

Aug. 25, 1964

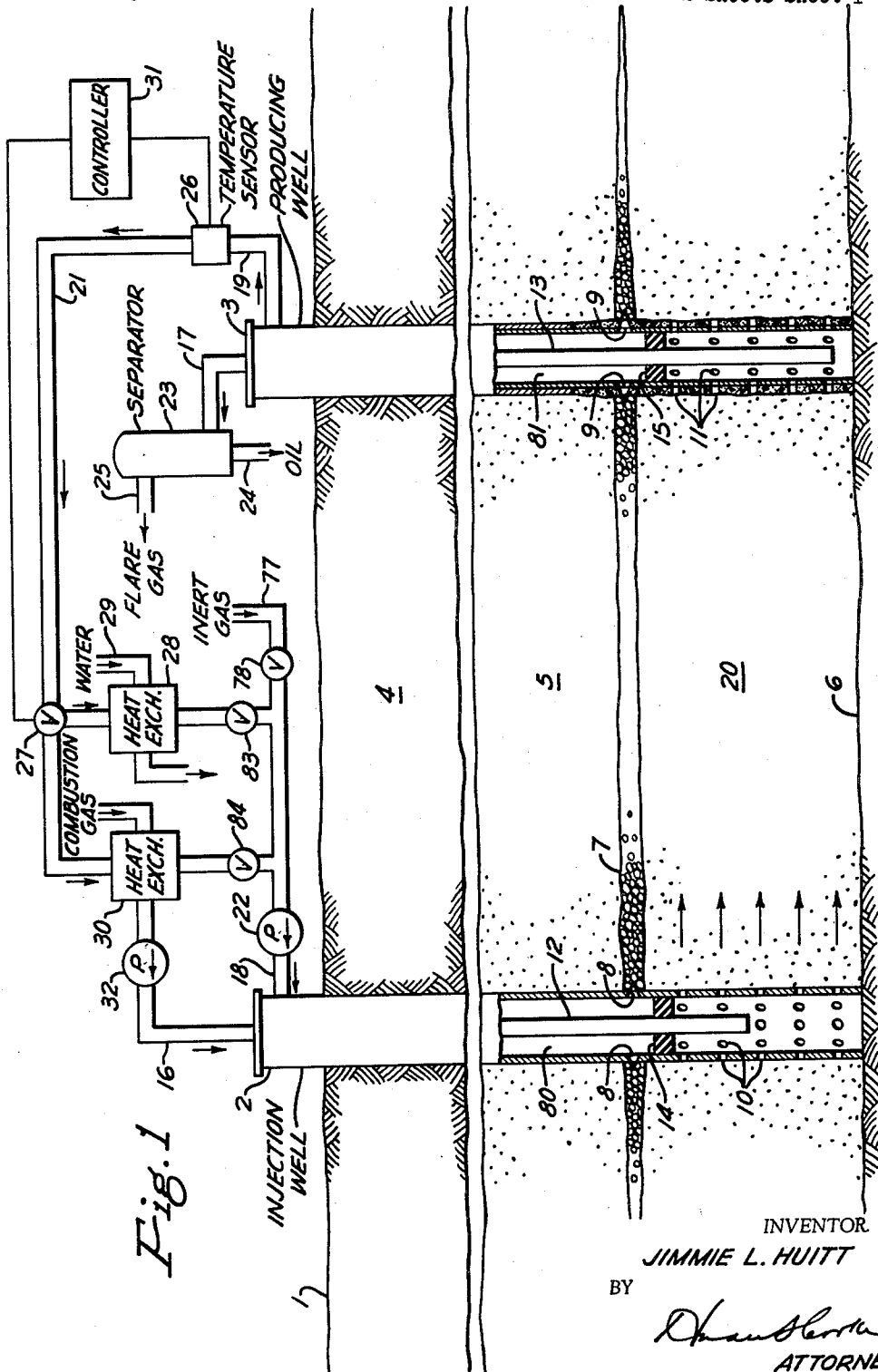
J. L. HUITT

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TEMPERATURE CONTROLLED IN-SITU COMBUSTION PROCESS

Filed Sept. 13, 1962

2 Sheets-Sheet 1



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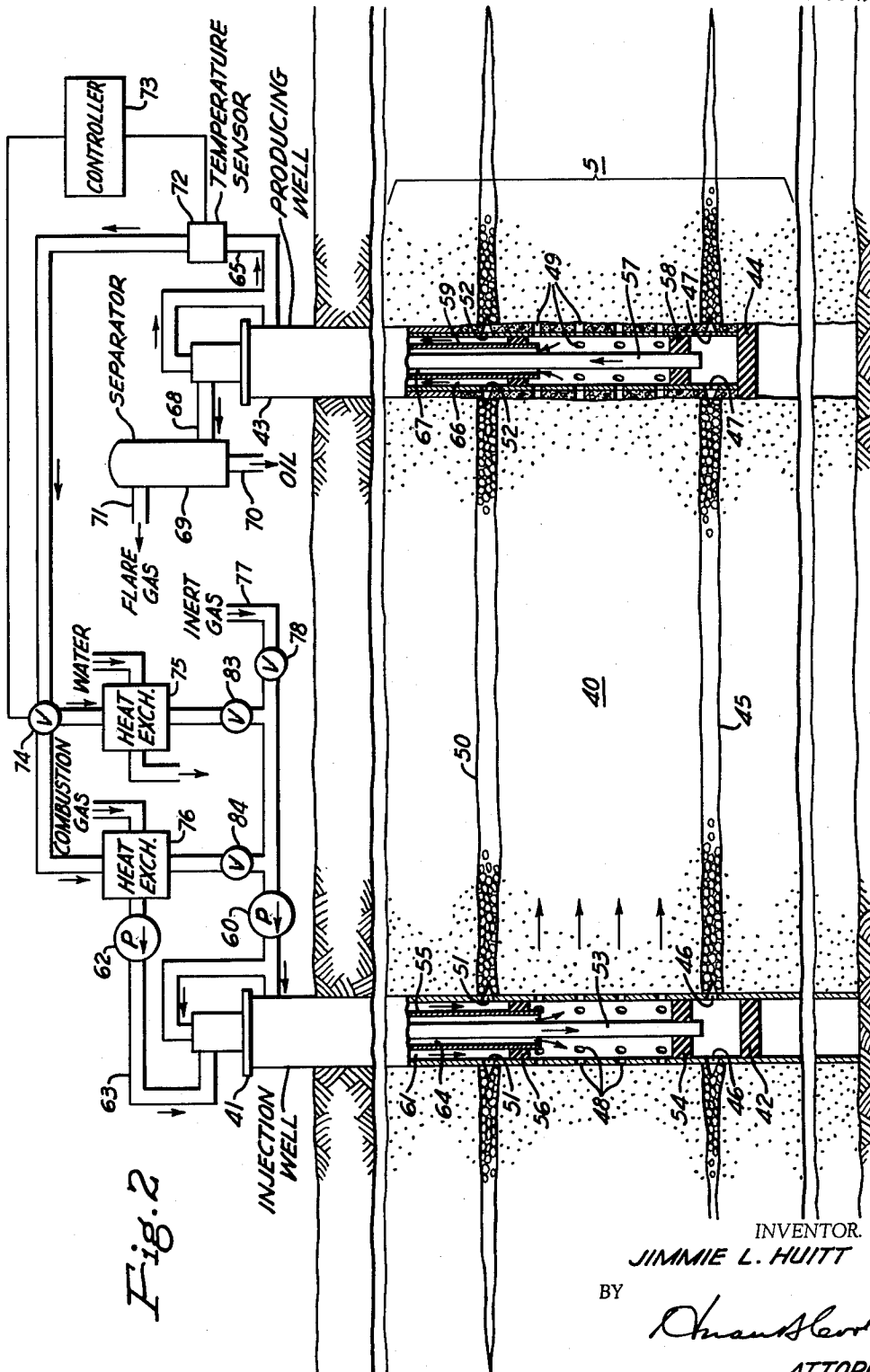
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2 Sheets-Sheet 2



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TEMPERATURE CONTROLLED IN-SITU COMBUSTION PROCESS

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4 Claims. (Cl. 166-4)

This invention relates to an in-situ combustion process for the recovery of petroleum and in particular concerns an in-situ combustion process having improved temperature control.

The so-called in-situ combustion process for the recovery of petroleum is well known. Numerous published descriptions of field operations of the process have indicated that control of the process is difficult and that adequate control is essential if the process is to be economic in the recovery of oil. It has further been determined that one of the most important control parameters is temperature. Temperature has a direct effect on the rate of the underground combustion reaction. It is also an important factor in the decomposition and volatilization of the produced petroleum, and to a lesser degree it affects the degree of recovery of the fluid products produced by the combustion through its effect on viscosity. For these reasons it is important that the temperature of an in-situ combustion process be controlled as independently of other variable as possible.

It is known that a limited degree of temperature control can be achieved through control of the oxygen concentration in the injected gas that supports the combustion of the in-situ oil. Attempts to control temperature in this manner have been unsatisfactory because the temperature is affected in only a secondary way, the primary factor in this type of control being the oxygen concentration which affects the rate of the chemical reaction which in turn affects the temperature only indirectly. Accordingly this type of control leaves much to be desired.

It is also known that a limited degree of temperature control can be achieved by introducing water with the injected combustion gas. The introduction of water however complicates the combustion reaction in that it not only dilutes the oxygen but the water upon turning into steam at high temperature may actually enter into the reaction occurring in the combustion zone and result in the production of undesirable reaction products such as hydrogen, carbon monoxide and low-molecular weight hydrocarbons. Accordingly this type of control is inadequate.

It is apparent that the inadequacies of the above-mentioned prior-art types of control arise from the fact that the parameter controlled is not temperature directly, but the latter is affected only secondarily because of changes in concentration and composition of the injected reacting gases. This invention provides independent control of temperature, so that the oxygen concentration, pressure, and composition of the injected gas can be maintained at optimum values for maximum recovery of desired products, and the temperature is then independently controlled to further maintain the most efficient and most economic in-situ combustion reaction temperature. Furthermore, complete stability of operation can be achieved by the use of this invention since changes in temperature do not also involve changes in concentration and composition of the reacting gas, and conversely changes in concentration and/or composition can be made while the temperature is maintained at a desired optimum value.

This invention is described in this specification together with examples of the manner in which it may be carried out with reference to the accompanying drawings in which

FIGURE 1 is a diagrammatic representation of apparatus both in the well and on the surface of the ground for carrying out an in-situ combustion process at the base of a petroleum-bearing formation using the temperature control of this invention; and

FIGURE 2 is a diagrammatic representation of apparatus for carrying out an in-situ combustion process in the middle regions of a petroleum-bearing formation using the temperature control of this invention.

This invention comprises an in-situ combustion process in which the vertical section where combustion is to take place is isolated on at least one side, i.e. top or bottom, and preferably on both sides, by a propped fracture zone extending from the injection well to the producing well and through which an inert gas is continuously circulated from one well to the other at a controlled temperature. The circulating gas employed is one that is chemically inert with respect to the combustion reaction and therefore itself does not participate in the chemical reaction. Substantial quantities of the circulating gas are circulated through the isolating fractures at the bounding surfaces of the active section, and by controlling the temperature of the circulating gas the operator controls the temperature at the bounding surfaces. By thus isolating a relatively thin section of the formation in which combustion is permitted to take place, the operator can attain a high degree of temperature control in the section. The combustion process is then repeated for successive sections of the petroleum-bearing formation until the entire formation has been treated thus attaining combustion under a high degree of control for the entire petroleum-bearing formation.

Referring to FIGURE 1 there is shown the surface of the earth 1 penetrated by a well 2 employed as an injection well and well 3 employed as a producing well as will become evident. The wells 2 and 3 penetrate the upper layers of earth 4 and are drilled through the petroleum-bearing formation 5 reaching substantially to its base as indicated at 6. Wells 2 and 3 are cased and the casing is cemented in conventional manner. A short distance above the producing formation a fracture 7 is provided by customary formation fracturing techniques. The fracture may be effected at the desired location by first notching the casing and formation as shown at 8 in the input well 2 as for example by means of the apparatus disclosed in application Ser. No. 19,792 filed April 4, 1960 now U.S. Patent 3,050,122. Thereafter fracturing pressure is applied at the notch 8 resulting in a fracture 7 at this point. The fracture 7 is propped in conventional manner by the injection of fracturing fluid containing suspended propping material preferably of large size. It is desirable that the fracture 7 have substantial flow capacity and the fracture 7 must be in communication with both the injection well 2 and the producing well 3 in order that circulation may be established between wells 2 and 3 through fracture zone 7. The fracture 7 is made to extend to the producing well 3. The depth at which the fracture 7 intersects well 3 is determined by setting the casing of the producing well 3 a short distance above where the fracture is expected, then injecting fluid into fracture 7 at the injection well 2 and determining in well 3 by means of a well flow meter the depth at which the fluid enters the producing well 3. A liner is then set in the producing well 3 below the casing and cemented in place. The liner and formation is then notched at this depth, the perforations being indicated by 9 in FIGURE 1.

The casing of injection well 2 is perforated as shown at 10 throughout the formation interval 20 to which the in-situ combustion process is to be applied. Similarly the liner and cement of the producing well 3 are perforated as shown at 11 throughout the formation interval

20. Tubing is then installed in the wells as shown at 12 and 13. The tubing 12 is open at its lower end and penetrates a packer 14 in injection well 2, the packer 14 being located just below the intersection of the fracture 7 with the well 2 and above the perforations 10. Similarly a packer 15 is installed in the well 3 just below intersection of the fracture 7 with the well 3 and above the perforations 11. The tubing 13 is open at its lower end and may contain conventional oil-well pumping equipment. The tubing 12 is also sealed at the casing head and is connected to pipe 16. Similarly the tubing 13 passes through the well head 3 and is connected to flow line 17.

With this system shown in FIGURE 1 it is apparent that the well 2 is provided with two injection channels, one being through the pipe 16, perforations 10 and into the lower portion 20 of the petroleum-bearing formation 5. The other channel is from the flow line 18 through the annular space 80 of the well 2 and through the notches 8 into the fracture zone 7.

Similarly two flow channels are provided in the producing well 3, one channel being from the producing formation 20 through the perforations 11 into the bottom end of the tubing 13 and out the flow line 17. The second channel is from the fracture zone 7 through notches 9 into the annular space 81 of well 3 and out the flow line 19.

Either forward or reverse burning type of reaction may be employed, these being well known in the art. By injecting an oxygen-containing combustion gas by compressor 32 through the pipe 16 and tubing 12 and into the producing formation 20, an in-situ combustion reaction is obtained in the formation section 20 lying between the fracture zone 7 and the base 6 of the producing formation. The composition of the combustion gas injected into the formation is conventional and does not per se form part of this invention. The term combustion gas is used herein to mean the gas that takes part in the in-situ combustion reaction. As is conventional in in-situ combustion operations the combustion gas contains oxygen which reacts with some of the oil in the formation to produce heat. Spontaneous combustion occurs to initiate most in-situ combustion operations, but if such does not occur, the combustion may be initiated by means of a downhole burner temporarily located opposite the section of the formation it is desired to ignite. As a result of the in-situ combustion there results spent combustion gas and petroleum vapors. The products produced through tubing 13 at the producing well 3 are passed through a separator 23 from which the oil is recovered at 24 and the gas flared at 25.

In this invention an inert gas is injected through pipe 18, annular space 80 and perforations 8 into the fracture zone 7, and extracted from the fracture zone at the producing well through the perforations 9, annular space 81, and pipe 19. Due to the relatively high permeability of the fracture zone 7 and the corresponding low resistance flow path through the fracture zone from the perforations 8 to the perforations 9, it is possible to circulate a large amount of inert gas through this loop. The pipe 19 is connected by means of pipe 21 to appropriate heat exchangers as will be more fully described later and is recirculated into the pipe 18 by means of compressor 22. Inasmuch as the gas that is circulated through the fracture zone 7 is chemically inert with respect to the in-situ combustion reaction taking place in formation 20, this circulating gas does not participate in the reaction. Circulation of the inert gas is essentially confined to the high permeability fracture zone and does not appreciably penetrate the formation 5 either above or below the fracture zone. However, during circulation of the inert gas through the fracture 7, this gas effects a cooling action of the formation adjacent the fracture 7, heat being dissipated from the formation 20 adjacent the fracture zone 7.

In this invention the temperature developed by the in-situ combustion reaction in the formation 20 is controlled by circulating inert gas through the fracture zone 7 adjacent to the in-situ combustion reaction. The recirculated inert cooling gas is any gas that will not participate in the combustion reaction, as for example nitrogen or air from which oxygen has been removed as engine exhaust gas, carbon dioxide, or the like. It is advisable to maintain a slight excess pressure in the inert gas circulating through the fracture system 7 so as to insure that the oxygen-containing combustion gas injected through tubing 12 shall not enter the fracture zone 7.

The fracture zone 7 can be at any selected depth in the petroleum-bearing formation and this invention provides a means of isolating the region 20 of the formation 5 in which combustion is occurring to a reasonably small portion 20 of the formation. The vertical extent of the formation section 20 that is isolated by the fracture zone 7 and the bottom 6 of the formation is relatively small and may be of the order of ten feet or less.

The circulating inert gas that passes through the fracture zone 7, is upon leaving the producing well 3, passed through a temperature sensor 26 and then via pipe 21 through a selection valve 27. Selection valve 27 permits the circulating inert gas to be passed either through a heat exchanger 28 where its temperature is reduced by circulating water introduced at 29, or alternatively the inert circulating gas may be passed through a heat exchanger 30 that serves to heat the injected oxygen-containing combustion gas injected through the pipe 16 and tubing 12 into the well 2. From the heat exchangers 28 and 30 the inert gas is returned to the fracture zone 7 by compressor 22. The temperature sensor 26 is connected to a controller 31 which in turn controls position of valve 27 in such manner that when the temperature of the inert gas in pipe 19 exceeds a predetermined value the controller 31 positions valve 27 to circulate all or a fraction of the inert circulating gas through the cooling heat exchanger 28. On the other hand, when the temperature of the gas in pipe 19 falls below a predetermined value, the controller positions valve 27 so that all or a fraction of the inert gas is circulated through heat exchanger 30 so that the hot inert gas serves to raise the temperature of the combustion gas injected by compressor 32 into the tubing 12 and thence into the combustion zone in formation 20. In most in-situ combustion operations the formation 20 has a relatively low permeability whereas the fracture zone 7 can be made by the use of large amounts of coarse propping agent to have a very high permeability thus permitting the circulation of comparatively large quantities of inert gas through the fracture zone by means of the compressor 22. The inert gas is thus capable of carrying away substantial quantities of heat from the combustion reaction zone.

Further more due to the inert nature of the circulating gas and the fact that it is maintained at a pressure slightly in excess of the pressure in the formation 20, the inert gas in the fracture zone 7 serves to arrest the combustion process at the intersection of the flame front and the fracture zone 7. By employing the process of this invention the in-situ combustion flame front is prevented from accelerating at its intersection with the fracture zone 7 by the reduction in reaction temperature effected by the circulation of the inert gas. This results in a straightening out of the flame front. It is apparent that the vertical thickness of the formation section 20 being treated and in which it is desired to maintain the combustion zone substantially vertical will depend on the relative permeabilities of the formation 20 and the fracture zone 7 as well as on the distance between wells 2 and 3.

Referring now to FIGURE 2 which shows the application of process of this invention to a portion of the producing formation 40 intermediate the top and bottom of the producing formation 5, the injection well 41 is plugged or packed off just below the region to be treated

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by means of packer 42. Similarly the producing well 43 is plugged or packed off at 44 below the region to be treated. A propped fracture 45 is produced at the bottom of the region 40 to be treated, the fracture 45 being produced by conventional procedures through notches 46 in the casing of well 41 in a manner similar to that previously described for producing the fracture 7 of FIGURE 1. The fracture 45 extends from the injection well 41 to the producing well 43 and forms a channel of comparatively high flow capacity between the wells 41 and 43. It is apparent that fracture zone 45 at the bottom of the region 40 to be treated may be the same fracture as was previously used in the treatment of the contiguous underlying portion of the producing formation, i.e. the fracture zone 7 of FIGURE 1 may be subsequently employed as the fracture zone 45 of FIGURE 2. The producing interval 40 to be treated is perforated substantially throughout its interval as shown at 48 as is also the interval 40 at the producing well 43 whose perforations are indicated by 49.

At the top of the producing interval being treated a second propped fracture system 50 is provided. The fracture 50 is produced in a manner similar to that used for making fractures 7 and 45. In making the fracture 50, the casing of well 41 and the contiguous formation are first notched at 51 and the fracture produced at the notch by employing straddle packers which isolate the rest of the well from the fracturing fluid. Intersection of the fracture 50 with the producing well 43 is determined by injecting fluid into the fracture 50 at the injection well 42 and determining where the fluid discharges into well 43 by means of a subsurface flow meter in well 43, after which a liner is set and cemented in place in well 43 and the liner notched or perforated at 52 to establish communication with the fracture zone 50. The fracture 50 thus extends from the injection well 41 to the producing well 43 and forms a channel of comparatively high flow capacity between wells 41 and 43. The thickness of the interval 40 being treated is such as to have a flow resistance from well 41 to well 43 through the producing interval 40 that is compatible with the flow resistance through the fracture zones 45 and 50.

It is preferred to provide the wells 41 and 43 with three flow channels, this being illustrated in FIGURE 2 by means of concentric strings of tubing. In well 41 the inner string 53 is equipped with a packer at 54 located just above the intersection of fracture zone 45 with the well 41. The tubing 53 thus provides communication from the top of the well to the fracture zone 45. A second string of tubing 55 has a packer at 56 that seals against the casing of the well so that the annular space between tubing 53 and tubing 55 provides a flow channel having access through the perforations 48 to the producing interval 40. The third channel in well 41 comprises the annular space 61 between tubing 55 and the casing of the well and this provides communication through notches 51 to the fracture zone 50.

Similarly three flow channels are provided in the producing well 43. The inner tubing string 57 is packed off against the casing by packer 58 located just above the perforations 47. The second string of tubing 59 is packed off against the casing just below the notches 52 so that the annular space 67 between tubing 57 and tubing 59 provides a channel by which fluids produced from the producing interval through perforations 49 may reach the surface of the ground. The annular space 66 between tubing 59 and casing of the well 43 communicates with the notches 52 and thereby communicates with the fracture zone 50.

At the top of the injection well 41 the compressor 60 injects a chemically inert gas into both the inner tubing string 53 and into the annular space 61. The compressor 60 thus forces inert gas into the fracture zone 50 and into fracture zone 45, these two flow channels being in parallel. The compressor 62 injects combustion-sustaining gas through pipe 63 which communicates with the annular

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space 64, the gas thus being injected into the producing interval 40 through the perforations 48. In the producing well 43 the fracture zone 45 is connected through perforations 47 and tubing 57 to flow line 65. The fracture zone 50 is connected through perforations 52 and the annular space 66 to flow line 65. The producing interval 40 being treated is connected through perforations 49 and annular space 67 to flow line 68 from which it is passed through a separator 69, oil being delivered at 70 and gas at 71. The flow line 65 is provided with a temperature sensor 72 connected to controller 73 that positions valve 74. Circulating gas which passes through the fractures 45 and 50 is preferably maintained at a pressure higher than that of the combustion gas in interval 40 and its temperature is controlled by means of the system shown. When the temperature of the circulating gas in flow line 65 exceeds a predetermined value the temperature sensor 72 connected to the controller 73 positions valve 74 to direct the inert gas through a cooling heat exchanger 75 from which the gas is returned to the input injection well 41 by compressor 60. If on the other hand the temperature sensor 72 indicates the circulated gas to be too low in temperature, the controller 73 positions valve 74 to divert the inert gas through heat exchanger 76 through which the combustion gas is passed and the latter is thereby heated in order to raise the temperature of the combustion zone.

Inert gas make-up is injected into the circulating system through pipe 77, valve 78 being closed except during such injection as required. Valves 83 and 84 may be used for manual adjustment of the respective flow rates through the heat exchangers during start-up period.

In FIGURE 2 the channels through fractures 45 and 50 for circulating inert gas are shown connected in parallel between the compressor 60 and the flow line 65, but it is apparent that if these two channels have widely differing flow resistances, it may be desirable to employ separate flow control means for the separate channels and separate compressors in place of single compressor 60. In such event it is desirable that the circulation from flow channel including fracture zone 45 be entirely separated from the circulation from flow channel including fracture zone 50 so that the temperature of the inert cooling gas circulating in these respective systems may be individually controlled. Thus for example it may under certain conditions be advisable to cool the circulating gas injected into the upper fracture zone 50 without cooling the circulating gas injected into the fracture zone 45. It is further contemplated that in the event that the circulating gas through one of the fracture zones such as 50 should require the addition of heat in order to raise the temperature of the contiguous portion of the formation interval being treated, such gas may be circulated through a conventional heater in order to raise its temperature a controlled amount prior to injection into the fracture zone. Separate additional heating of the combustion-supporting gas especially during the start-up period may also be required as is conventional in in-situ combustion operations.

This invention provides temperature control for the upper and/or lower boundaries of a petroleum-bearing formation interval that is being produced by an in-situ combustion process, such control maintaining an optimum temperature in the producing interval. It is apparent that the thickness of the interval 40 being capable of controlled treating by the method of this invention depends on the ratio of permeabilities attained in the respective fracture zones 45 and 50 and that existing in the formation 40. Due to the relatively larger permeability attained in the fracture zones the amount of gas circulated through the fracture zones is substantially greater than that injected into the combustion zone thereby enabling the temperature of the circulating gas to have a substantial effect on the temperature prevailing in the contiguous formation interval 40 at and near its boundary.

In addition to providing temperature control, this in-

vention is also effective in an in-situ combustion operation to ameliorate the tendency of the combustion front to accelerate across the top of a formation that has high gas saturation in its upper layers. Because of the higher permeability associated with the gas saturation the injected combustion-supporting gas often bypasses through the upper portion of the formation, so that the upper portion of an in-situ combustion zone may be burned through before the lower oil-saturated portions can be burned. By employing this invention the various regions of the petroleum-bearing formation may be isolated and separately treated, this avoiding large variations in permeability in any zone being treated. Thus by placing the upper fracture 50 of FIGURE 2 just under the gas-saturated portion of the formation 5 the in-situ combustion front is confined to the lower oil-saturated portion of the formation. An important advantage of this invention lies in its ability to confine an in-situ combustion process to a desired zone. The inert gas-cooled bounding fracture serves as a barrier that prevents the combustion front from moving across it, thus confining the combustion to desired formation zones.

In the appended claims the term combustion gas means gas that takes part in the in-situ combustion of petroleum in the formation, and the term initiating the in-situ combustion reaction encompasses the usual spontaneous ignition of the reaction.

What I claim as my invention is:

1. An in-situ combustion process for extracting petroleum from a petroliferous subterranean formation which comprises
 - providing an input well penetrating the formation,
 - providing an output well penetrating the formation,
 - isolating a relatively thin section of the formation by producing at least one propped fracture that provides a path of low resistance communication between said input well and said output well,
 - providing in said input well an independent flow channel to said fracture,
 - packing off said fracture from said thin section of formation in said input well,
 - injecting through said input well combustion gas into said isolated thin section of formation, initiating an in-situ combustion reaction in said thin section of formation,
 - injecting into said fracture through said independent flow channel of said input well inert gas of controlled temperature, and
 - extracting through said output well spent combustion gas and petroleum from said isolated thin section of formation.
2. An in-situ combustion process for extracting petroleum from a petroliferous subterranean formation which comprises
 - providing an input well penetrating the formation,
 - providing an output well penetrating the formation,
 - isolating a relatively thin section of the formation by producing at least one propped fracture that provides a path of low resistance communication between said input well and said output well, packing off said fracture from said thin section of formation in said input well,
 - providing in said input well an independent flow channel to said fracture, packing off said fracture from said thin section of formation in said output well,
 - providing in said output well an independent flow channel to said fracture,
 - injecting through said input well combustion gas into said isolated thin section of formation, initiating an in-situ combustion reaction in said thin section of formation,
 - injecting into said fracture through said independent flow channel of said input well inert gas of controlled temperature,

- extracting through said output well spent combustion gas and petroleum from said isolated thin section of formation, and
- extracting said inert gas from said fracture through said independent flow channel of said output well.
3. An in-situ combustion process for extracting petroleum from a petroliferous subterranean formation which comprises
 - providing an input well penetrating the formation,
 - providing an output well penetrating the formation,
 - isolating a relatively thin section of the formation by producing at least one propped fracture that provides a path of low resistance communication between said input well and said output well, packing off said fracture from said thin section of formation in said input well,
 - providing in said input well an independent flow channel to said fracture, packing off said fracture from said thin section of formation in said output well,
 - providing in said output well an independent flow channel to said fracture,
 - injecting through said input well combustion gas into said isolated thin section of formation,
 - injecting into said fracture through said independent flow channel of said input well inert gas of controlled temperature, initiating an in-situ combustion reaction in said thin section of formation,
 - extracting through said output well spent combustion gas and petroleum from said isolated thin section of formation,
 - extracting said inert gas from said fracture through said independent flow channel of said output well, and
 - measuring the temperature of said extracted inert gas.
4. An in-situ combustion process for extracting petroleum from a petroliferous subterranean formation which comprises
 - providing an input well penetrating the formation,
 - providing an output well penetrating the formation,
 - isolating a relatively thin section of the formation by producing at least one propped fracture that provides a path of low resistance communication between said input well and said output well, packing off said fracture from said thin section of formation in said input well,
 - providing in said input well an independent flow channel to said fracture, packing off said fracture from said thin section of formation in said output well,
 - providing in said output well an independent flow channel to said fracture,
 - injecting through said input well combustion gas into said isolated thin section of formation,
 - injecting into said fracture through said independent flow channel of said input well inert gas of controlled temperature, initiating an in-situ combustion reaction in said thin section of formation,
 - extracting through said output well spent combustion gas and petroleum from said isolated thin section of formation,
 - extracting said inert gas from said fracture through said independent flow channel of said output well,
 - measuring the temperature of said extracted inert gas, and
 - controlling the temperature of said injected inert gas inversely as the temperature of said extracted inert gas, whereby the reaction temperature of the combustion process in said isolated section of formation is controlled.

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