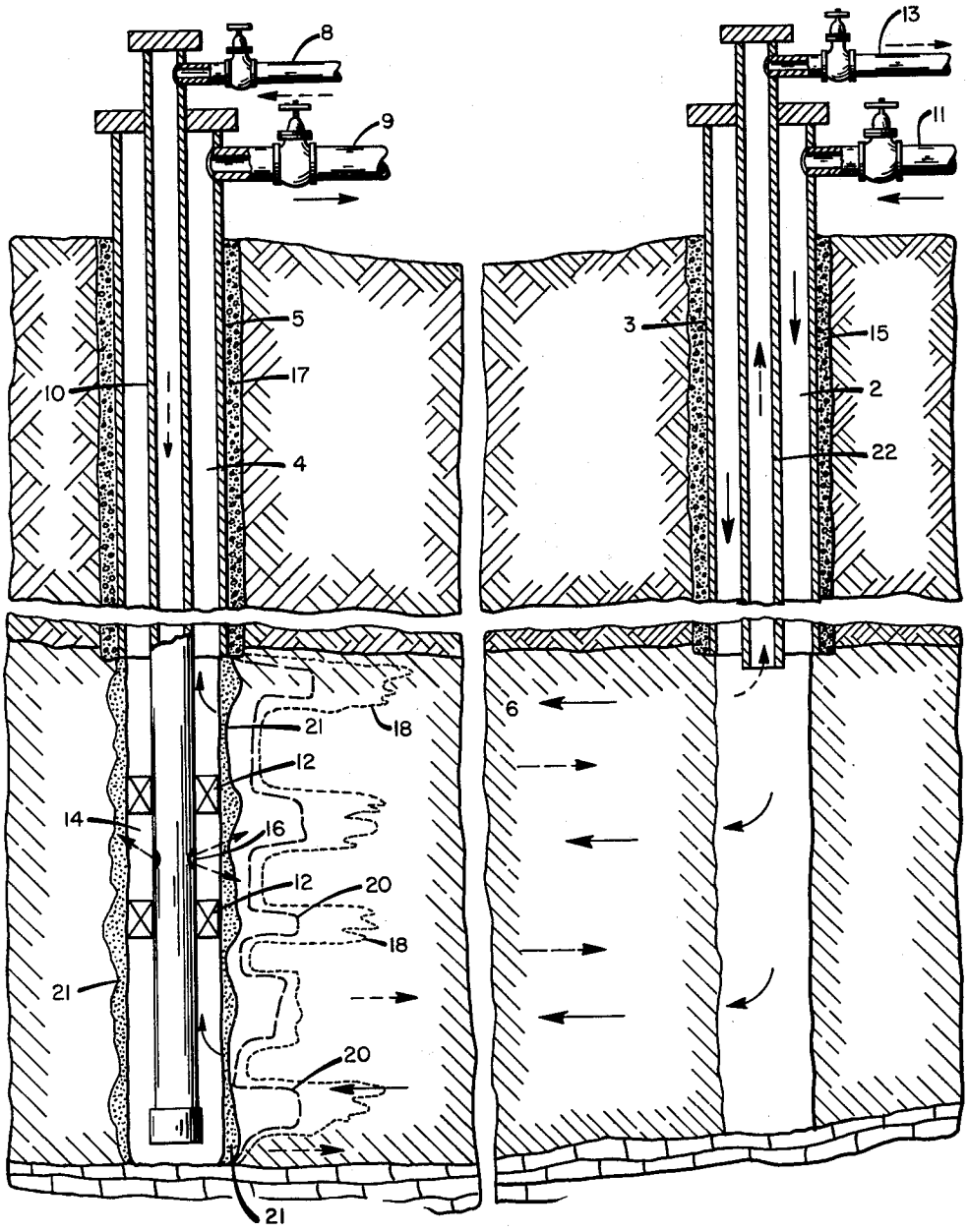
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METHOD FOR PRODUCING PETROLEUM BY UNDERGROUND COMBUSTION

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INVENTOR.
JAMES E LATTA
BY Arthur M. Clay
ATTORNEY

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METHOD FOR PRODUCING PETROLEUM BY UNDERGROUND COMBUSTION

James E. Latta, Chicago, Ill., assignor to Pan American Petroleum Corporation, Tulsa, Okla., a corporation of Delaware

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The present invention relates to a method for the in-place burning of underground carbonaceous deposits. In particular, it is concerned with a novel method for establishing a more uniform combustion front during reverse burning operations, wherein said deposits vary rather widely in their permeability.

Some of the largest known 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 localities 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.

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 included within the scope of my invention. This is for the reason that the cold portion of the reservoir rock yielding the heavy oil lies between the producing well and the burning zone. In or near the burning zone the viscosity of the oil is at a minimum; however, as the pressure gradient 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.

Accordingly, the only way in which combustion can be effected in reservoirs of the type contemplated herein involves the "reverse combustion process." This method is described in detail in U.S. 2,793,696 to Morse in which conditions are provided such that the combustion zone travels toward the injection well, i.e., countercurrent to the flow of the air through the reservoir.

It has been observed that in the application of underground combustion processes in the recovery of tar or crude petroleum from deposits thereof, variations in permeability of the reservoir occur. This, of course, causes the flow of fluids predominantly through these more permeable areas resulting in a highly non-uniform combustion front. Because of this, it is difficult to control the operation and a lower ultimate oil recovery is experienced. These variations in permeability can be due to a number of causes such as, for example, differences in the solid material and its compacting, variations in fluid saturation, the presence of fissures and cracks, etc. In an underground combustion operation, especially reverse combustion, it is indicated that performance is not uniform where significant differences in permeability, especially to gas flow, are encountered. Where these variations exist, the largest portion of the injected air finds its way into the most permeable zones causing a combustion front to be created in those zones and to move out away from the well before the oil in the less permeable zones has had an opportunity to ignite and become a part of a common combustion front traveling toward the producing well or wells. These conditions generally do not improve as the process continues but, on the contrary, tend to become much worse, making it extremely difficult to produce the recoverable oil from the less permeable zones.

It is, therefore, an object of my invention to provide a method for rendering the configuration of a combustion front more uniform when passing through a reservoir of varying permeability by first subjecting the deposit involved to a forward combustion step, continuing the latter until the front has moved out away from the well a short distance, e.g., one or two feet, and thereafter conducting a reverse burning operation in said deposit in such a way that said front moves in a direction opposite that in which the oxygen-containing gas used to feed the combustion process is flowing.

Briefly, my invention comprises treating or conditioning a carbonaceous deposit varying substantially in permeability, prior to a reverse combustion step, by effecting forward combustion in said deposit for a limited time, whereby the resulting condensation products and cooled liquids flowing ahead of the combustion front and toward the producing well tend to seek out the more permeable zones, thus causing them to approach the degree of permeability possessed by the other zones in the deposit. In this way, the permeability of the deposit to be burned is converted into zones of more uniform permeability.

Whether or not the forward combustion step has been carried out for a sufficient length of time can be determined, for example, by taking a second permeability profile of the deposit and then comparing the two in order to determine if the permeability is sufficiently uniform throughout to employ reverse combustion effectively.

In order to determine whether the process of my invention should be used in a particular underground combustion project, gas permeability profiles should be run as mentioned above. If the permeability in the deposit is substantially non-uniform, then the process of my invention can be employed to advantage. By the expression "substantially non-uniform," as used with reference to the permeability of certain zones in the deposit to be burned, I mean zones having sufficiently high permeability to permit burning through to the injection well before the majority of said section has been burned to a similar extent. If such conditions exist without some measure being taken to equalize the permeability throughout the deposit, the injected air after the initial breakthrough does not contact the unburned material but tends to bypass it via the path or paths formed by the burning of the more permeable zones.

It is realized that carbonaceous deposits of the type contemplated herein are seldom if ever completely homogeneous in composition and/or physical makeup. Hence it is expected that even under the more ideal conditions, variations in permeability throughout a given deposit will exist. However, if these variations do not exceed the less permeable zones by values of from about 10 to 15 percent, reverse combustion may be carried out without excessive fingering and premature breakthrough at one or two levels before the balance of the combustion front reaches the injection well. Otherwise expressed, if the pressure required to inject air at any level in said deposit does not vary more than about 50 p.s.i., then it is generally proper to proceed with the reverse combustion operation. It is within the scope of my invention, nevertheless, to employ this forward burning step prior to reverse combustion as a precautionary or as a standard treatment for the purpose of insuring the formation and maintenance of a substantially uniform combustion front throughout the entire operation. By providing a condition of this sort in the reservoir, it will be appreciated that maximum recovery of hydrocarbon products can be realized.

A further embodiment of my invention comprises effecting a forward combustion step in a reservoir in which

reverse combustion has already been initiated. Such measures may be employed to advantage where troublesome variations in permeability occur during reverse combustion. Evidence of the presence of these difficulties can be provided by a suitable observation well or wells between the injection and producing wells. Thus, if it is determined by temperature measurements in an observation well that a narrow section, for example, one or two feet in thickness, of the deposit is hotter than the rest of the section, this is an indication that non-uniform burning within the deposit is taking place. The operator under such circumstances should then discontinue reverse combustion temporarily and burn forward for a limited period of time, for example, from 12 to 24 hours, to permit preferential condensation of fluids in the more permeable sections of the deposit. In this manner, the permeability of the deposit is rendered more uniform and reverse combustion can then be resumed.

A number of conditions control or influence the efficiency with which the reverse combustion phase of the process of my invention is carried out. One of the more important factors in this connection is the air injection 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. High 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 injection rates, i.e., about 40 s.c.f./hr./ft.^{2}, or less, 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.

At temperatures below about 400° F., little oil is recovered by reverse 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. When the pressure was increased to 265 p.s.i., 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. was about .17 ft./hr. Whereas, at 265 p.s.i., 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. Accordingly, in order to secure high oil recovery efficiency by employing reverse combustion injection rates of from about 75 to 100 s.c.f./hr./ft.^{2}, preferably from about 90 to 100 s.c.f./hr./ft.^{2}, should be employed. Under such conditions, combustion zone temperatures from the order of 800° to 900° F. will be produced.

When performing the forward combustion step air injection rates should be sufficient to produce combustion front temperatures of the order of from about 1500° to 2500° F.

The process of my invention will be further illustrated by reference to the accompanying drawing in which an injection well **2** and a producing well **4** penetrate an oil- or tar-bearing formation **6** of varying permeability. Casing **3** and **5** in wells **2** and **4**, respectively, is run to the top of zone **6** and cemented to the surrounding formation at **15** and **17**, leaving an open hole from that level to the bottom of oil-bearing zone **6**. Both wells are equipped with tubing

strings **10** and **22**. An initial permeability test of the formation is made by injecting air which follows a path indicated by the dashed arrows through pipe **8** and tubing **10** carrying spaced packers **12** and into packed-off zone **14** via ports **16**. By moving packers **12** up and down the open hole to pack off narrow zones followed by an air injection step, the permeability of each of these zones can be established. During these tests, valved lines **9** and **11** are closed while lines **8** and **13** are open. For example, an initial air injection test may show a permeability profile similar to that indicated by dotted line **18**. Packers **12** are then removed, combustion initiated in the open hole or well **4** in any convenient manner such as, for example, by means of a burner and forward combustion sustained in the form of combustion front **21** by forcing air into the formation via tubing **10** until a pressure drop of from about 50 to 100 p.s.i. is observed, indicating that condensation products are beginning to reduce the permeability of the formation. A second permeability test is then run showing a change in the permeability profile as illustrated by dashed line **20**. Thereafter, air is injected into well **2** and formation **6** as indicated by the solid-line arrows via line **11**. Combustion front **21** then proceeds toward injection well **2** countercurrently to the flow of injected air. Products of combustion, condensed oil and heavy oil are forced into well **4** and produced out the annulus and pipe **9**.

By the present description, it will be apparent that I have furnished the art with a novel and unobvious method for rendering the permeability of a reservoir more uniform to gas flow. This, in turn, makes possible the creation of a more uniform combustion front when said reservoir is subjected to reverse combustion.

It is to be emphasized that the process of my invention is primarily applicable to reservoirs having a low effective initial or native permeability. By the expression "low effective initial permeability," I mean 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. 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 air injection rate is insufficient to produce a combustion zone temperature of about 700° to about 800° F.

I claim:

1. In a process for subjecting a tar sand deposit to a reverse combustion operation, said deposit being penetrated by a producing well and an injection well and wherein the pressure required to inject a gas into at least any two zones of said deposit differs more than about 50 p.s.i., the improvement which comprises:

igniting the face of said deposit adjacent said producing well,

supplying an oxygen-containing gas to the resulting ignited portion via said producing well so as to propagate a combustion front into said deposit in the same direction as said gas is flowing therethrough,

continuing introduction of said gas via said producing well until a pressure drop of from about 50 to about 100 p.s.i. is observed between said wells, indicating that condensation products are beginning to reduce the permeability of said deposit,

making a gas permeability profile of that portion of said deposit containing said two zones,

repeating the above cycle until the permeability of said deposit including said zones is such that the pressure required to inject a gas into any level in said deposit does not vary more than about 50 p.s.i.

thereafter injecting an oxygen-containing gas stream into said deposit via said injection well so that said front moves through said deposit in a direction opposite to the flow of said stream and toward said injection well, and

recovering hydrocarbon products from said deposit via said producing well.

2. In a process for conducting a reverse combustion operation in a tar sand deposit penetrated by an injection well and a producing well, wherein the pressure required to inject a gas into at least any two zones of said deposit differs more than about 50 p.s.i., the improvement which comprises:

igniting the face of said deposit in said producing well,

supplying the resulting ignited deposit with an oxygen-containing gas via said producing well whereby a combustion front forms and is caused to move into said deposit in the same direction as the flow of said gas therethrough,

continuing the introduction of said gas via said producing well until a pressure drop of not more than about 100 p.s.i. is observed between said wells indicating that condensation products are beginning to reduce the permeability of said zones,

making a permeability profile of that portion of said deposit containing said two zones,

repeating the above cycle as many times as are necessary until the permeability of said deposit including said zones in such that the pressure required to inject a gas into any level in said deposit does not vary more than about 50 p.s.i.

thereafter injecting an oxygen-containing gas stream into said deposit via said injection well whereby said front moves through said deposit in a direction opposite the flow of said stream, and

recovering hydrocarbon products from said deposit via said producing well.

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