Dec. 1, 1964 R. F. MELDAU ET AL 3,159,215

ASSISTED PETROLEUM RECOVERY BY SELECTIVE COMBUSTION IN MULTI-BEDDED RESERVOIRS

Filed Sept. 23, 1958 4 Sheets-Sheet 1

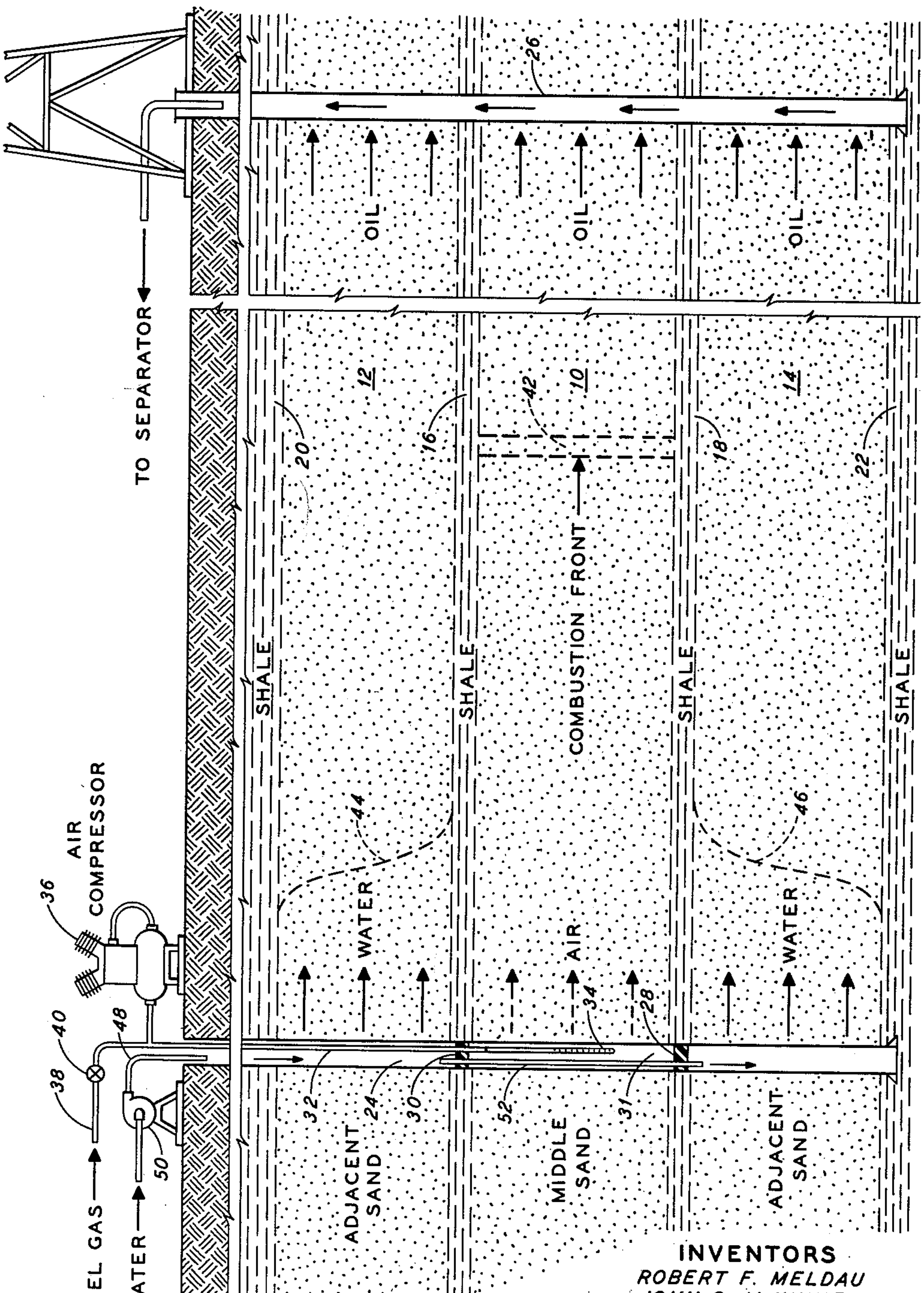

FIG. 1

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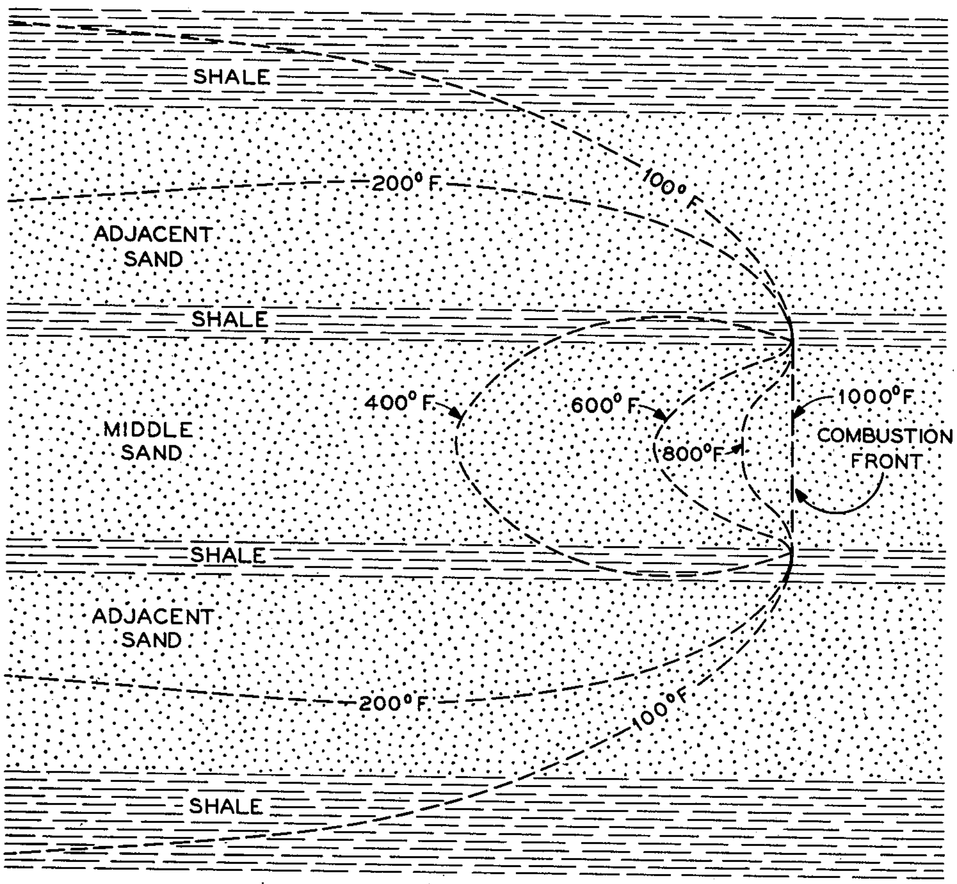

FIG. 2

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Filed Sept. 23, 1958 4 Sheets-Sheet 3

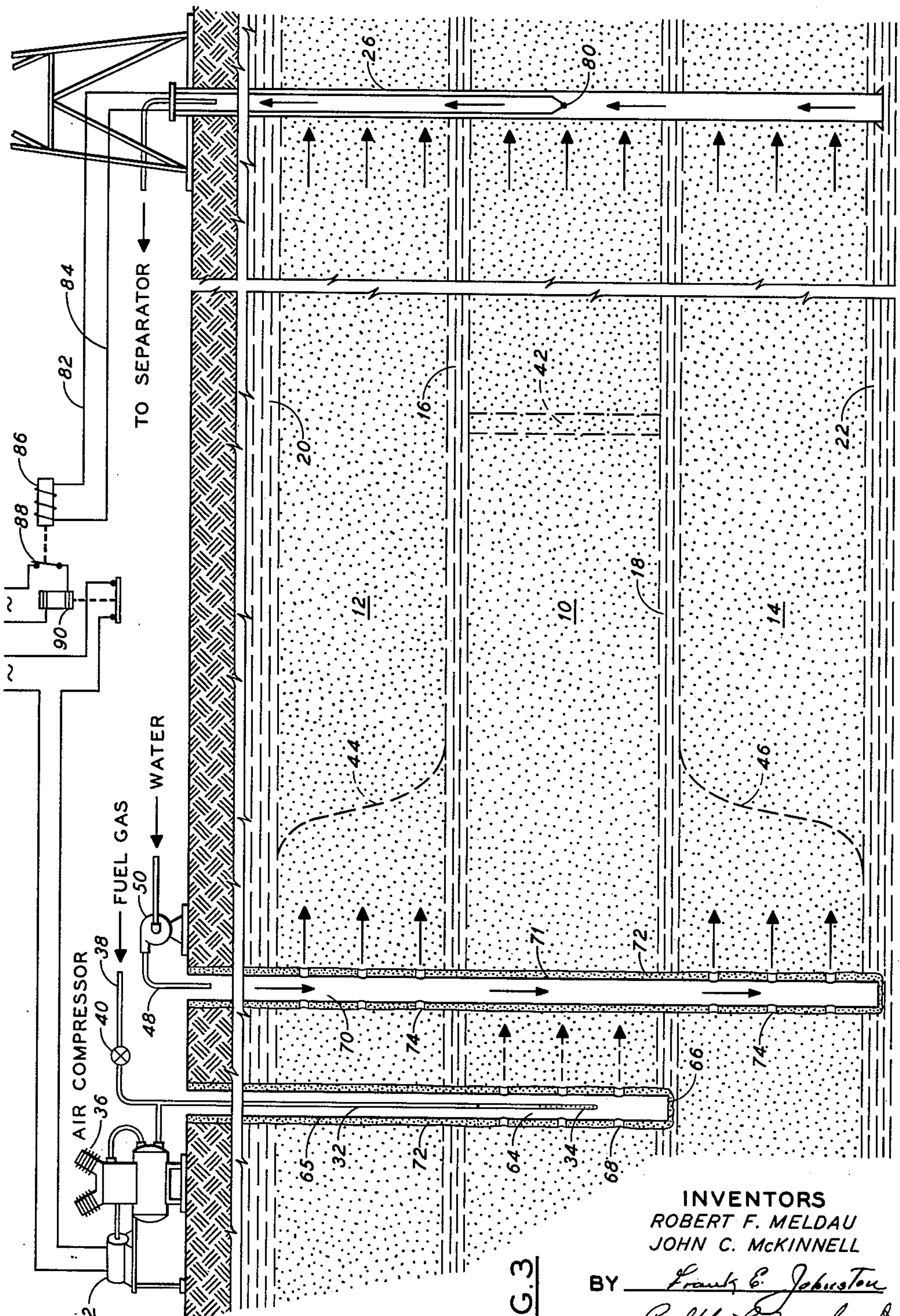

FIG. 3

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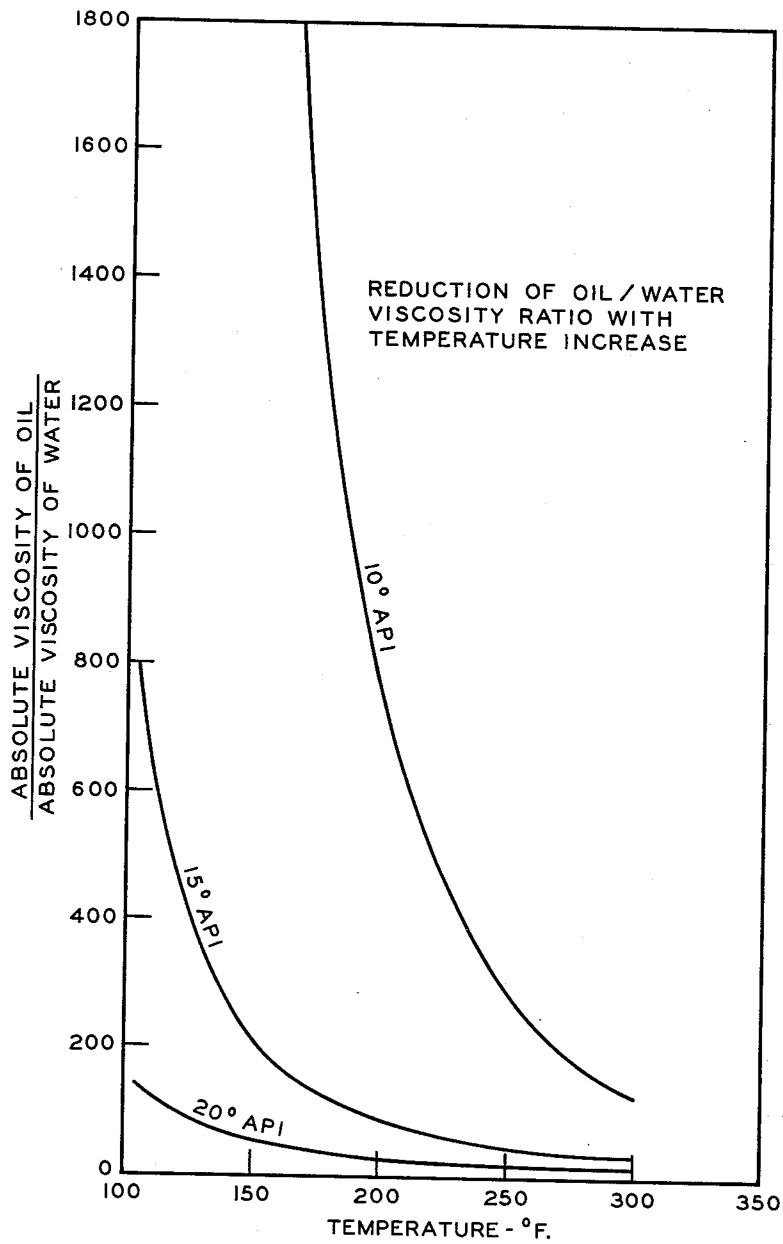

FIG. 4

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ASSISTED PETROLEUM RECOVERY BY SELECTIVE COMBUSTION IN MULTI-BEDDED RESERVOIRS

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5 Claims. (Cl. 166—10)

The present invention relates to assisted oil recovery methods. More particularly, it relates to an improved method of assisting recovery of oil from an underground reservoir by consecutively and simultaneously injecting thermal energy to selected portions of the reservoir.

It is an object of the present invention to increase the recovery of petroleum from an underground reservoir that comprises a series of oil-permeable zones containing mobile oil separated by relatively thin, impermeable zones, such as sandstone formations that have shale or other fluid barriers between said members. The method of the invention is specifically useful where more than one fluid-impermeable zone separates several oil-bearing zones. However, the method is also useful in any reservoir where the fluid-permeable, e.g., sand, zones are sufficiently isolated from each other to permit wells penetrating them to be sealed or packed-off from each other.

In assisted oil recovery, frequently referred to as secondary recovery of oil from an underground reservoir, it has been proposed to ignite an oil-producing formation and then supply a critical amount of oxygen in the form of compressed air to that formation to form a combustion front that both heats the oil and generates gas to force oil to flow from the air injection well toward a fluid-producing well. In practice, it has been found that it is difficult to ignite and maintain combustion in reservoirs such as those encountered in California and the Gulf Coast area where oil-producing zones frequently comprise a plurality of oil-producing zones that are formed of sand and are interlaminated by shale beds that lie parallel to the sand beds. One of the reasons for this difficulty is the differences in fluid permeability of the various oil-producing zones. Where these differences exist, the air and combustion will preferentially occur in the zone of greatest permeability (the path of least resistance to flow). Additionally, the cost of an assisted oil recovery project using all air as the injection fluid has been found to be more expensive than conventional water flooding operations, since the investment in air compressor horsepower, as compared to equivalent water pump capacity, is relatively great. While this added cost is justified by the greater recovery of oil using a combustion drive, as compared to a water drive, the oil-bearing zone must be thick and relatively uniform in permeability to obtain maximum benefit. However, when the oil zone is relatively thin or non-uniform in permeability, we have found that much of the heat generated by the combustion process is lost to the overlying and underlying shale and sand zones.

In accordance with a preferred method of carrying out the present invention, one of the more permeable, oil-bearing zones in a series of multiple zones is packed off in an injection well so that oxygen, in the form of air, can be pumped into that zone to ignite and continue combustion therein. When the invention is practiced in a pair of permeable oil-bearing zones, it is preferred to initiate combustion in the more fluid permeable zone if one of the zones has a greater permeability to fluid flow than the other. The fluid-impermeable zones either overlying or underlying this first oil-bearing zone prevent

vertical flow of fluids to adjacent oil zones. Sufficient air is then supplied to this middle zone to maintain combustion of a part of the hydrocarbon fluid so that the burning front is progressively advanced away from said injection well an adequate distance through the oil-bearing zone toward one or more production wells. In advancing the combustion front, the overlying and underlying shale and sand bodies are progressively heated by conduction losses from the combustion front and form a heat reservoir that extends from near the injection well to the combustion front. After the combustion front has been advanced in this way, a drive liquid, such as water, conveniently supplied at surface temperatures is pumped into the adjacent heated oil-bearing zones. Where oil-producing zones both overlie and underlie the combustion zone, water may be pumped into both the over- and underlying beds. The water thus supplied moves into a heated oil bearing strata and both the displacing water and the displaced oil are progressively heated as they move together from the injection well toward the producing well.

The progressively heated oil in the overlying and underlying beds is displaced by the heated water in a more efficient manner than if the oil and water were at normal formation temperature. When the oil in the overlying and underlying beds is progressively displaced by heated water, the oil is recovered in a more efficient manner than if the oil and water were at normal formation temperature before contacting the heated zone as in a countercurrent flow of liquid and air in the parallel zones. Additionally, the areal sweep efficiency of the injected water is improved because of the improved mobility ratio of the displacing water to the displaced crude oil. This ratio is progressively reduced as both the water and oil are gradually heated by absorbing heat losses from the middle strata wherein combustion is occurring, and from the overlying and underlying impermeable strata. Since the flow of both injected air and injected water produce flow in the same direction through all three strata, hydrocarbon fluids can be intermingled as they are produced from all of the oil-bearing zones into the production wells.

Further objects and advantages of the present invention will become apparent from the following detailed description taken in conjunction with the accompanying drawings.

In the drawings:

FIG. 1 is a schematic representation in vertical section of a series of oil-bearing zones separated by shale zone fluid barriers through which an injection well and one production well penetrate to illustrate a preferred method of carrying out the invention.

FIG. 2 is a schematic representation of the thermal profiles through a plurality of producing zones such as those shown in the systems of FIGS. 1 and 3.

FIG. 3 is a view similar to FIG. 1 illustrating an alternative system for injecting water and air to assist recovery of petroleum in accordance with the invention.

FIG. 4 is a graph illustrating the reduction of oil/water viscosity ratio with temperature increase.

As an aid to the understanding of the method of the present invention, reference is now made to the drawings, and in particular to FIG. 1. As there shown, our method is directed to assisting recovery of petroleum from an underground reservoir system comprising a plurality of hydrocarbon containing zones including a first or middle zone 10 that has both an overlying oil-bearing zone 12 and an underlying zone 14. Both oil zones 12 and 14 are isolated from middle zone 10 by shale members 16 and 18 respectively. Further, other shale zones, such as 20, overlying upper oil zones 12, and 22 underlying lower zone 14, may separate other hydrocarbon producing zones from those illustrated in the present embodiment. The term "earth formation" is also used hereinafter to define such a multi-bedded series of zones that define such a petroleum reservoir.

In the embodiment of the invention of FIG. 1, all of the oil-bearing zones 10, 12 and 14 are penetrated by a first well 24 indicated as an assisted-recovery injection well, and a second well 26, operated as a producing well. Since, in accordance with the invention, it is desired to ignite and burn mid-zone 10 to create an expanding heat reservoir that will drive petroleum toward well 26, a pair of packers 28 and 30 are positioned in injection well 24 respectively to isolate middle zone 10 from upper and lower zones 12 and 14. An air injection line 32 that may include a burner 34 is positioned within the now isolated zone, indicated as 31, and is connected to an air compressor 36 at the earth's surface. With zone 10 isolated in this manner, ignition and combustion of the oil zone 10 may be initiated by supplying fuel gas from line 38 through valve 40. After ignition of oil-bearing zone 10, fuel gas may be cut off by closing valve 40 and combustion continued merely by supplying air under pressure. The combustion front, indicated generally as 42, is then progressively advanced toward production well 26 a distance sufficient to establish the proper size heat bank for the particular system being treated. This distance will, of course, depend upon the thickness of sand zone 10, shale members 16 and 18, the thermal diffusivity in said sand and shale members and the velocity of the burn front. Then, with the combustion front 42 moving toward producing well 26, in accordance with this invention, we inject water into overlying and underlying sand beds 14 and 12. In the schematic illustration of FIG. 1, it is assumed that combustion front 42 has advanced to approximately the position indicated by the dash lines when water at atmospheric temperature is pumped into zones 12 and 14 under pressure. As indicated by dash lines 44 and 46 in the respective zones 12 and 14, progress of water in said zones will be greater where the temperature is higher due to the decreased viscosity of the heated oil. As indicated, such water flooding of zones 12 and 14 is accomplished by supplying water through line 48 discharged by water pump 50. A cross-over pipe 52 permits water pressure to be applied to lower zone 14 through packers 28 and 30 that isolate zone 10 from the remainder of the well bore.

Oil produced from all of the three zones, 10, 12 and 14 is permitted to intermingle in producing well 26. As indicated, the outflow from that well is transmitted to a separator (not shown), wherein the secondary drive fluid may be separated from the produced oil.

FIG. 2 in general illustrated the thermal fronts in the three adjacent zones when the different drive fluids are flowing, as in the arrangement of FIG. 1. As indicated, the combustion front such as that in middle zone 10 of FIGS. 1 and 3 will be relatively uniform in area and substantially vertical to the overlying and underlying fluid impermeable beds. The temperature of this zone indicated as 1000° F., will be in the range of from 750–1500° F., but will decrease both on the air injection and the fluid production side of that front. However, the solid material such as the sand grains and the shale particles composing the burned out oil-bearing zone and the overlying shale sections, such as 16 and 18 in FIG. 1, on the injection side of the combustion front will be heated by conduction from the burning zone and they will have a temperature sufficiently great to cause heating in the area directly above and below the combustion sand.

In the art of water flooding, the displacement efficiency of crude oil is improved if the mobility ratio of the dis-

placing water to the displaced oil is reduced. The mobility ratio is defined as the ratio:

$$\left(\frac{\text{Relative water permeability}}{\text{Relative oil permeability}}\right)\times\left(\frac{\text{Absolute viscosity of oil}}{\text{Absolute viscosity of water}}\right)$$

The ratio of

$$\frac{\text{Relative water permeability}}{\text{Relative oil permeability}}$$

is a function of the oil and water saturations and the characteristics of the producing sand. The oil/water viscosity ratio depends markedly upon temperature.

The object of the present invention is to reduce this mobility ratio of the displacing water to the displaced oil and consequently improve the recovery of oil by making use of heat normally lost in an underground combustion process. FIG. 4 shows the reduction in oil/water viscosity ratio as the temperature is increased from 100° F. to 300° F. for representative crude oils. As an example, an increase in temperature from 100° F. to 300° F. in a system containing 15° API oil will result in a thirty-fold reduction of oil/water viscosity ratio.

It is preferred to progressively advance the burning front from the injection well toward the production well for a time sufficient to heat the adjacent upper and lower oil-impermeable zones by conduction of heat from said burning front and reduce the oil/water viscosity ratio in both the upper and lower oil-permeable zones to a value less than about 200. Flood water is then injected through the injection well into the upper and lower producing zones to successively absorb heat from said oil impermeable zones. Air and flood water are simultaneously pumped into the respective zones to advance both the water and oil in said zones toward said production well while maintaining said oil/water viscosity ratio in said upper and lower oil-permeable zones at said value. Oil is produced at the production well from all producing zones.

The mechanism for improved oil recovery in the adjacent water flooded sands is as follows:

First: The injected water is heated by contact with progressively warmer environment as it moves toward the position of the combustion front in the combustion sand.

Second: Oil displacement by the injection water is improved as the injection water approaches progressively warmer oil in the oil-bearing sands in which water is injected. The displacement of oil by water is a maximum where the oil reaches a maximum temperature and minimum viscosity. This point will always be behind the position of the combustion front but will vary, depending upon the system in which the process is applied.

It is, of course, understood that displacement of oil by water in a water-flooding operation is not strictly a piston-like displacement wherein equal amounts of formation oil are displaced by a corresponding volume of the driving water. Rather, the displacement is effected by entrainment of oil particles released from the interstitial spaces in the oil reservoir by water flowing past these spaces. Hence, reduced viscosity of reservoir oil as compared to the entraining water greatly increases the efficiency of oil displacement by the injection of water. However, the freedom of the oil particles to enter the flood water is also dependent upon the relative sizes and distribution of the pore spaces wherein they are contained. Larger spaces may, of course, permit the flood water to channel, and thereby decrease the areal sweep and coverage of the flood. For this reason, if the entire length of the formation is heated simultaneously, such preferentially high permeable paths can be established. Hence, it is an important aspect of this invention to sweep both the combustion front and the water progressively from the injection wells to the production wells to reduce the possibility of such channeling.

In FIG. 2, the general temperature profiles of a progressing multi-bedded fire and water flood in a system such as that shown in FIG. 1 are illustrated by the isotherm lines, designated as 100° F., 200° F., etc. In the example illustrated by FIG. 2, the thickness of the burned middle sand is about 10 feet, the thermal diffusivity is about 0.05 square feet per hour, the burn front velocity is about 0.5 feet per day, and the maximum burn front temperature is 1000° F. The temperatures indicated represent increases over original reservoir temperatures. It will be noted that the maximum temperature extends over quite a limited area, but an increase in temperature of from 100° F. to 300° F. is quite broad through both of the adjacent sands.

FIG. 3 illustrates an alternative arrangement for carrying out the method of the present invention, wherein separate wells are used for the injection of air and water into the selected oil-bearing sands. As indicated, well **64** is drilled into middle sand **10** and has an air supply line **32** that supports a burner **34** opposite that zone to start combustion of the residual petroleum therein. As shown, well **64** may be cemented off at bottom **66** above lower producing zone **14**. Zone **10** and well **64** are also isolated from upper zone **12** by cement **72** located adjacent upper shale section **16**. Perforations **68** through casing **65** and cement **72** permit communication between zone **10** and well **64**. It will be noted that air injection well **64** is positioned ahead of water injection well **70** so that combustion may be started and extended both vertically and horizontally in middle zone **10** prior to the time the combustion front passes through well **70**. Communication between well **70** and middle zone **10** is prevented by cement **72** that bridges between casing **71** and upper and lower shale members **16** and **18**. Perforations **74** opposite both zones **12** and **14** permit access through casing **71** for well **70**.

As further shown in the embodiment of FIG. 3, combustion in the middle zone **10** is desirably stopped some distance from production well **26** to prevent well damage. The approach of the combustion front can be detected by a thermocouple **80** positioned in producing well **26** adjacent to, or opposite, oil-producing zone **10**. Thermocouple **80** disconnects power to drive motor **92** and air compressor **36**. For this purpose, lines **82** and **84** from thermocouple **80** energize sensitive relay **86** when the temperature in the well reaches a preselected value. This controls, in turn, circuit breaker **90** through switch **88** to cut off power for air compressor **36**. Thus, when the temperature of the produced fluid in zone **10** reaches the preselected value, the combustion process dependent upon air is automatically stopped. After such a temperature value is produced in fluid flowing out of middle zone **10**, it may be desirable to inject water into the middle zone, as well as into the upper and lower producing zones **12** and **14**. Thus, further maximum thermal economy can be obtained in assisting recovery from the reservoir. An estimate of flow rates can also be used to determine the proper time to stop air injection in zone **10**. For this purpose a flow meter and integrating system can be substituted for thermocouple **80**.

In each of the systems shown in FIGS. 1 and 3, it is, of course, desirable to maintain sufficient pressure in middle zone **10** to prevent backflow of oil or water from the producing horizons **12** and **14** due to higher pressures that may exist in said producing sands. This backflow after combustion ends can be eliminated by injecting low volumetric rates of water, air or gas into middle zone **10** at the injection well such as **24** in FIG. 1, and **64** in FIG. 3.

The present method, of course, may be used either in a line drive system or a five spot, or circular, pattern of the injection and producing wells. A line drive system is one in which a plurality of injection wells are drilled into the formation along a line, such as the edge, of a producing field, or a geological fault, so that the produced oil is driven toward a similar line or pattern of producing wells at a distance selected to permit maximum recovery of oil from multiple producing horizons. On the other hand, a five spot, or circular, pattern of wells for assisted oil recovery is one where the injection well is in the center of a plurality of producing wells that are radially spaced outwardly from the injection well. In either of such systems, the combustion front is moved progressively outward from the injection well toward the producing well, and progressively with said lateral movement at least one adjacent and parallel producing horizon is flooded by any secondary drive fluid, including water containing other miscible or immiscible materials, that will progressively absorb heat from the thermal bank or reservoir. Then, the heat is carried vertically and outwardly from said heat bank to the liquids in said adjacent formation by conduction and by the drive fluids flowing therethrough.

It will be apparent to those skilled in the art that the present system permits an appreciable increase in efficiency of assisted recovery from a multi-bedded oil-producing reservoir stratified by impermeable horizons. Greater use of the thermal energy supplied by the compressed air and the burned oil in one zone is utilized to improve progressively the water flood efficiency of the adjacent oil-producing beds. Various changes in the method of injecting and recovering fluids in multi-bedded reservoirs and arrangements for positioning injection and production wells will occur to those skilled in the art. All such modifications or changes falling within the scope of the appended claims are intended to be included therein.

We claim:

1. The method of assisting recovery of oil from an underground reservoir that includes at least a pair of substantially parallel, permeable hydrocarbon fluid producing zones separated by a relatively thin fluid-impermeable zone and said reservoir having at least an injection well and a production well penetrating all of said zones which comprises the steps of initiating combustion of said hydrocarbon fluid in one of said fluid producing zones adjacent said injection well, said one zone having greater permeability to fluid flow therethrough than the other of said pair of producing zones, injecting air through said injection well into said one zone to establish combustion of said hydrocarbon fluid and to extend the burning area vertically across the thickness of said one zone to form a burning front, continuing said air injection to maintain said combustion burning front and to advance it progressively a distance toward said production well greater than the thickness of said one oil producing zone whereby the adjacent thinner oil-impermeable zone is progressively heated by conduction from said burning front to form a heat reservoir for said other adjacent fluid producing zone, then injecting water through said injection well into said other producing zone to permit heat from said oil-impermeable zone to be absorbed progressively therein as said water flows concurrently with said combustion burning front, and continuing to inject said air and water, respectively, to simultaneously and progressively move through said producing zones and assist recovery of oil from both of said producing zones into said production well.

2. The method in accordance with claim 1 wherein other production zones are parallel to said pair of oil producing zones and separated therefrom by other relatively thin fluid-impermeable zones, and wherein combustion is initiated and maintained in at least the middle fluid producing zone by injecting air therein through an injection well and water is injected under pressure through said injection well into both the overlying and underlying producing zones, said water moving concurrently with

said combustion to assist recovery of oil from said production zones.

3. The method of assisting recovery of oil from an underground reservoir that includes at least three substantially parallel permeable hydrocarbon fluid-producing zones, each of said fluid-producing zones being separated by a relatively thin fluid-impermeable zone, and said reservoir having at least one injection well and at least one production well penetrating said zones which comprises the steps of initiating combustion of a portion of the hydrocarbon fluid adjacent said injection well in the middle zone of said three fluid-producing zones, injecting air through said injection well to said middle zone to maintain combustion of the hydrocarbon fluid therein to form a combustion front, advancing said combustion front in said middle zone by continuing injection of air thereinto for a time sufficient progressively to force hydrocarbons to flow from said zone into said at least one production well and to significantly increase the temperature of the adjacent oil-impermeable zones by thermal conduction from said combustion front, then introducing flooding water through said injection well into the upper and lower fluid producing zones to conduct heat stored in said fluid-impermeable zones to the fluids in said upper and lower fluid producing zones, said water advancing substantially in the same direction as said advancing combustion front and continuing supply of both air and water, respectively, to all of said producing zones to simultaneously and progressively move through said producing zones and assist recovery of oil simultaneously from all of said zones in said production well.

4. The method of assisting recovery of oil from an underground reservoir that includes at least a pair of substantially parallel, permeable oil producing zones separated by a relatively thin fluid impermeable zone and said reservoir having at least a production well penetrating all of said zones and at least one injection well permitting separate communication between earth's surface and said pair of oil producing zones which comprises the steps of initiating combustion of a portion of the oil in one of said producing zones adjacent said injection well, said one zone having greater permeability to fluid flow therethrough than the other of said pair of oil producing zones, injecting air through said injection well into said one zone to extend combustion of said oil vertically across the thickness of said one zone to form a burning front, continuing air injections through said injection well to progressively advance said burning front from said injection well toward said production well for a time sufficient to reduce the oil/water viscosity ratio to a value less than about 200, then introducing water through said injection well into said other producing zone to absorb heat from said oil-impermeable zone, said water advancing in the same direction as said burning front and continuing to pump said air and water, respectively, to assist recovery of oil simultaneously and progressively from both of said producing zones into said production well while maintaining said oil/water viscosity ratio in said zones at about said value.

5. The method of improving the oil/water viscosity ratio in a multibedded reservoir to assist the simultaneous recovery of oil from at least two of the oil-producing zones, said multibedded reservoir including at least three substantially parallel, permeable oil-producing zones separated by relatively thin fluid-impermeable zones and said reservoir having a production well penetrating said zones and at least one injection well permitting simultaneous but separated communication between the earth's surface and the middle zone and between the earth's surface and the other oil-producing zones which comprises the steps of initiating combustion of a portion of the oil in the middle zone adjacent to said injection well, injecting air through said injection well into said middle zone to extend combustion of said oil vertically across the thickness of said middle zone to form a burning front, progressively advancing said burning front from said injection well toward said production well for a time sufficient to heat the adjacent upper and lower oil-impermeable zones by conduction of heat from said burning front and reduce the oil/water viscosity ratio in both the upper and lower oil-permeable zones to a value less than about 200, then injecting flood water through said injection well into said upper and lower producing zones to successively absorb heat from said oil-impermeable zones, said water advancing the same direction as said burning front and continuing to pump simultaneously said air and water, respectively, to advance both the water and oil in said zones toward said production well while maintaining said oil/water viscosity ratio in said upper and lower oil-permeable zones at said value, and simultaneously producing oil into said production well from all of said producing zones.

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