep of the succeeding combustion front is greatly increased to more effectively recover all the oil from the oil-bearing formation.

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CHARLES E. O'CONNELL, *Primary Examiner.*

BENJAMIN HERSH, *Examiner.*