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RECOVERY OF PETROLEUM BY COMBINATION REVERSE-DIRECT IN SITU COMBUSTION

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The present invention relates to an improved method for recovering carbonaceous materials from underground formations. More particularly, it is concerned with a novel underground combustion method for the recovery of such materials.

While the present description 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 intended to pertain likewise to the recovery of oil from oil shale and to the gasification of coal. In either of these types of carbonaceous deposits, if the native permeability thereof is insufficient, permeability may be induced in a known manner. The term "carbonaceous" as used herein is intended to refer to materials comprising either free or combined carbon.

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 various 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 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.

Underground combustion 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 millidarcys, are higher than can be applied economically and/or without causing uncontrolled fracturing of the formation which would lead to channeling and bypassing.

Conventional underground combustion, 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, 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.

In U.S. Patent 2,793,696 to Morse, a process is described for the recovery of oil by means of an underground

combustion process in which conditions are provided such that the combustion zone travels toward the injection well—countercurrent to the flow of the air through the reservoir. This method is ordinarily referred to as "reverse burning" or "reverse combustion." While this procedure has been employed on a limited scale to recover oil under conditions of low reservoir permeability, it has not met with unqualified success. Moreover, in accordance with the teachings of the Morse patent, once the combustion zone has passed through the formation from the production well to the injection well, very little, if any, residual oil or tar remains in recoverable form. Actually, there may be some cases where the nature of the reservoir oil is such that substantially all of it distills and/or is cracked. However, where the oil is so high boiling that none or very little of it distills or is cracked at the temperatures reached by reverse burning, such process is ineffective.

We have now discovered that additional oil recovery can be realized from oil-containing formations in which a reverse burning operation has been performed, merely by continuing the injection of air or other oxygen-containing gas after the reverse burning step. Completion of the latter phase is evidenced by a substantial rise in temperature at the face of the injection well.

Contrary to prior belief, we have found that after reverse burning has been completed in a reservoir, there sometimes remains a substantial amount of residual petroleum that can be recovered by continuing the flow of air through the formation and causing the combustion zone to reverse its former course, i.e., to flow concurrently with the injected air stream. Under conditions of this sort, relatively little difficulty is experienced in driving normally viscous hydrocarbons to the production well because their viscosity remains low while passing through the hot reservoir rock previously heated during the aforesaid reverse combustion step.

The process of our invention is employed to advantage in reservoirs having an initial effective permeability so low that substantially none of the hydrocarbon in place is distilled or cracked during reverse combustion. For example, in tar sands in which the initial effective permeability is so low that the maximum amount of air injected results in a peak or maximum combustion zone temperature of not more than about 300° or 400° F., no oil is produced during the reverse combustion phase of the process. However, on following this step with forward combustion, at combustion zone temperatures ranging from about 1000° to about 2000° F., economical oil recoveries are realized. Such results are made possible because in the reverse burning step the reservoir rock is heated and the viscosity of the hydrocarbon in place is greatly reduced. Forward combustion can then be used to force the oil of reduced viscosity through the heated reservoir without the difficulties referred to above which are normally encountered in attempts to recover heavy oil by the use of forward combustion alone.

The process of our invention is primarily applicable to reservoirs having a low effective initial or native permeability. By the expression "low effective intial permeability," we means a formation in which conventional forward combustion alone cannot be carried out owing to the fact that the oil temporarily reduced in viscosity in the combustion zone increases in viscosity when it contacts cold reservoir rock on its way to the producing well and hence its resistance to flow through the rock becomes so great that it is either uneconomical or impossible to continue air injection. Stated otherwise, forward combustion alone is considered feasible only when the flow capacity of the reservoir in millidarcy feet is greater 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 possible air injection rate is insufficient to produce a combustion zone temperature in excess of about 400° or 500° F.

The oil or tar recoveries realized when employing reverse combustion temperatures of not more than about 400° F., followed by forward combustion, are substantially higher than those secured when higher reverse combustion temperatures are used, as is shown in the table below. This is, indeed, considered surprising that such higher recoveries are possible with the combination of low reverse combustion temperatures followed by conventional forward combustion. The idea of heat treating or "toasting" a formation containing heavy viscous oils or tars, without producing them, by means of a low temperature reverse combustion step prior to carrying out forward combustion is—to our knowledge—a completely new concept.

The process of our invention will be further illustrated by the following specific example:

EXAMPLE

The work carried out involved the use of a combustion cell 8 inches in diameter, 14 feet long, and constructed of Schedule 40 stainless steel. The inlet end was closed by a flange which contained connections for air feed and thermocouples. The outlet end was closed by a flange from the center of which the effluent pipe extended. The cell operated in a horizontal position. It was packed with Athabasca tar sand in a vertical position, with the air feed end upward. A 2-inch layer of alundum particles was placed at the bottom. The longitudinal thermocouple wells were then installed in a plane, rotated 90° from the plane of the fixed thermocouples and one quart of tar sand was added at a time. After each addition, the sand was tamped using a packer with holes to keep the thermocouple wells properly spaced. The depth was measured at frequent intervals and the density was computed using depth and weight of tar sand added. After charging a 10 ft. depth of tar sand, the remaining 4 ft. was packed with clean sand. The cell was then flanged up and placed in a horizontal position. After measuring the permeability of the packed tar sand, air was fed at the flow rate desired for combustion and the cell discharge pressure was adjusted to 250 p.s.i.g. The external heaters were positioned and the discharge end of the cell was heated until movement of the temperature profile in the bed showed that combustion of tar sand had begun. Thereafter the heaters were adjusted during reverse combustion to keep bed temperatures nearly uniform in cross-section. During forward combustion, the heaters were adjusted to maintain the maximum temperature at about 1100° F. The cross-sectional area of the cell used in calculating the results was 0.347 sq. ft. The results obtained and the conditions employed in one particular set of runs are shown below.

The above results dramatically demonstrate the superiority in total oil recovered when operating in accordance with the present claims as opposed to operating at reverse combustion temperatures of 540° and 550° F. The reported results in Run 1 show that 63.2 weight percent of the original tar in place as recovered, whereas at 540° F. (Run 4) reverse combustion temperature the total recovery was 26.1 weight percent and at 550° F. (Run 2) reverse combustion temperature, total hydrocarbon recovery was 39.6 weight percent. While the product obtained in the runs reported in which the reverse combustion temperature was over 500° F., was improved in quality over that obtained at a maximum reverse combustion temperature of 378° F., the product from the latter process was cracked to give an oil yield of 45 weight percent comparable in quality to that produced by the other two procedures using higher reverse combustion temperatures. In addition to the 45 weight percent yield obtained in accordance with the conditions of the method covered by the present claims, there was produced a total of 18 weight percent petroleum coke and fuel gas, based on the weight of the original tar in place. This, it is submitted, is a very significant advantage our process possesses over Trantham et al. U.S. 3,126,955, since in the latter patent the coke is burned in place—requiring more process air—and the gas is so diluted with CO_2 and nitrogen that its fuel value is greatly diminished. In this connection, the gas produced by cracking of our product above ground is, of course, not diluted by nitrogen, CO_2, or other inerts.

A further important point is that the total air requirements for our process are much lower than those necessary when operating the reverse combustion phase in the 750° to 800° F. temperature range taught by the prior art, typically Trantham et al. U.S. 3,126,955. Thus, in the above table, it will be seen that in Run 1, i.e., the run carried out in accordance with the present invention, the ratio of air to produced oil was 31,200 s.c.f. per barrel. In the only other runs reporting this ratio, i.e., Runs 2 and 4, using reverse combustion temperatures of 540° and 550° F., respectively, the corresponding ratios were 115,000 s.c.f. per barrel and 73,700 s.c.f. per barrel. With compressed air costing at the rate of 3 cents per 1,000 s.c.f., the economic advantage of our combustion method over the type of procedure taught by the prior art is apparent. Specifically, this means that oil recovered by the prior methods would very likely be of the order of two to three times more expensive on the basis of air costs alone than oil produced by the process of the present claims. These figures become more favorable to our process when it is realized that the latter also yields valuable above-ground petroleum coke and a fuel gas of appreciable heat value.

A number of conditions control or influence the efficiency with which the reverse combustion phase of the process of our invention is carried out. One of the more important factors in this connection is the air injection

Table

Run	1	2	3	4	5	6
Reverse Combustion:						
Tar content of charge, wt. percent	14.7	14.7	16.81	9.6	17.53	16.23
Oil yield, wt. percent of original tar	0.0	11.0	41.0	6.3	25.0	29.8
Gravity of oil produced,° API at 60° F	-------	24.5	21.5	26.4	20.3	22.4
Average pressure, atm. absolute	18.5	18.3	1.56	18.0	1.39	1.25
Maximum combustion zone temperature, ° F	378	550	800	540	869	450–645
Original tar sand temperature,° F	84	80	80	77	80	80
Air feed flux, s.c.f.h./sq. ft	11.1	51.0	51	50.4	55.5	7.5
Combustion zone velocity, ft./hr	0.115	0.212	0.119	0.319	0.105	0.066
Subsequent Forward Combustion:						
Oil yield, wt. percent of original tar	63.2	28.6	8.3	19.8	10.0	14.0
Gravity of produced oil,° API at 60° F	10.1	25.4	-------	19.5	-------	-------
Maximum combustion zone temperature,° F	1,100	1,100	-------	1,058	-------	-------
Air feed flux, s.c.f.h./sq. ft	[1] 11.1–43.2	50.8	-------	49.7	-------	-------
Combustion zone velocity, ft./hr	[1] 0.008–0.064	0.041	-------	0.0616	-------	-------
Reverse Combustion Plus Forward Combustion:						
Oil yield, wt. percent of original tar	63.2	39.6	49.3	26.1	35.0	43.8
Air feed/product oil ratio, M s.c.f./bbl. Based on observed air feed rate	31,200	73,700	-------	115,000	-------	-------

[1] Refers to range.

rate and its effect on combustion zone temperature. The combustion zone temperature, as well as the combustion zone velocity, during reverse burning increase with increased air injection rates. Heat losses to the surrounding formation have little or no effect on combustion zone temperature. However, combustion zone velocity decreases directly with increasing heat loss. When lower oil recoveries are obtained at constant combustion zone temperature, it is an indication that heat losses are increasing or have increased. Constant combustion zone temperature under such circumstances is maintained by burning more hydrocarbon in place, thus causing lower recovery. Higher combustion zone temperatures involve the burning of larger amounts of oil in place. Accordingly, oil recovery efficiency falls off at the higher combustion zone temperatures. At low enough injection rates the temperature achieved is not ordinarily considered sufficient to vaporize or crack appreciable amounts of the tar or oil. Under such conditions the oil recovery efficiency by reverse combustion is low.

Of the material remaining in the reservoir after completion of reverse combustion, the coke fraction is greater, the higher the combustion zone temperature. As far as we have been able to determine, the temperature boundaries with respect to coke formation are about 500° F. and about 1,000° F. In other words, very little hydrocarbon is coked at combustion zone temperatures below 500° F. and after combustion at temperatures of the order of about 1,000° F. most residual material is in the form of coke. The material consumed during reverse combustion most likely depends on the combustion zone temperature. Thus, at low temperatures the primary fuel is essentially the reservoir tar or viscous oil, while at higher combustion zone temperature the principal fuel is partially coked hydrocarbon.

Another factor affecting combustion zone temperature is the pressure prevailing in the reservoir during combustion. This is readily shown when the system is operated at constant air injection rates. For example, in a series of tests carried out in Athabasca tar sands, combustion zone temperatures of about 870° F. were generated at air injection rates of the order of 60 s.c.f./hr./ft.^{2} and at pressures near atmospheric, i.e., about 15 to 25 p.s.i.a. When the pressure was increased to 265 p.s.i.a., the combustion zone temperature was found to decrease to about 650° F. at the same air rate. Likewise, at an air injection rate of 60 s.c.f./hr./ft.^{2}, the combustion zone velocity at pressures of the order of 15 to 25 p.s.i.a. was about .17 ft./hr. Whereas, at 265 p.s.i.a., the velocity was about .45 ft./hr. at the same air rate. Thus, it will be seen that both combustion zone velocity and temperature are dependent upon and can be controlled by reservoir pressure.

The pressures used in carrying out the process of the present invention may vary widely depending on a number of conditions such as the permeability of the reservoir, the desired combustion zone temperature, the air injection rate, etc. In general, it may be said that the pressure employed should exceed that of the reservoir but should not be sufficiently great to cause uncontrolled fracturing of the formation and undesirable channeling and bypassing of the injected air.

Coke formation at the higher combustion zone temperature aids in solving one of the main problems of producing oil from Athabasca tar sands. This is for the reason that the McMurray formation in which these tar sands are found is unconsolidated. By first performing a reverse burning step on such formation, however, it is possible to condition the formation by the partial conversion of the in-place hydrocarbon into coke. This results in consolidation of the sand. Such coke formation will occur near the face of the producing well bore, particularly where high injection rates are used to initiate combustion in the producing well. The resulting coked zone has very good permeability.

Oil recovery conditions accompanying forward combustion following reverse burning, however, are not typical of those prevailing when forward combustion alone is employed. The principal difference in carrying out forward combustion in accordance with our invention is the complete absence of water which has been removed during the previous reverse burning phase. Furthermore, at the temperature prevailing after the reverse phase, no water of combustion formed during the forward phase will condense, unless the reservoir pressure is in excess of the steam saturation pressure. The absence of liquid water is of particular importance since when it is present, it seriously interferes with the flow of oil and gas. The nature of the oil in place is also altered as a result of partial oxidation and substantial quantities of it may be coked depending on the combustion zone temperature.

Although the process of our invention possesses a number of advantages when applied to tar-containing formations of the type contemplated herein, there are three practical advantages thereof which are considered particularly outstanding.

(1) Saving of air required for reverse combustion.

(2) Less oil is burned on reverse combustion, leaving more to be recovered in the forward combustion step.

(3) The product recovered, while principally tar, can be cracked above ground to produce a good grade of crude oil in addition to substantial quantities of coke and gas useful for fuel purposes.

From the foregoing description it will be seen that we have provided the art with an underground thermal recovery procedure capable of producing petroleum from formations which cannot be successfully produced by means of conventional forward combustion methods. Also, we have provided an integrated procedure for recovery of increased quantities of oil over those obtainable by subjecting the same reservoir to reverse combustion alone.

Although the process of our invention, as applied to the recovery of oil, has been directed largely to petroleum tars and low gravity oils, it is likewise applicable to higher gravity crudes. Thus, our invention may be used to recover oil from reservoirs which have already been subjected to primary and/or secondary recovery methods. Also, it may be applied to reservoirs containing high gravity oil but low reservoir energy, e.g., very little, if any, dissolved gas.

While we have mentioned only the use of air as an oxygen source in carrying out our process, oxygen-enriched air, of course, may be employed. Also, it may be desirable to recycle a portion of the combustion products from the producing well, particularly carbon dioxide, and mixing said products with the air injection stream.

This is a continuation-in-part of our copending application U.S. Serial No. 759,801, filed September 8, 1958, now abandoned.

We claim:

1. In a process for the recovery of hydrocarbons by means of underground combustion from a carbonaceous deposit having a low initial effective permeability, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit via said injection well an oxygen-containing gas, initiating combustion of the oil in place in said reservoir at the bore of said producing well, thereafter supplying an oxygen-containing gas through said injection well to the resulting burning zone to maintain said zone and to propagate it through said reservoir toward said injection well, the injection of said gas into said injection well being in an amount sufficient to create a maximum temperature in said reservoir of not more than about 400° F., continuing injection of an oxygen-containing gas through said injection well without forcing liquid hydrocarbons into said producing well until said zone has reached at least the immediate area of the injection well, thereafter introducing an oxygen-containing

gas into said reservoir via said injection well at an increased injection rate whereby the course of said zone is reversed and is caused to travel concurrently with said gas toward said producing well, and recovering hydrocarbons from said producing well.

2. In a process for the recovery of hydrocarbons by means of underground combustion from a carbonaceous deposit having a low initial effective permeability, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit via said injection well an oxygen-containing gas, initiating combustion of the oil in place in said reservoir at the bore of said producing well, temporarily supplying an oxygen-containing gas through said producing well to maintain said combustion and to propagate a combustion zone through said reservoir away from said producing well, discontinuing the injection of said gas into said producing well and thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said reservoir toward said injection well, the injection of said gas into said injection well being in an amount sufficient to create a maximum temperature in said reservoir of not more than about 400° F., continuing injection of an oxygen-containing gas through said injection well without forcing liquid hydrocarbons into said producing well until said zone has reached at least the immediate area of the injection well, thereafter introducing an oxygen-containing gas into said reservoir via said injection well at an increased injection rate whereby the course of said zone is reversed and is caused to travel concurrently with said gas toward said producing well, and recovering hydrocarbons from said producing well.

3. In a process for the recovery of hydrocarbons by means of underground combustion from a reservoir having a low initial effective permeability, said reservoir being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said reservoir via said injection well an oxygen-containing gas, initiating combustion of the oil in place in said reservoir at the bore of said producing well, temporarily supplying an oxygen-containing gas through said producing well to maintain said combustion and to propagate a combustion zone through said reservoir away from said producing well, discontinuing the injection of said gas into said producing well and thereafter supplying said gas through said injection well to said zone to maintain said zone and to propagate it through said reservoir toward said injection well, the injection of said gas into said injection well being in an amount sufficient to create a maximum temperature in said reservoir of not more than about 400° F., continuing injection of said gas through said injection well without forcing liquid hydrocarbons into said producing well until said zone has reached at least the immediate area of the injection well, thereafter introducing an oxygen-containing gas into said reservoir via said injection well at a rate sufficient to create a combustion zone temperature of from about 1,000° to about 2,000° F. whereby the course of said zone is reversed and is caused to travel concurrently with said gas toward said producing well, and recovering liquid hydrocarbons through said producing well resulting from the concurrent travel of said gas and combustion zone through said reservoir.

4. The process of claim 3 in which the hydrocarbon component of said reservoir is essentially a bituminous tar.

5. The process of claim 3 in which the hydrocarbon component of said reservoir is essentially a low gravity crude.

6. In a process for the recovery of hydrocarbons by means of underground combustion from a reservoir having a low initial effective permeability, said reservoir being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said reservoir via said injection well an oxygen-containing gas, initiating combustion of the oil in place in said reservoir at the bore of said producing well, temporarily supplying an oxygen-containing gas through said producing well to maintain said combustion and to propagate a combustion zone through said reservoir away from said producing well, discontinuing the injection of said gas into said producing well and thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said reservoir toward said injection well, the injection of said gas into said injection well being in an amount sufficient to create a maximum temperature in said reservoir ranging from about 300° to about 400° F., continuing injection of an oxygen-containing gas through said injection well without forcing liquid hydrocarbons into said producing well until said zone has reached at least the immediate area of the injection well, thereafter introducing an oxygen-containing gas into said reservoir via said injection well at an increased injection rate whereby the course of said zone is reversed and is caused to travel concurrently with said gas toward said producing well, and recovering hydrocarbons from said producing well.

7. In a process for the underground combustion of a carbonaceous deposit selected from the group consisting of petroleum tars and heavy viscous oils, said deposit being penetrated at spaced points by an injection and a producing well, the improvement which comprises injecting into said deposit via said injection well an oxygen-containing gas, initiating a combustion zone at a point in said deposit remote from said injection well, said point not exceeding the distance between said wells and falling substantially on a line connecting said wells, thereafter supplying an oxygen-containing gas 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 at least the immediate area of said injection well, controlling the temperature at a given oxygen-containing gas flux of said combustion zone while the latter is moving toward said injection well by means of regulating the reservoir pressure, subsequently introducing an oxygen-containing gas into said deposit via said injection well whereby the course of said zone is reversed and travels concurrently with said gas toward said producing well, and recovering fluid through said producing well resulting from the concurrent travel of said gas and combustion zone.

8. In a process for the underground combustion of a carbonaceous deposit selected from the group consisting of petroleum tars and heavy viscous oils, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit via said injection well an oxygen-containing gas, initiating combustion of the oil in place in said reservoir at the bore of said producing well, thereafter supplying an oxygen-containing gas through said injection well to the resulting burning zone to maintain said zone and to propagate it through said reservoir toward said injection well, the injection of said gas into said injection well being in an amount sufficient to create a maximum temperature in said reservoir of not more than about 400° F., continuing injection of an oxygen-containing gas through said injection well without forcing liquid hydrocarbons into said producing well until said zone has reached at least the immediate area of the injection well, thereafter introducing an oxygen-containing gas into said reservoir via said injection well whereby the course of said zone is reversed and is caused to travel concurrently with said gas toward said producing well, and recovering hydrocarbons from said producing well.

References Cited by the Examiner

UNITED STATES PATENTS

3,126,955 3/64 Trantham et al. ---------- 166—11

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