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INITIATION OF COMBUSTION IN A SUBTERRANEAN PETROLEUM OIL RESERVOIR

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This invention relates to recovery of petroleum oil from subterranean reservoirs and relates more particularly to the combustion method of recovering petroleum oil from subterranean reservoirs.

Petroleum oil is generally recovered initially from most subterranean reservoirs as a result of gas pressure or natural water drive forcing the oil from the oil-bearing formation or reservoir to the producing well and to the surface of the earth. As recovery of oil from the reservoir continues, the reservoir energy gradually decreases and finally becomes insufficient to force the oil to the surface of the earth, although a major portion of the oil originally in the reservoir remains therein. In other reservoirs, the reservoir energy, from the standpoint of the characteristics of the petroleum oil or otherwise, may be insufficient to force the oil from the reservoir to the producing well. To recover oil from these reservoirs, pumping may be employed but when the rate of recovery by pumping falls to an uneconomically low level, or pumping is ineffective, as for example where the viscosity of the oil is too high to effect movement thereof by pumping, oil may often be economically recovered by the employment of methods such as gas drive or water drive. It has recently been proposed to recover oil from reservoirs where these methods are uneconomical or ineffective by combustion or burning of a part of the oil in place in the reservoir, the combustion being supported by continuous injection of air or other oxidizing medium through an input well or wells, whereby as a result of decreased viscosity and distillation and viscosity breaking, the unburned oil, along with distillation and viscosity breaking products, may be carried to and recovered from an output well or group of output wells.

It has been proposed to initiate combustion of the oil in place in the reservoir by placing charcoal in the input well adjacent to the reservoir, the liner, if the well contains a liner, being perforated where it contacts the reservoir, injecting air or other combustion supporting medium through the input well and into the reservoir, and igniting the charcoal. It has also been proposed to initiate combustion of the oil in place in the reservoir by locating an electric heater in the input well adjacent to the reservoir, the liner, if any, being perforated, supplying air or other combustion supporting medium through the input well and into the reservoir, and supplying electric current to the heater. Combustion may be effected by these and similar methods but in many instances the combustion cannot be sustained. While conditions within the reservoir, as determined by analysis of core samples taken from the reservoir, and otherwise, and conditions of rate of flow of the combustion supporting medium are favorable for the maintenance of combustion, shortly after combustion is first effected, the concentration of combustion supporting medium in the effluent gases begins to increase and increases until the effluent gases have practically the same composition as the combustion supporting medium, signifying cessation of combustion. Further, the pressure required to maintain the

necessary or desired rate of supply of combustion supporting medium to the reservoir begins to increase toward excessively high values. Subsequent attempts to initiate sustained combustion within the reservoir by the same methods encounter the same result and many reservoirs are subject to being regarded as unsuitable for treatment by the combustion process because of impossibility of sustaining combustion after initiation.

It is an object of this invention to extend the applicability of the combustion process for recovery of oil from subterranean oil-containing reservoirs. It is another object of this invention to provide a method for initiating combustion within a subterranean petroleum reservoir. It is another object of this invention to provide a method for maintaining combustion within a subterranean petroleum oil reservoir after combustion has been first effected. These and other objects of the invention will become apparent from the following description thereof.

In accordance with the invention, a subterranean oil-containing reservoir having an input well leading thereto and an output well leading therefrom is supplied through the input well with combustion supporting medium and with heat to effect combustion within the reservoir, and thereafter the supply of combustion supporting medium is maintained while the supply of heat is alternately discontinued and continued until sustained combustion is effected within the reservoir.

In the practice of the invention, the reservoir is heated at the input well to a sufficient temperature and supplied with combustion supporting gas in sufficient amount to effect combustion of the oil within the reservoir. As heat and combustion supporting gas are supplied to the reservoir, the ratio between the rate at which the combustion supporting gas is supplied to the reservoir and the pressure at which the gas is supplied to the reservoir will begin to increase but will thereafter decrease. Heat and combustion supporting gas are continued to be supplied to the reservoir at least until the rate-pressure ratio of the gas decreases to below its original value and at this time the supply of heat to the reservoir is discontinued. However, the supply of combustion supporting gas is continued. With the supply of heat discontinued and the supply of combustion supporting gas continued, the rate-pressure ratio of the gas will thereafter begin to increase, and the heat supply is discontinued at least until the rate-pressure ratio of the gas begins to increase. After the rate-pressure ratio of the gas begins to increase, heat is again supplied to the reservoir and the rate-pressure ratio of the gas, which was previously increasing, will again begin to decrease. Heat is continuously supplied to the reservoir at least until the rate-pressure ratio of the gas begins to decrease and, at this time, the supply of heat is again discontinued. The rate-pressure ratio of the gas will thereafter begin to increase and the supply of heat is discontinued at least until the rate-pressure ratio of the gas begins to increase and thereafter heat is again supplied to the reservoir. If the rate-pressure ratio of the gas does not begin to decrease, sustained combustion will have been effected, and the supply of heat is discontinued. However, if the rate-pressure ratio of the gas begins to decrease when the supply of heat is continued, the procedure of discontinuing the supply of heat, and again supplying heat, while maintaining the supply of combustion supporting gas, is repeated thereafter until such time that the rate-pressure ratio of the gas no longer decreases when heat is being supplied to the reservoir signifying that combustion is proceeding satisfactorily in the reservoir. The supply of heat is then discontinued and combustion will be maintained by supplying combustion supporting gas to the reservoir.

At a minimum, two cycles of discontinuing the supply

of heat to the reservoir and thereafter supplying heat to the reservoir will be required in order to initiate sustained combustion, i. e., combustion which can be maintained by supplying combustion supporting gas to the reservoir. However, a greater number of cycles may be required. No general rule can be given as to the number of cycles that will be required since the number of cycles required will depend upon reservoir conditions, the rate and pressure at which the combustion supporting gas is supplied, and the extent to which the rate-pressure ratio of the gas is allowed to decrease before thereafter supplying heat. In each case, therefore, the cycle of discontinuing the supply of heat and thereafter supplying heat is repeated at least twice, and as many more times as may be required, to initiate sustained combustion.

Prior to the time sustained combustion is effected, the rate-pressure ratio will increase during the time that heat is not being supplied to the reservoir and will decrease during the time that heat is being supplied to the reservoir and there will be a lag between the time that the supply of heat is discontinued or continued and the time that the rate-pressure ratio changes its direction from an increase to a decrease or from a decrease to an increase. In each cycle, heat is supplied to the reservoir at least until the rate-pressure ratio of the gas begins to decrease, and the supply of heat is discontinued until at least the rate-pressure ratio of the gas begins to increase. Heat may be continuously supplied to the reservoir, after the rate-pressure ratio of the gas has begun to decrease, until the rate-pressure ratio of the gas has decreased to any desired extent below its previous maximum value. For example, the heat may be supplied to the reservoir until the rate-pressure ratio of the gas has decreased to about one-half its previous maximum value before the supply of heat is discontinued. Generally, the extent to which the rate-pressure ratio of the gas is permitted to decrease before the supply of heat is discontinued will depend upon the economics of supplying combustion supporting gas to the reservoir at increased pressure and the capacity of the equipment supplying the gas. Similarly, the supply of heat to the reservoir may be discontinued, after the rate-pressure ratio of the gas has begun to increase, until the rate-pressure ratio of the gas has increased to any desired extent above its previous minimum value, as for example, twice its previous minimum value. However, it is preferred not to permit the rate-pressure ratio of the gas to increase above the rate-pressure ratio of the gas at the time the heat and combustion supporting gas is first supplied to the reservoir in order that excessive cooling of the reservoir, involving waste of heat in the next heat-supplying step of the cycle, is avoided.

Heat is supplied to the reservoir by any suitable means that can be controlled with respect to discontinuing and continuing the supply of heat to the reservoir when desired. It is preferred, for supplying heat to the reservoir, to employ a heater positioned in the input well alongside the reservoir. Suitable types of heaters include electric heaters and gas-fired heaters, but an electric heater is preferred. The heater need not be positioned alongside the reservoir but may be positioned in the input well at any point above the reservoir since sufficient heat may be supplied to the reservoir by reason of the combustion supporting gas passing over the heater prior to entering the reservoir. Similarly, heat may be supplied to the reservoir by heating the combustion supporting gas at the surface of the earth prior to entering the input well.

Temperatures required to effect combustion within the reservoir depend upon the character of the petroleum oil within the reservoir but a temperature of 700° F. will ordinarily effect combustion. However, higher temperatures may be employed, as for example, 1400° F. Lower temperatures, such as 400° F. or 500° F., will often be satisfactory. These temperatures may be readily obtained with electric heaters and gas-fired heaters, and where heat is supplied to the reservoir by heating the combustion supporting gas at the surface of the ground prior to entering the input well, the gas may be readily heated to these and higher temperatures in electrically operated or gas-, liquid-, or solid fuel-fired heat exchangers or by other means.

The combustion supporting gas is preferably air. However, any gas capable of supporting combustion within the reservoir may be employed. For example, oxygen, oxygen-enriched air, air admixed with inert gas to reduce the proportion of oxygen, oxygen admixed with inert gas, and flue gases containing oxygen may be employed.

The pressures employed for supplying the combustion supporting gas to the reservoir must be sufficient to obtain the desired rate of supply of combustion supporting gas to the reservoir. Pressure drop of the combustion supporting gas, of course, will occur in the reservoir and the pressure drop will depend upon the permeability of the formation and upon other factors such as the fluid saturations of the reservoir. Accordingly, no general rule can be given with respect to the pressures to be employed for supplying the combustion supporting gas. However, pressures can be selected in operation of the process to give the desired rate of supply of the combustion supporting gas to the reservoir and the amount of combustion supporting gas required may be determined from analysis of core samples taken from the reservoir and otherwise.

The following example will be illustrative of the invention. In the example, the times referred to indicate the total accumulated time from the beginning of operation.

A subterranean petroleum oil reservoir located in Oklahoma and containing Mid-Continent base crude and having an input well leading thereto and an output well leading therefrom was heated by means of an electric heater positioned in the input well alongside the reservoir and air was pumped into the input well and into the reservoir. The temperature of the heater was 500° F. and the air was supplied to the input well at a rate of 510 standard cubic feet per hour at a pressure of 105 pounds per square inch gauge, the rate-pressure ratio being 4.9. Air and heat were continued to be supplied to the reservoir and, after 15 hours, carbon dioxide appeared in a concentration of 0.5 percent in the effluent gases from the output well. During this 15-hour period, the rate-pressure ratio of the gas increased to 7.5 with the air pressure increasing to 120 pounds per square inch gauge and the air rate increasing to 895 standard cubic feet per hour. The temperature of the heater had increased to 980° F. With continued supply of heat and air to the reservoir, the concentration of carbon dioxide in the effluent gases from the output well increased but later decreased and the concentration of oxygen in the effluent gases decreased but later increased indicating cessation of combustion. Further, the air rate decreased despite an increase in the pressure until at 84 hours the air rate had decreased to 245 standard cubic feet per hour and the pressure had increased to 150 pounds per square inch gauge, the rate-pressure ratio being 1.6. At this point, the electric heater was turned off but the supply of air was continued.

After the supply of heat was discontinued, the rate-pressure ratio slowly increased and at 115 hours the air rate had increased to 505 standard cubic feet per hour at a pressure of 146 pounds per square inch gauge, the rate-pressure ratio being 3.5. At this time, the electric heater was turned on. At 118 hours, the concentration of carbon dioxide in the effluent gases began to increase, the concentration of oxygen in the effluent gases began to decrease, and the air rate had decreased to 295 stand-

ard cubic feet per hour and the pressure had increased to 150 pounds per square inch gauge, the rate-pressure ratio being 2.0. The average temperature of the heater betweten 115 hours and 118 hours was 610° F. Heat was continuously supplied to the reservoir until 205 hours, at which time the air rate was 480 standard cubic feet per hour, the pressure was 150 pounds per square inch gauge, the rate-pressure ratio being 3.2, and the concentration of carbon dioxide in the effluent gases was 6.5 percent. The average temperature of the heater between 118 hours and 205 hours was 1050° F. At 205 hours the electric heater was turned off to determine whether combustion would be self-sustaining with air being supplied to the reservoir. However, with the supply of heat discontinued, the concentration of carbon dioxide in the effluent gas slowly began to drop and at 252 hours had decreased to zero indicating that combustion was not self-sustaining. At this time, the air rate was 1045 standard cubic feet per hour and the pressure was 150, the rate-pressure ratio being 7.0. The heater was then turned on for the third time at 259 hours and at 261 hours the carbon dioxide concentration in the effluent gases began to increase. At 261 hours, the air rate was 815 cubic feet per hour, the pressure was 150 pounds per square inch gauge, and the rate-pressure ratio was 5.4.

As heat was continued to be supplied to the reservoir for the third time, the rate-pressure ratio dropped to a minimum of 2.0 and then began to increase and at 451 hours the rate-pressure ratio was 3.2 with the rate being 480 standard cubic feet per hour and the pressure 150 pounds per square inch gauge. The carbon dioxide concentration in the effluent gases was 9 percent. The average temperature of the heater between 259 hours and 451 hours was 1250° F. The electric heater was turned off for the third time, again to determine whether combustion was self-supporting, but the carbon dioxide concentration in the effluent gases began to decrease and the rate-pressure ratio increased, indicating that combustion had again ceased.

At 1,013 hours, combustion having ceased, the electric heater was turned on for the fourth time and the carbon dioxide concentration began to increase. At 1,064 hours, the rate-pressure ratio was 26.2, the air rate being 3,150 standard cubic feet per hour and the pressure 120 pounds per square inch gauge. The temperature of the heater was 1,340° F.

At 1,202 hours the electric heater was turned off and during the time between 1,064 and 1,202 hours the carbon dioxide concentration in the effluent gases and the air rate were increasing. At the time the heater was turned off, the rate-pressure ratio was 27.7, the air rate being 3,050 standard cubic feet per hour, and the pressure being 110 pounds per square inch gauge, and the concentration of carbon dioxide in the effluent gases was 14 percent. Thereafter, there were no increases in the rate-pressure ratio, the concentration of carbon dioxide in the effluent gases did not increase, and combustion was maintained only by supplying air to the reservoir.

Having thus described my invention, it will be understood that such description has been given by way of illustration and example and not by way of limitation, reference for the latter purpose being had to the appended claims.

I claim:

1. A process of initiating combustion in a subterranean petroleum oil reservoir comprising supplying said reservoir through an input well leading thereto with air under pressure and with heat to effect combustion of petroleum oil within said reservoir, thereafter maintaining the supply of air to said reservoir, continuing the supply of heat to said reservoir until the rate-pressure ratio of the air decreases, next discontinuing the supply of heat to said reservoir until the rate-pressure ratio of the air increases, thereafter continuing the supply of heat until the rate-pressure ratio of the air decreases, and then alternately discontinuing the supply of heat and continuing the supply of heat with change in the rate-pressure ratio of the air until sustained combustion is effected within said reservoir.

2. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material comprising passing under pressure into said subterranean formation through an input well leading thereto a combustion supporting medium for said combustible material and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases until sustained combustion is effected within said subterranean formation.

3. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material comprising passing air under pressure into said subterranean formation through an input well leading thereto and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said air into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said air decreases, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said air increases, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said air decreases, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said air increases and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said air decreases until sustained combustion is effected within said subterranean formation.

4. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material comprising passing under pressure into said subterranean formation through an input well leading thereto a combustion supporting medium for said combustible material and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases below its original value, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases until sustained combustion is effected within said subterranean formation.

5. A process of initiating combustion of a combustible

material in a subterranean formation containing said combustible material comprising passing under pressure into said subterranean formation through an input well leading thereto a combustion supporting medium for said combustible material and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases below its original value, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium has increased above said original value, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases below said original value, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases above said original value and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases below said original value until sustained combustion is effected within said subterranean formation.

6. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material comprising passing under pressure into said subterranean formation through an input well leading thereto a combustion supporting medium for said combustible material and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value until sustained combustion is effected within said reservoir.

7. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material compresing passing under pressure into said subterranean formation through an input well leading thereto a combustion supporting medium for said combustible material and supplying heat to said subterranean formation to effect combustion of said combustible material, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value, next discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases to at least twice its previous minimum value, thereafter continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value, and then alternately discontinuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases to at least twice its previous minimum value and continuing the supply of heat to said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases to at least one-half its original value until sustained combustion is effected within said subterranean formation.

8. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material and having an input well leading thereto comprising positioning a heater in said input well at a point such that upon operation of said heater heat will be supplied to combustion supporting medium passed under pressure into said subterranean formation through said input well, passing under pressure into said subterranean formation through said input well a combustion supporting medium and operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, next discontinuing operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases, thereafter operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, and then alternately discontinuing operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases and operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases until sustained combustion is effected within said subterranean formation.

9. A process of initiating combustion of a combustible material in a subterranean formation containing said combustible material and having an input well leading thereto comprising positioning a heater in said input well at a point such that upon operation of said heater heat will be supplied to combustion supporting medium passed under pressure into said subterranean formation through said input well, passing under pressure into said subterranean formation through said input well a combustion supporting medium and operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation, thereafter continuing passage of said combustion supporting medium into said subterranean formation, continuing operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, next operating said heater to reduce the supply of heat to said combustion supporting material to an amount insufficient to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases, thereafter operating said heater to supply heat to said combustion supporting medium in an amount to

bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases, and then alternately operating said heater to reduce the supply of heat to said combustion supporting medium to an amount insufficient to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium increases and operating said heater to supply heat to said combustion supporting medium in an amount to bring its temperature above the ignition temperature of said combustible material upon entering said subterranean formation until the rate-pressure ratio of said combustion supporting medium decreases until sustained combustion is effected within said subterranean formation.

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