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METHOD OF CONTROLLING AN UNDERGROUND COMBUSTION ZONE

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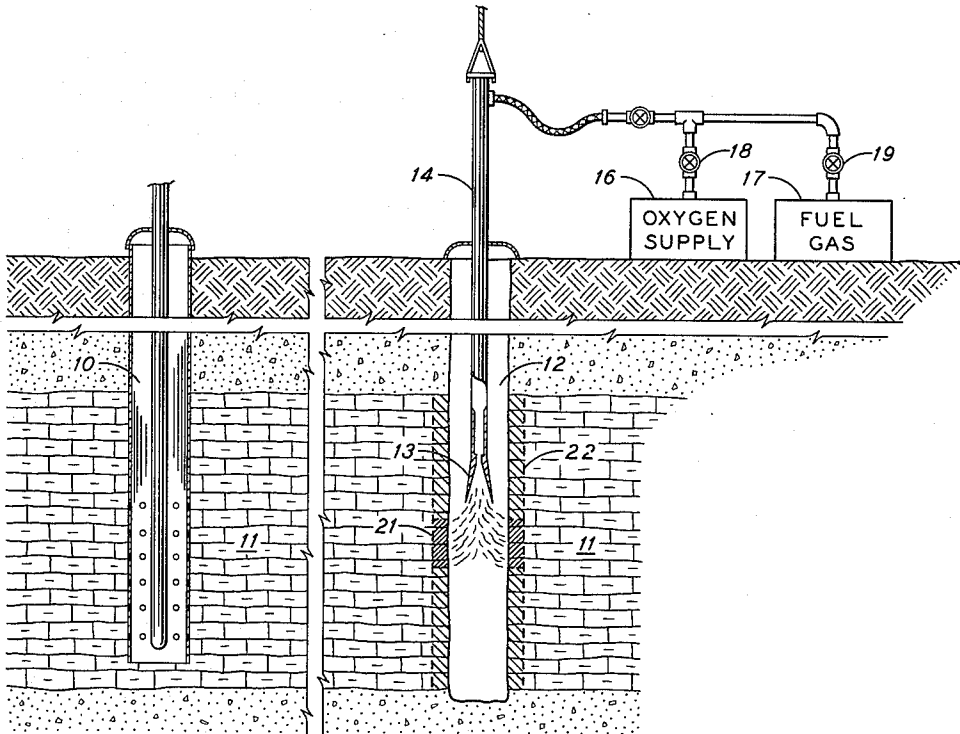


FIG. 1

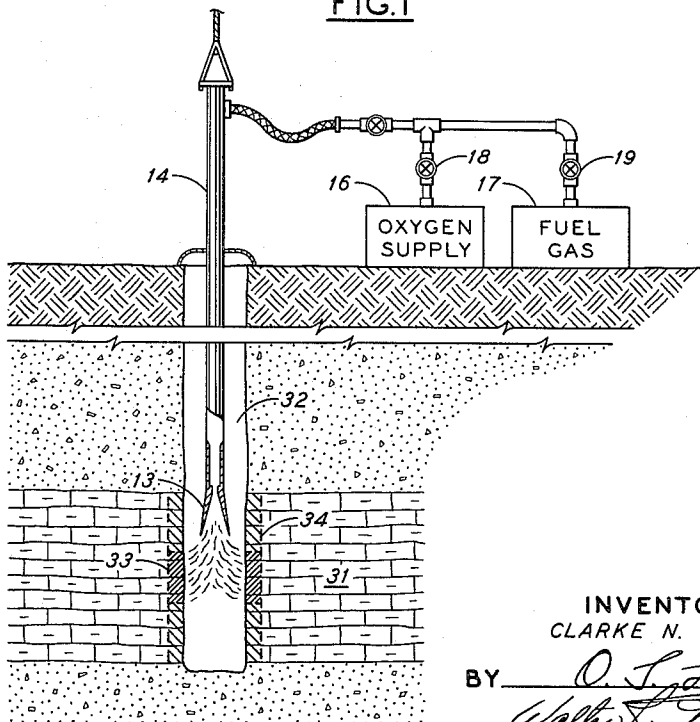


FIG. 2

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METHOD OF CONTROLLING AN UNDERGROUND COMBUSTION ZONE

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This invention relates in general to underground combustion in petroliferous formations and relates more particularly to methods of controlling such combustion.

Underground combustion, in which a portion of the oil in a petroliferous formation is burned in place to provide thermal energy, is a very promising tool in the effort to increase the recovery of petroleum from known petroleum accumulations which have been substantially depleted by conventional primary or secondary recovery methods, or, in the case of the use of underground combustion as a formation-permeability increasing technique, to aid in stimulating production from the formation. Such underground combustion involves essentially the creation of a combustion zone in the formation and the control of this combustion zone, usually through control of the oxygen and combustible gas supplied thereto, to cause the combustion zone to advance through the formation.

There are numerous applications in the use of underground combustion where it is desirable to control the horizontal movement of the combustion zone. Such control is desirable, for instance, in an underground combustion drive for secondary recovery where there is a considerable vertical extent of formation to be ignited and it is desired to produce substantially uniform ignition in this vertical extent prior to producing any substantial horizontal movement of the combustion zone. Also, in such a case, it is usually desirable to produce ignition of the entire circumferential extent of the formation around the injection well bore. Heretofore, such control has been difficult or impossible owing to the fact that the injection of the oxygen-containing, combustion-supporting gas into the formation in contact with the combustion zone causes the combustion zone to expand horizontally more rapidly than vertically through the formation by making oxygen available to the formation hydrocarbons in the presence of the elevated temperature of the combustion zone to produce combustion of a portion of the formation hydrocarbons.

An additional application in which it is desirable to accurately control the combustion front is in the use of underground combustion as a permeability increasing tool. In such an application, in which a combustion zone is established in the formation adjacent the well bore and the thermal energy from the combustion zone is utilized to increase the formation permeability by combustion of the combustible substances therein, such as waxes and asphalts, and by shrinkage or decomposition of the non-combustible constituents, it is desirable that the combustion zone be confined to a relatively small portion of the formation immediately adjacent the well bore. Such confinement is preferable both to avoid contamination of the formation out from the well bore with distillation products from the combustion zone and to maximize the thermal energy of the combustion zone in the critical permeability area immediately adjacent the well bore.

In accordance with the present invention, a combustion zone which has been created in a petroliferous formation is controlled by regulating the oxygen and combustible gas content of a gaseous mixture supplied thereto to control the horizontal advance of the zone. Where it is desired to hold the combustion zone substantially stationary horizontally in the formation, the injected gaseous mixture

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is made gas-rich by increasing the combustible gas content thereof to a suitably high value. This value of combustible gas content in the gas-rich mixture is sufficiently high so that substantially all of the injected oxygen will be combined with this combustible gas in the combustion zone to increase the temperature of the combustion zone, without causing any substantial horizontal movement of the combustion zone. This lack of horizontal movement of the combustion zone results from the fact that since substantially all of the injected oxygen is combined in the combustion zone with the injected combustible gas, little or no oxygen remains to combine with the hydrocarbons in place and produce combustion thereof. This action is also aided by the fact that the oxygen preferentially combines with the relatively lighter hydrocarbons in the injected combustible mixture, rather than with the heavier hydrocarbons or coke in place in the formation. Through the use of this control, the combustion zone may be maintained substantially stationary horizontally in the formation to permit attainment of the peak temperature of the combustion zone throughout the vertical and circumferential extent of the petroliferous formation to be ignited, thus producing ignition of substantially all of the vertical and circumferential extent of the formation. After the combustion zone has expanded to the desired vertical extent, the combustion drive may be continued by adjusting the oxygen content of the injected gas to cause the combustion drive to proceed substantially horizontally through the formation.

In the case of using the method of the present invention for controlling an underground combustion zone to increase the permeability of a petroliferous formation adjacent a well bore, the combustion zone is started in the formation adjacent the well bore by any suitable known means such as a gas-air burner, an electrical heater, chemical reaction, or spontaneous oxidation. After the combustion zone is thus created, it is maintained in substantially the same position in the formation by adjusting the oxygen and combustible gas content of the injected gaseous mixture to produce a gas-rich mixture so that substantially all of the injected oxygen is combined with the injected gaseous combustible mixture in the combustion zone, without producing combustion of any substantial portion of the hydrocarbons in place in the formation away from the combustion zone. The combustion zone is thus maintained at an elevated temperature, the level of which is controllable directly by the rate of injection of the gas and oxygen-containing mixture, in substantially the same position in the well bore until the desired permeability increase has been accomplished through combustion of the combustible components in the treated portion of the formation and shrinkage or decomposition of the non-combustible constituents in the treated portion of the formation. After such permeability increase has been accomplished, the combustion zone may be extinguished, such as by cutting off the supply of oxygen thereto, and after extinction of combustion, the formation may be produced in the normal manner through the well bore.

Objects and advantages of the present invention will be readily apparent from the following description when read in connection with the accompanying drawing in which:

FIG. 1 illustrates the application of the method of the present invention to the control of the start of an underground combustion drive for secondary recovery; and

FIG. 2 illustrates the application of the method of the present invention to the control of underground combustion for increasing the permeability of a formation immediately adjacent a producing well.

Referring to FIG. 1 by character of reference, reference numeral 11 designates a petroliferous formation located at some depth in the earth through which an underground combustion drive is to be transported. Formation 11 may be overlaid by one or more layers of overburden and is penetrated by an injection well bore 12 extending from the surface of the earth to formation 11. Petroleum products from the underground combustion drive may be produced from one or more adjacent producing wells 10. A combustion zone may be produced in the portion of the formation 11 adjacent well bore 12 by any suitable known means, such as auto-oxidation, the impregnation of the formation with chemicals capable of producing an exothermic reaction, an electric heater, or, as shown in the drawing, by means of a gas-air burner 13 disposed adjacent a portion of formation 11. Burner 13 has connected thereto at least one length of conduit 14 connecting the burner to the surface. A suitable combustible mixture may be injected through tubing 14 and ignited at burner 13 to provide the thermal energy required to initiate combustion in formation 11. Conduit 14 may be connected at the surface to a suitable source of oxygen 16 and a source of fuel gas 17. Oxygen source 16 may, for example, be a compressor which compresses air for injection into tubing 14. Similarly, fuel gas source 17 may be a compressor operating on a suitable supply of fuel gas such as that which may be available in the field. Sources 16 and 17 may be provided with suitable means such as valves 18 and 19, respectively, for controlling the flow of gas through conduit 14.

To start the ignition, oxygen from source 16 and fuel gas from source 17 are supplied through conduit 14 in a combustible mixture to burner 13 where the combustible mixture is ignited by suitable means to provide thermal energy for heating formation 11 to combustion temperature. If the vertical extent of formation 11 is large compared to the size of burner 13, the combustion zone initially produced in formation 11 by burner 13 will be relatively localized adjacent burner 13, as shown by zone 21 in the drawing. Additionally, this initial combustion zone may be localized circumferentially of the well bore so that it does not extend radially around the well bore. In such a case it is desirable to enlarge this combustion zone to substantially the entire vertical and/or circumferential extent of formation 11 before producing any substantial horizontal movement of the combustion zone away from the injection well.

To accomplish this vertical and/or circumferential enlargement after the initial ignition of formation 11 has been produced, the composition of the gaseous mixture injected through tubing 14 from sources 16 and 17 is adjusted to a gas-rich mixture; that is, the gas content of the injected mixture is made quite large with respect to the oxygen in the mixture so that all of the oxygen injected will be combined with a portion of the injected combustible gas in the combustion zone 21, thus raising the peak temperature of the combustion zone. However, this will produce substantially no horizontal movement of the combustion zone 21, since all of the injected oxygen is combined in the combustion zone with the injected combustible gas and hence, substantially no free oxygen remains to combine with the hydrocarbons in place in formation 11. This action is also aided by the preferential combination of the injected oxygen with the lighter hydrocarbons in the injected combustible gas, as opposed to the heavier hydrocarbons or coke in place in the formation.

The center of the combustion zone is thus substantially immobilized horizontally in the formation while the combustion zone expands vertically and/or circumferentially, owing to the increased peak temperature of the combustion zone which produces combustion of the hydrocarbons in place immediately adjacent the edges of combustion zone 21. The combustion zone thus ex-

pands vertically and/or circumferentially until it reaches the general proportions defined by area 22 in formation 11 adjacent the well bore. Thus, substantially the entire vertical and/or circumferential extent of formation 11 adjacent the well bore is occupied by the combustion zone.

After such vertical and/or circumferential enlargement or expansion of the combustion zone, the forward or horizontal progress of the combustion through formation 11 may be commenced by increasing the oxygen content of the injected gaseous mixture so that combustion of some of the hydrocarbons in place in formation 11 occurs. The exact method of controlling this forward or horizontal advance of the combustion zone is taught in U.S. 2,771,952, Clarke N. Simm, in which the mass velocity of the injected oxygen is maintained between critical maximum and minimum limits as a function of formation porosity, oil saturation and cross-sectional area of the combustion zone in the formation. The important factor in such a combustion drive is to maintain only a relatively narrow portion of the formation at an elevated temperature at any given time, thus reducing the thermal energy requirements for the combustion process. As the combustion zone thus proceeds through the formation, gaseous and liquid hydrocarbons are driven ahead by the combination of the thermal energy and the gas drive effect of the injected gas, and these removed hydrocarbons may be recovered from the recovery wells 10.

The composition of the injected gaseous mixture during the vertical and/or circumferential enlargement process should be controlled within fairly narrow limits. For example, when the concentration of the combustible components in the injected gaseous mixture is between 60 to 80%, I have found that the combustion zone is substantially immobilized horizontally in the formation, since substantially all of the injected oxygen within this composition range is combined with the injected gaseous combustible mixture in the combustion zone and substantially no free oxygen is available to combine with hydrocarbons in place in the formation. When the gaseous combustible component exceeds 80% of the total injected mixture, there is a risk of a loss of stability of the combustion zone, owing to the temperature decrease in the combustion zone produced by the cooling effect of the injected gas. That is, as the combustible gas content exceeds 80%, the cooling effect produced by the injected gas more than offsets the temperature increase produced by combustion of the injected oxygen with a portion of the injected gaseous combustible mixture, so that the net effect is a decrease in the temperature of the formation. Accordingly, the percentage of gaseous combustible mixture is preferably maintained below 80% during the vertical and/or circumferential enlargement process.

When the concentration of gas components in the injected combustible mixture is between approximately 40 and 60%, the combustion zone tends to move back toward the source of the injection, i.e., the injection well bore. That is, when operating in this percentage range of combustible gas in the mixture, a type of retarded or slow motion flash back of the combustion flame occurs in which the peak temperature of the combustion zone moves upstream toward the source of injection. Accordingly, to maintain the combustion zone substantially horizontally stationary or immobilized in the formation, the combustible gas content of the injected mixture is preferably maintained at at least 60% of the total injected mixture. Use of the 40% to 60% mixture is useful, but requires caution against unguarded return of the flame front into the injection well bore with resulting possible damage from excess temperature.

FIG. 2 illustrates an additional embodiment of the present invention in connection with the control of a combustion zone for increasing the permeability of a

producing formation immediately adjacent a well bore. It is assumed that a formation 31 has been producing petroleum through a well bore 32 and that formation 31 has become plugged with waxes, asphalts or other material around the well bore. In accordance with the present invention, a combustion zone is established in formation 31 immediately adjacent well bore 32 by any of the methods described above in connection with the embodiment of FIG. 1, such as gas-air burner 13. Burner 13 is again connected through conduit 14 to source 16 of oxygen and source 17 of combustible gas. A gaseous combustible mixture is supplied from sources 16 and 17 through conduit 14 to burner 13 and ignited at burner 13 to provide thermal energy to produce a combustion zone 33 in formation 31 adjacent well bore 32.

After the start of such a combustion zone, the composition of the gaseous mixture supplied to burner 13 is adjusted to be gas-rich, with a minimum oxygen content, and preferably with a combustible gas content of between 60 and 80% of the total injected gas. This produces an action similar to that described above in connection with the embodiment of FIG. 1, in which substantially all of the injected oxygen is combined with the injected combustible gas in the combustion zone 33, so that substantially no horizontal enlargement of the combustion zone occurs. The combustion zone 33 does enlarge vertically and circumferentially to substantially the total vertical and circumferential extent of formation 31 to produce combustion of combustible components in the formation such as waxes and asphalts, and to produce shrinkage or decomposition of the non-combustible constituents of the formation such as carbonates. This combustion and shrinkage of these components produces a beneficial effect on the permeability of the formation in the critical permeability zone immediately adjacent the well bore.

Since the combustion zone is confined horizontally to the portion of the formation immediately adjacent the well bore, there is little likelihood of producing plugging or gumming up of the formation with distillation products which might be produced by the combustion zone and driven out a considerable distance into the formation. After the combustion zone has been in existence for a sufficient length of time to produce the desired permeability increasing effect, as determined by the characteristics of the particular formation, the supply of injected gas is discontinued to extinguish the combustion zone 33. After such extinction, the formation 31 may be produced normally through well bore 32 and associated tubing, with an increased permeability in the portion of formation 31 immediately adjacent well bore 32.

An additional application of the present invention is in the control of a localized combustion zone which is initially established at some distance out in a formation away from a well bore. In such a case it may be desirable to cause the combustion zone to return to the portion of the formation adjacent the well bore to produce a vertical and circumferential expansion of the combustion zone prior to beginning the horizontal advance of the combustion zone into the formation. Such a situation might arise in a case where the underground combustion zone was initiated by auto-ignition or auto-oxidation, in which the hydrocarbons in place ignite spontaneously under the action of injected oxygen without requiring the use of special ignition techniques or devices.

Where such auto-ignition does occur, it is likely that it will commence out in the formation at some distance from the injection well bore, since the rate of heat generation by auto-oxidation is relatively low and the cooling action of the injected oxygen or oxygen-containing gas in the portion of the formation immediately adjacent the well bore is usually sufficient to prevent occurrence of auto-oxidation in this area. Thus, the auto-oxidation will most probably occur in some portion of

the formation away from the well bore where this cooling action is reduced by the increased cross-sectional area of the formation.

Where such a combustion zone occurs, the method of the present invention may be utilized by adjusting the composition of the injected gaseous mixture to be "gas-rich" in the range from 40 to 60% combustible gas. The use of a gas having a composition within this range causes a type of retarded or slow motion flash back of the combustion flame toward the source of injection, in a manner similar to that described above. The velocity with which the combustion flame moves back toward the injection well is a function of the thermal conductivity of the formation, the rate of injection of the gaseous mixture and to a lesser extent, the temperature and pressure in the formation.

The combustion zone thus moves stably back through the formation toward the injection well bore under the action of the controlled composition of the injected gaseous mixture. Upon arrival at the portion of the formation adjacent the well bore, the composition of the gaseous mixture is changed so as to have between 60 to 80% combustible gas content. This action substantially immobilizes the combustion zone horizontally, while causing it to expand vertically and circumferentially around the well bore, in a manner similar to that described above. After this vertical and circumferential expansion, the forward or horizontal progress of the combustion zone may be commenced through appropriate control of the injected oxygen.

Although but a few embodiments of the present invention have been described, it will be apparent to those skilled in the art that various changes and modifications may be made therein without departing from the spirit of the invention or the scope of the appended claims.

I claim:

1. The method of establishing a combustion zone uniformly throughout the vertical extent of a petroliferous formation penetrated by a well bore comprising the steps of injecting an oxygen-containing gas into said formation to produce auto-oxidation of the petroliferous material in said formation for producing a combustion zone at some distance out from said well bore, injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation in contact with said combustion zone, adjusting the concentration of said combustible gas in said gaseous mixture to below 60% to cause said combustion zone to move through said formation toward said well bore, and increasing the concentration of said combustible gas in said mixture to greater than 60% when said combustion zone reaches the portion of said formation adjacent said well bore, so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said combustion zone, whereby the temperature of said combustion zone increases as a result of combustion of said mixture in said zone to cause said combustion zone to spread vertically in said formation while the horizontal position of said combustion zone remains substantially constant.

2. The method of establishing a combustion zone uniformly throughout the vertical extent of a petroliferous formation penetrated by a well bore comprising the steps of injecting an oxygen-containing gas into said formation to produce auto-oxidation of the petroliferous material in said formation for producing a combustion zone at some distance out from said well bore, injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation in contact with said combustion zone, adjusting the concentration of said combustible gas in said gaseous mixture to between 40 and 60% to cause said combustion zone to move through said formation toward said well bore, and increasing the concentration of said combustible gas in said mixture to greater than 60% when said combustion

zone reaches the portion of said formation adjacent said well bore so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said combustion zone, whereby the temperature of said combustion zone increases as a result of combustion of said mixture in said zone to cause said combustion zone to spread vertically in said formation while the horizontal position of said combustion zone remains substantially constant.

3. The method of establishing a combustion zone uniformly throughout the vertical extent of a petroliferous formation penetrated by a well bore comprising the steps of injecting an oxygen-containing gas into said formation to produce auto-oxidation of the petroliferous material in said formation for producing a combustion zone at some distance out from said well bore, injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation in contact with said combustion zone, adjusting the concentration of said combustible gas in said gaseous mixture to below 60% to cause said combustion zone to move through said formation toward said well bore, and increasing the concentration of said combustible gas in said mixture to between 60 and 80% when said combustion zone reaches the portion of said formation adjacent said well bore, so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said combustion zone, whereby the temperature of said combustion zone increases as a result of combustion of said mixture in said zone to cause said combustion zone to spread vertically in said formation while the horizontal position of said combustion zone remains substantially constant.

4. The method of establishing a combustion zone uniformly throughout the vertical extent of a petroliferous formation penetrated by a well bore comprising the steps of injecting an oxygen-containing gas into said formation to produce auto-oxidation of the petroliferous material in said formation for producing a combustion zone at some distance out from said well bore, injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation in contact with said combustion zone, adjusting the concentration of said combustible gas in said gaseous mixture to between 40 and 60% to cause said combustion zone to move through said formation toward said well bore, and increasing the concentration of said combustible gas in said mixture to between 60 and 80% when said combustion zone reaches the portion of said formation adjacent said well bore, so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said combustion zone, whereby the temperature of said combustion zone increases as a result of combustion of said mixture in said zone to cause said combustion zone to spread vertically in said formation while the horizontal position of said combustion zone remains substantially constant.

5. The method of increasing the permeability of a petroleum-bearing subterranean formation containing petroleum and penetrated by a well bore to increase the production of petroleum products from said formation into said well bore, comprising the steps of injecting a gaseous mixture containing oxygen and at least one combustible gas into said formation through said well bore, igniting said gaseous mixture to initiate combustion of petroleum in at least a localized zone of the wall of said well bore penetrating said formation, adjusting the concentration of said combustible gas in said gaseous mixture to above 60% so that combustion remains substantially horizontally stationary in the vicinity of said well bore while combustion is extended vertically along the length of the interface between said formation and said well bore and circumferentially around the entire wall of said well bore while its temperature is increased as a result of said combustion, discontinuing injection of said gaseous mixture to extinguish combustion in said com-

bustion zone, and then producing said petroleum products through said well bore.

6. The method of increasing the permeability of a petroleum-bearing subterranean formation penetrated by a well bore to increase the production of petroleum products from said formation, comprising the steps of injecting a gaseous mixture containing oxygen and at least one combustible gas into said formation through said well bore, igniting said gaseous mixture to establish at least a localized zone of combustion in the wall of said well bore, adjusting the combustible gas content of said gaseous mixture to between 60 and 80% relative to said oxygen so that substantially all of said oxygen is combined with said combustible gas in the vicinity of said zone of combustion, continuing the injection of said gaseous mixture at said adjusted gas-oxygen content so that said localized zone of combustion remains substantially stationary horizontally in said formation adjacent said well bore and expands vertically and circumferentially of said well bore while its temperature is increased as a result of said combustion of said oxygen with said gas, discontinuing injection of said gaseous mixture to extinguish combustion in said combustion zone, and then producing said petroleum products through said well bore.

7. The method of establishing a combustion zone uniformly throughout the vertical and circumferential extent of a formation containing petroliferous material penetrated by a well bore comprising the steps of injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation, igniting said gaseous mixture in said well bore to establish a localized combustion zone in said formation at the well bore wall, adjusting the concentration of said combustible gas in said gaseous mixture to between 60 and 80% so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said combustion zone, continuing the injection of said gaseous mixture at said concentration so that the temperature of said formation adjacent said localized combustion zone increases as a result of combustion of said mixture in said well bore to cause said combustion zone to spread vertically and circumferentially in said formation adjacent said well bore while the horizontal position of said combustion zone within said formation remains substantially constant.

8. The method of controlling a combustion zone in a formation containing petroliferous material penetrated by a well bore comprising the steps of injecting a gaseous mixture containing oxygen and a combustible gas through said well bore into said formation to contact said petroliferous material, igniting said gaseous mixture in said well bore to establish a localized combustion zone in said petroliferous material in the wall of said well bore penetrating said formation, adjusting the concentration of said combustible gas in said gaseous mixture to above 60% so that substantially all of said injected oxygen is combined with said combustible gas in the vicinity of said localized combustion zone, and continuing the injection of said gaseous mixture at said adjusted concentration to increase the temperature of said localized combustion zone as a result of combustion of said mixture in said well bore while the horizontal position of said combustion zone within said formation remains substantially constant.

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