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METHOD OF FORWARD IN SITU COMBUSTION WITH WATER INJECTION

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The present invention is concerned with a novel method for conducting underground combustion operations. More specifically, it is directed to a method for carrying out a forward combustion process under conditions requiring less air than is necessary for conventional methods.

Briefly, the process of our invention provides for a substantial savings in air compression costs while at the same time securing improved oil recovery over that obtainable by conventional combustion methods. Also, with our invention a reduction in temperature of the forward combustion front can be obtained by injecting a noncombustible liquid, such as water, together with air or an oxygen-containing gas, or by means of injecting alternate slugs of water and air during forward combustion. The details of this operation and an explanation as to how the desired results are secured will be developed in this discussion.

Some of the largest known liquid petroleum deposits in the world are the Athabasca tar sands located in northern Alberta. It has been estimated that this area alone contains approximately three hundred billion barrels of oil. Other huge deposits of a similar nature are to be found in areas of the United States and in Venezuela. Owing, however, to the highly viscous nature of these deposits, their production has presented an extremely difficult problem. Numerous proposals have been made in an effort to recover such material including, for example, processes involving mining the tar sand and thereafter centrifuging it in the presence of certain solvents and surface-active agents to separate the tar from the sand with which it is associated. Also, attempts have been made to recover oil from the tar sand by subjecting the latter to treatment with hot water and separating the resulting upper oil layer. These and other methods which have been used, however, all require large labor and capital expenditures rendering such procedures economically unattractive.

Forward combustion in oil reservoirs, i.e., an operation in which the combustion zone is propagated from a point near the face of an injection well toward a producing well, as a means of recovering deposits of this type has likewise been suggested. In general, however, the very high differential pressures that must be applied between input and producing wells to recover the oil presents an extremely difficult problem. Frequently, the pressures that must be applied to shallow reservoirs of low permeability, i.e., less than 100 millidarcies, are higher than can be applied economically and/or without causing uncontrolled fracturing of the formation which would lead to channeling and bypassing.

Forward combustion is impossible with heavy, viscous hydrocarbons of the type contemplated herein. This is for the reason that the hot portion of the reservoir rock yielding the heavy oil lies between the injection well and the burning zone. In this zone the viscosity of the oil is at a minimum; however, as the pressure of the system forces the oil toward the producing well, the oil decreases in temperature to that of the unburned portion of the reservoir. Eventually, resistance to flow through the reservoir to the producing well becomes so great that combustion can no longer continue because it is impossible to supply air at a satisfactory rate to the burning zone. Reservoirs of this type have a low effective permeability;

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however, they can be made sufficiently permeable to permit forward combustion if the now generally known technique of reverse burning is first applied. By the expression "low effective permeability" we refer to a reservoir in which the flow capacity thereof in millidarcy feet is less than about 30 times the oil viscosity in centipoises. The aforesaid expression, as applied to situations where reverse combustion alone cannot be used to recover oil in commercial quantities, refers to reservoirs where the maximum air injection rate is insufficient to produce a combustion zone temperature of about 800° F.

In all instances where present methods of forward combustion are used in oil recovery from oil reservoirs, very large quantities of air are required in proportion to the oil actually recovered. This is true because the combustion zone in conventional forward burning processes does not move forward from a given location until the fuel supply at that point has been exhausted. In the process, some of the oil is pushed ahead toward the producing well or wells. However, a very substantial amount of oil must be burned. Because the combustion zone in a conventional forward burning process does not move until a fuel supply in that location is no longer available, large quantities of air are necessary to move the front forward. Since air injection costs ordinarily constitute a major item of expense in operations of this kind, it will be apparent that any appreciable reduction in the amount of air necessary for the job increases very substantially the economic incentive for recovering valuable gaseous and liquid products by means of underground combustion.

Accordingly, it is an object of our invention to provide a method whereby the forward combustion process can be effected without the use of the large quantities of air resulting in high air-oil ratios. It is another object of our invention to effect forward combustion in a reservoir under conditions such that the combustion zone can move toward the producing well in the direction of air flow without having to burn all of the residual hydrocarbons. It is a further object of our invention to provide an improved method for conducting forward combustion in a reservoir by first igniting the formation to form a combustion zone, maintaining said combustion zone while forcing it through the reservoir in the same direction as the injected fluid, by either injecting into said reservoir a mixture of air and a noncombustible fluid, such as water, or by alternately injecting air and a suitable fluid. It is still another object of our invention to provide a procedure by which the oil remaining in a previously waterflooded reservoir can be recovered by means of thermal or underground combustion methods.

The process of our invention is generally applicable to any reservoir in which an ordinary forward burning process can be conducted. The process comprises first igniting the reservoir, after which air or equivalent oxygen-containing gas is injected in an amount sufficient to establish a definite combustion zone or front. When this front is formed in this type of reservoir, temperatures of the order of 800° to 2500° F. are generated. Thereafter, water or other suitable condensable fluid is injected into the formation and then contacts the front, whereby the latter is cooled and the resulting vapors are forced on ahead of the front pushing oil along with them. These hot vapors moving forward contact cold reservoir rock and condense, thereby heating that portion of the reservoir. Accordingly, after this injection step, air or other oxygen-containing gas is introduced into the reservoir to develop another high-temperature front in the vicinity of the reservoir rock just heated as the result of the aforesaid condensation. Water injection is then resumed and air injection is stopped. These cycles are repeated until the combustion front reaches the producing well or wells.

At this point it should be emphasized that between the injection well or wells and the combustion front an appreciable carbonaceous residue remains, particularly in the case of tar sand and viscous oil reservoirs. The oil actually moved forward through the reservoir by the process of our invention is at least equivalent to that obtained by ordinary forward combustion. The important fact is that such oil is moved through the reservoir by the use of much less air than was formerly required.

The phenomenon involved in our invention can probably be better explained by describing another, and generally preferred, embodiment employing the simultaneous injection of air and a noncombustible fluid. Thus, when a combustion front has been formed, a mixture of air and a fluid such as, for example water, is injected resulting in both vaporization of the water and cooling of the reservoir rock at the point of vaporization. This local reduction in temperature is so substantial that the oxygen present, on contact with the cooled carbonaceous material, does not cause the latter to burn. The steam thus generated, however, moves forward together with vaporized and liquid hydrocarbons through the reservoir. Where this steam condenses, the reservoir is heated. The temperature of this zone never becomes excessive with water present, however, because as the temperature tends to increase the water evaporates at a corresponding rate to remove the heat. Under such conditions, the combustion zone thus formed has its highest temperature at or near the leading edge thereof.

The process of our invention finds specific application in tar sands and heavy, viscous oil reservoirs which generally have such low permeability and/or high oil viscosity initially that they must first be subjected to a reverse combustion step before forward combustion can be carried out with any degree of success. Reverse combustion may be employed under conditions such that little or no oil is produced during this part of the process. This is possible if maximum temperatures do not exceed about 400° F. At such temperatures the viscosity of the oil or tar is reduced enough so that forward combustion can be carried out. If reverse combustion is performed at temperatures above 400° F., e.g., 600° to 800° F., substantial amounts of hydrocarbons are produced during this step. In a subsequent forward combustion operation, oil can be recovered as generally described and claimed in copending application U.S. Serial Number 759,801, filed September 8, 1958, by Frank E. Campion et al, now abandoned. In either case, however, the forward burning step can be modified, in accordance with our invention, to recover at least as much oil as could be obtained by burning forward in the usual fashion. The economics of our process, however, are much more favorable because 10 to 50 percent as much air is used than is required by conventional forward burning methods to obtain the same oil recovery.

In order to obtain the benefits of our invention, it is desirable to control the air-water ratio used. This, of course, is in turn dependent upon the heavy oil or tar content of the reservoir and upon the porosity thereof. As has been previously mentioned, we desire to operate in such a way as to leave a carbonaceous residue between the injection well and combustion front. When this result is produced, it means that the combustion front temperature is lower than normally exists in the case of conventional combustion methods. In order to obtain the advantages of our invention, the amount of water injected should be at least in excess of the amount necessary to fill the pore space back of the burning front not filled by said residue. This is true for the reason that in order to maintain the cooler combustion front, water should be present in the vicinity thereof so that steam can be formed and projected ahead of the front while cooling is effected in that portion of the reservoir where the steam is produced. The air used should be at least the minimum required to sustain burning in the presence of any given quantity of water used.

In the case of tar sands or heavy oils, we ordinarily pre-

fer to operate with air-water ratios such that from about 10 to about 30 percent of the carbonaceous material originally in place is left in the reservoir after completion of the forward burning step. This means, in general, that the air-water ratio may range from 500 s.c.f. per barrel of water injected to about 3000 s.c.f. per barrel. Preferably, we usually employ air-water ratios of the order of from about 750 s.c.f. to about 2000 s.c.f. per barrel of water. These ratios not only apply to the heavy oil but also are applicable to higher gravity, e.g., 40° API oils. We have found that at air-water ratios above about 3000 s.c.f. per barrel no carbon residue is left. In such instances the oil recovery is not as good as is obtained with air-water ratios coming within the range we teach. Thus, while we have observed that at air-water ratios in excess of 3000 s.c.f. per barrel no carbon residue is left, there is no advantage in employing such higher ratios because the additional air apparently is used up in consuming the carbonaceous residue (that would otherwise be laid down at the lower air-water ratios taught herein) without any increase in the amount of oil recovered. This means then that with air-water ratios above 3000 s.c.f. per barrel the excess air is wasted. The higher the reservoir temperature prior to forward combustion the less air is required. Air-water ratios in excess of about 3000 s.c.f. per barrel of water injected are generally unnecessary, and therefore uneconomical to use, as pointed out above. In fact, higher air-water ratios than afforded by the above-mentioned maximum generally tend to defeat the purpose of our invention since hotter combustion fronts are created, resulting in a decrease in residual carbonaceous material. Within the above-stated ranges of air-water ratios, the amount of water generally needed for a particular project should ordinarily range from about 2 to about 10 barrels, or higher, per barrel of oil originally in place, greater quantities of water being required for reservoirs of low porosity and oil saturation.

It may be desirable to change injection wells after the reverse combustion step has been completed so that water and air are injected into the well that served as the production well during reverse burning. When well spacing is small, e.g., less than about 300 feet, and the reservoir is thick, e.g., greater than 10 feet, heat losses are overcome by injecting air into the reservoir at a rate as low as 2000 s.c.f.d./ft. of formation thickness. Conversely, when the well spacing is large and the formation is thin, the air injection rate should substantially exceed 2000 s.c.f.d./ft. of formation thickness to combat increased heat losses.

Also, if desired, a suitable hydrocarbon solvent such as, for example, kerosene, which is relatively volatile compared to the oil in place, may be injected prior to the water injection step. In this way, the subsequent steam bank formed when water is injected into the hot reservoir operates on a more volatile and mobile solvent bank. This combination of steps, accomplished by air injection during or after water injection, is particularly adapted to the recovery of hydrocarbons from tar sands. Generally speaking, the quantity of such solvent to be employed may range from about 1 to about 10 percent of the reservoir pore space.

Our invention may be further illustrated by the following specific example:

EXAMPLE

On a 2½ acre spacing, 5 wells are drilled to an approximate depth of 1000 feet in a 5-spot pattern. These wells penetrate a 10-foot thick layer of tar sand, the top of which is at a depth of about 945 feet. This sand contains approximately 15 weight percent oil in place, corresponding to about 54,000 barrels in the 2½ acres. The tar sand in the 4 perimeter wells is ignited and a combustion front is formed by a flow of air to these wells from the central injection well. Alternatively, this front can be established by carrying out the ignition step after air from the aforesaid injection well has reached the perimeter

wells. The reverse combustion operation thus initiated is carried out at an air flux sufficient to give a maximum temperature within the main portion of the reservoir during this portion of the process of about 400° F. After the reverse combustion front has reached the central injection well, as evidenced by an increase in temperature in the latter well opposite the tar sand, forward combustion in accordance with our invention is initiated by injecting an air-water mixture in which air is present in an amount varying from 1000 to about 3000 s.c.f. per barrel of water used. This mixture is injected at a pressure of about 1000 p.s.i. During the forward combustion step, the reservoir is observed to reach a maximum temperature of 1000° F. The front moves toward the perimeter wells at the rate of about .5 to about 1 foot per day. At the conclusion of the operation about 38,000 barrels of tar, corresponding to a 70 percent recovery, are produced from the 4 wells, requiring an air-oil ratio of 7000 s.c.f./bbl. Employment of forward combustion in the absence of water, as taught by the process of our invention, under the above reservoir conditions, results in an air-oil ratio of 25,000 s.c.f./bbl. In obtaining this result a combustion zone temperature of about 2500° F. is produced to recover about 27,000 barrels of tar.

While the present disclosure thus far emphasizes the applicability of the process of our invention to the recovery of oil from underground reservoirs of petroleum tars and viscous crudes, e.g., having an API gravity of not more than about 10°, the principles taught herein are likewise intended to be useful in reservoirs containing higher gravity oil, e.g., up to about 40° API, having an initial permeability sufficiently high to permit forward combustion, as will be shown below.

In carrying out a series of runs in which a sandstone core 1 foot in diameter and 11 feet long is enclosed in casing 12.75 inches O.D. and 11.25 feet in length, the core is saturated with a crude oil of the type designated below. The complete combustion cell is equipped with suitably located thermocouples and the unit is placed in a vertical position. The annulus between the core and the casing is packed with 34.13 pounds of sand ground and screened through a 100 mesh sieve. Saturation of the core with the oil under investigation is carried out by first flushing with about 20 s.c.f. of CO₂. Thereafter, the cell is evacuated to about 10 cm. of mercury absolute pressure. The oil is then pumped into the bottom of the core at a rate of from about 5 to 7 gallons per hour—flushing CO₂ from the system—until about 3 gallons of oil are produced from the opposite end. The initial oil

saturation in the core in each case is approximately 95 percent. Nitrogen is next injected at the lower end of the cell at a rate of about 25 s.c.f.h. until the oil production rate at the opposite end of the cell declines to approximately 200 cc. per hour.

At this point, the procedure is varied. In one group of runs, the cell is flooded with water before forward combustion is begun. In the other run, forward combustion is initiated after introduction of nitrogen is discontinued. In waterflooding the core, water is fed to the top of the cell at an initial rate of about 4 gallons per hour and the rate increased as necessary at the start to produce a pressure differential across the core of at least about 50 p.s.i. This is continued until the produced water-oil ratio exceeds 100:1. for two consecutive hours. Thereafter, the temperature of the cell from the inlet end up to about one-tenth of its length is increased to from 500° to 600° F. The remainder of the cell is held at room temperature, i.e. below 90° F. The core is under a system pressure of about 500 p.s.i. When the upper one-tenth of the core is raised to a temperature within the above range, air is introduced at the top at a rate of about 10 s.c.f.h. When forward combustion has begun in the cell, the air rate is increased to about 25 s.c.f.h. over a period of about one hour (28 s.c.f.h. air per square foot of core).

Before water injection is started, the combustion front is allowed to move about one foot away from the inlet end of the cell. At that time, the air and water streams are premixed and then introduced into the inlet end of the cell at the desired rate.

The peak combustion zone temperature moves at a rate of about 0.2 foot per hour. This operation is continued until the peak temperature reaches the exit end of the cell and decreases to about 400° F., after which the cell is depressured to atmospheric pressure. The pressure encountered during these runs varies widely. Generally, pressure drop across the core increases to 200 to 300 p.s.i. soon after the start of operations. Further increase in pressure is observed when the air-water mixture is introduced. Usually, such pressure drop ranges from about 300 to 400 p.s.i. After 50 to 60 hours, the pressure drop across the core decreases rapidly, usually to about 200 p.s.i., and after about 75 hours may be as low as 50 p.s.i.

The carbonaceous residue remaining after our process is carried out is determined by further introduction of air into the reheated core until CO₂ is no longer detected in the effluent gas.

In employing the above described procedure with the designated crudes, the following results are obtained:

Table

Crude Oil	Source		Core Saturation After Gas Drive, Percent of Pore Volume	Injected Air-Water Ratio, s.c.f./bbl.	Oil Recovery		
	Field	Formation			Liquid Oil, Percent	Combustion Products, Percent	Carbon Residue, Percent
Fourbear.....	Fourbear Field, Wyoming.	Tensleep.....	69.7	1,550	92.5	7.5	1.4
Do.....	do.....	do.....	72.6	2,300	88.2	9.9	2.2
Slaughter ¹	Slaughter Field, Texas.	San Andres.....	61.7	1,720	92.0	7.6	.36
Shannon ¹	Shannon Field, Wyoming.	Shannon.....	79.4	1,700	93.8	5.8	.41
Sloss ¹	Sloss Field, Nebraska.	Muddy "J".....	25.6	3,180	64.6	36.2	None

Crude Oil	Time, Hrs.	Maximum Press., p.s.i.	Maximum Temp., ° F.	Gallons of Oil in Place	Air-Oil Ratio ² s.c.f. bbl.	Avg. O ₂ Content in Vent Gas Before Break-through, mol. percent
Fourbear.....	100	980	830	14.8	5,400	0.65
Do.....	96	930	900	15.2	6,000	1.00
Slaughter ¹	58	550	950	13.7	3,900	2.50
Shannon ¹	60	615	850	10.9	3,500	1.00
Sloss ¹	37	550	900	5.3	12,900	1.00

¹ Core waterflooded prior to combustion.

² Based on reacted O₂.

While a number of conclusions can be drawn from the data in the above table, the fact is demonstrated that at an air-water ratio substantially in excess of 3000 s.c.f./bbl., i.e., 3180 s.c.f./bbl. no coke or carbon is laid down and the percent oil recovery is much poorer than is found in cases where such ratio is below 3000 s.c.f./bbl. With higher air-water ratios more of the oil is burned as is reflected by the fact that in the Sloss crude run, 36 percent of the petroleum was converted to gaseous products.

In view of the foregoing description a number of variations will be apparent to those skilled in the art without departing from the scope of our invention. For example, we have previously pointed out that in carrying out the process of our invention a carbonaceous residue is formed during the forward combustion phase corresponding to from about 10 to about 30 percent of the original material. This residue can be readily burned by means of a second forward combustion step under a variety of circumstances. For example, a gas of appreciable B.t.u. content can be prepared by first establishing a hot (2000° to 2500° F.) combustion front and thereafter injecting sufficient steam to bring the temperature of the front down to about 900° F. The hot coke and steam react to produce carbon monoxide and hydrogen in amounts comparable to those found in the product produced by the water-gas reaction, however, lower B.t.u. content gas is produced by the use of air-steam mixtures. After the temperature has decreased to about 900° F., air is then introduced to regenerate a combustion front temperature in the range of about 2500° F., and the above cycle repeated. Owing to the highly permeable nature of the reservoir after completion of the first forward combustion step, gasification of the resulting carbonaceous residue is readily and rapidly accomplished. In this way maximum recovery of valuable products from the reservoir is accomplished.

The term "carbonaceous," as used herein, is intended to refer to materials comprising either free or combined carbon.

This is a continuation-in-part of our copending application Serial No. 79,135, filed December 29, 1960, now abandoned.

We claim:

1. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises initiating a zone of combustion therein at a point adjoining said producing well, thereafter supplying air through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent the injection well, subsequently further introducing air and water into said deposit through said injection well in a ratio of from about 500 to about 3000 s.c.f. of air per barrel of water, whereby the course of said zone is reversed and travels concurrently with the injected air and water mixture toward said producing well, and recovering fluids resulting therefrom through said producing well.

2. The process of claim 1 in which the air injection rate during the reverse combustion step is such that the maximum temperature reached in the main portion of said deposit during such step is about 400° F.

3. The process of claim 1 in which the air and water are injected as a mixture.

4. The process of claim 1 in which the oxygen-containing gas and water are injected in the form of alternate slugs during the forward combustion step whereby said gas and water travel through said deposit in the same direction as said front.

5. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises initiating a zone of

combustion therein at a point adjoining said producing well, thereafter supplying air through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent the injection well, subsequently further introducing air and water into said deposit through said injection well in a ratio of from about 750 to 2000 s.c.f. of air per barrel of water, whereby the course of said zone is reversed and travels concurrently with the injected air and water mixture toward said producing well, and recovering fluids resulting therefrom through said producing well.

6. In a process for the underground combustion of a carbonaceous deposit being penetrated at spaced points by an injection well and a producing well and having been first subjected to a waterflooding operation to produce at least some product therefrom, the improvement which comprises injecting air into said deposit via said injection well, initiating a zone of combustion therein at a point adjoining said injection well, thereafter supplying air and water in a ratio of from about 500 to 3000 s.c.f. of air per barrel of water through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said producing well, and recovering fluids resulting therefrom through said producing well.

7. In a process for the recovery of oil from a hydrocarbon reservoir, said reservoir being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting water into said reservoir via said injection well to flood said reservoir in accordance with known methods, recovering oil from said reservoir via said producing well, thereafter initiating a zone of combustion in said reservoir at the face of said injection well, next propagating said zone through said reservoir by injecting therein via said injection well an oxygen-containing gas and water in a ratio of from about 500 to about 3000 s.c.f. of said gas per barrel of water, and recovering oil from said reservoir via said producing well.

8. The process of claim 7 in which air is the oxygen-containing gas.

9. The process of claim 8 in which the air-water ratio ranges from about 750 to about 2000 s.c.f. per barrel of water.

10. In a process for the recovery of valuable products from a carbonaceous deposit in which forward combustion can be effected without further treatment, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises igniting said deposit adjacent the face of said injection well to form a combustion front, thereafter propagating the resulting combustion front through said deposit by injecting therein via said injection well air and water in a ratio of from about 500 to about 3000 s.c.f. of air per barrel of water, and recovering valuable products from said producing well.

11. The process of claim 10 in which the oxygen-containing gas and water are introduced as a mixture.

12. The process of claim 10 in which the oxygen-containing gas and water are injected in the form of alternate slugs during the forward combustion step whereby said gas and water travel through said deposit in the same direction as said front.

13. In a process for the recovery of valuable products from a carbonaceous deposit in which forward combustion can be effected without further treatment, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises bringing said deposit at the face of said injection well to ignition temperature followed by the injection of air to establish a combustion front at the face of said injection well, propagating the resulting combustion front through said deposit by injecting through said injection well air and water in a ratio of from about 500 to about

3000 s.c.f. of air per barrel of water whereby products of said deposit are forced toward said producing well leaving a carbonaceous residue in the wake of said front, and recovering fluids resulting from the combustion process through said producing well.

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