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METHOD FOR TRACING THE MOVEMENT OF FLUID INTERFACES

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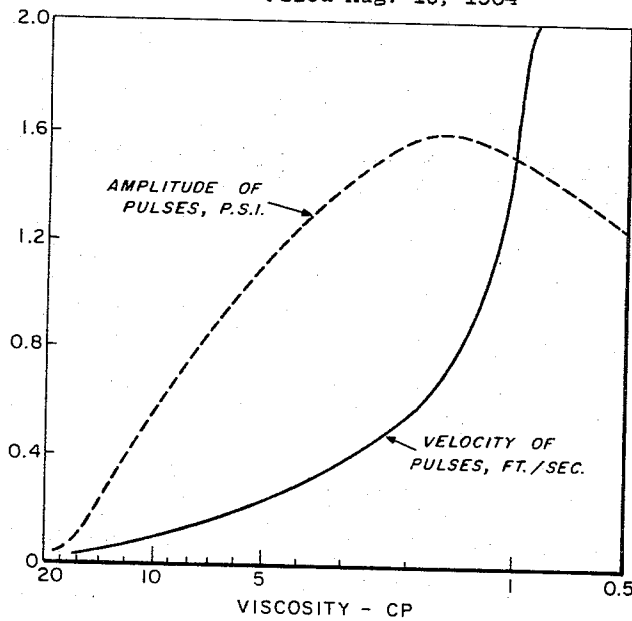


FIG. 1

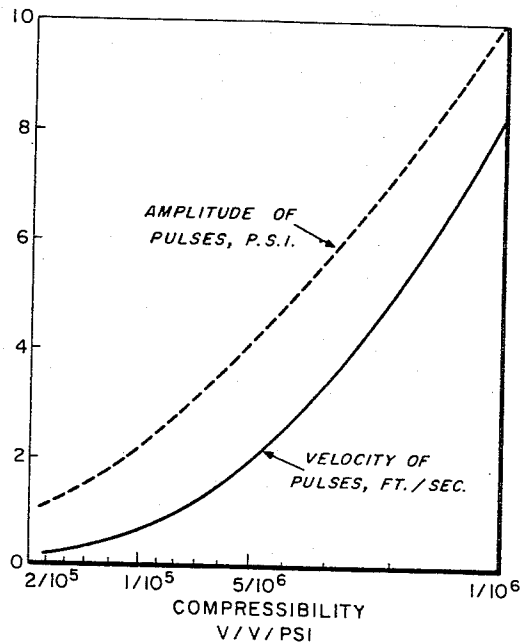


FIG. 2

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METHOD FOR TRACING THE MOVEMENT OF FLUID INTERFACES

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8 Claims. (Cl. 73-155)

This invention relates to the testing of porous subterranean reservoirs for the purpose of locating fluid interfaces and tracing their movement within such reservoirs. In a particular aspect the invention relates to the displacement of petroleum from subterranean reservoirs by either natural or artificial drives. In a specific embodiment, pressure-pulse surveys are employed to trace the movement of an interface between a driving fluid and the reservoir oil.

Various natural mechanisms of oil recovery, and an even greater variety of artificial recovery processes, involve the movement within the reservoir of an interface between two fluids having a different viscosity and/or a different compressibility. Common examples include an oil-gas interface, characteristic of both the natural gas-cap drive and the injection of gas for pressure maintenance; and the oil-water interface, characteristic of both the natural water drive and of waterflooding, perhaps the most common of artificial recovery methods.

Knowledge of the position and movement of such interfaces will usually allow improved evaluations of reservoirs, facilitate lease equipment design, and improve overall recovery efficiency. For example, the success of a pattern waterflood frequently depends upon the ability of the operator to obtain a satisfactory distribution of the flood water throughout the flood pattern. This can be a severe problem, since the reservoir is seldom homogeneous or isotropic, but instead contains zones having directional permeabilities, as well as fractures or channels having a relatively high permeability to the injected water. These irregularities tend to prevent the formation of a smoothly advancing flood front, which causes much of the reservoir to be by-passed, thereby limiting the recovery of oil.

Despite these heterogeneities, irregular advances in a flood front can be minimized in many instances by the proper regulation of injection pressures and production flow rates, in order to counter-balance the heterogeneities. Such measures, although highly desirable, have not become routine, since they require that the operator have considerable knowledge concerning the nature and extent of the heterogeneities, before the flood has progressed beyond its early stages. Sufficient information concerning reservoir irregularities is seldom available.

Accordingly it is one object of the present invention to follow the progress of a flood front in order to control the distribution of the injected fluid by adjusting pressures and flow rates at the various injection and production wells, to counter-balance the effect of reservoir heterogeneities.

Briefly, any change in the position of an interface between two reservoir fluids is determined by measuring the velocity and amplitude of a pressure pulse in traversing the reservoir between spaced wells located on opposite sides of the interface. The velocity and amplitude of the pulse are directly related to the permeability-thickness product of the reservoir, and inversely related to the viscosity and compressibility of the fluids occupying the pore space. Differences in pulse velocity and amplitude, as determined periodically during the progress of a flood, are a measure of the relative quantities of the two fluids

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between a given well pair, and are therefore indicative of the position of an interface between the pulse input and responsive wells.

The pulse-testing method to be used in accordance with the present invention is disclosed in the copending application of Robert A. Greenkorn and Carlton R. Johnson, entitled, "Method for Determining Reservoir Heterogeneities," Ser. No. 323,651, filed Nov. 14, 1963, now abandoned. The pulse-testing method is generally characterized by the step of introducing a small change in the fluid energy content of the reservoir at a given point, and thereafter determining the effect of the change at one or more spaced points within the reservoir. For example the flow rate into an injection well, or from a production well, is changed slightly and the influence of the change is then determined at one or more spaced wells. It has been discovered that the velocity and amplitude of the resulting pressure disturbance are a direct measure of the fluid transmissibility between the input well and the responsive well.

It is frequently desirable to transmit a pattern of pressure changes, or a plurality of pulses, into the reservoir through the input well and to detect the corresponding pattern or plurality of output pulses at the responsive well. Treatment of the responsive signal by conventional correlation techniques makes it possible to identify the character of these signals independently of interfering signals or noise.

The generation of a pressure pulse at a well is typically achieved by changing from one flow rate to another, whether injection or production flow as the case may be, and then returning the well to its initial rate of flow. The input pulse amplitude is the difference between the initial and the adjusted rates of flow. A suitable pulse amplitude may be generated by a change in flow rate ranging from 30 barrels per day up to as much as 5,000 barrels per day or more, depending upon reservoir transmissibility and well spacing. That is, a 30 barrels per day change in flow rate may be adequate between wells spaced less than 100 feet apart in a reservoir having limited transmissibility, whereas 5,000 barrels per day change in flow rate may be conveniently feasible in a reservoir having unusually high transmissibility, and where the well spacing is in excess of one mile.

The duration of a pulse is the time interval during which the adjusted flow rate is maintained. Suitable pulse duration require that the adjusted rate be maintained for at least 5 seconds and as much as several hours, depending primarily upon the selected difference between the adjusted flow rate and the normal flow rate of a given well. For example, a strong pulse is generated by shutting in a 5,000 barrels per day well for a few seconds, while it would take a matter of hours to generate a substantial pulse by shutting in a 30 barrels per day flow.

If a test is being run to determine only the arrival time or velocity of a pressure pulse, then a single pressure change at the input well is usually adequate. Moreover the input disturbance may be generated by a step-wise progression of increasing flow rates or a step-wise progression of decreasing flow rates. However, to obtain additional information from the output pulse amplitude and shape it is preferable to generate an input signal characterized by a first pressure change (increase or decrease) followed by a return to the original pressure after a short time.

In certain instances a single change of flow rates at the input well may not provide a clearly identifiable response at an adjacent well because of the difficulty of distinguishing the desired response from inherent background pressure fluctuations. As a practical matter therefore it is sometimes necessary to initiate a plurality of flow rate

changes, pulses, or other intelligent patterns of pressure variations at the input well to provide an unmistakable responsive pattern of pressure change in an adjacent well.

Accordingly, suitable input pulse durations and amplitudes for a usually given area are best determined by first monitoring the background pressure fluctuations in a representative number of wells. A stable reservoir characterized by small or negligibly inherent pressure fluctuations is amenable to pulse testing with a relatively weak pressure disturbance whereas stronger pulses require a less stable reservoir. Pulse amplitudes and durations are preferably selected to maximize the contrast between the desired pressure response and the natural background variations.

The responsive pressure change is generally detected by means of a very sensitive pressure measuring device located either directly in a responsive well bore, or connected to the well head at the surface. In most reservoirs, the responsive signal will be less than 0.1 p.s.i., and generally less than 0.01 p.s.i. In a few reservoirs, due to their extremely high transmissibilities, responsive pressure changes of as much as 2 p.s.i. have been observed. Responses of this magnitude, however, are less preferred since they are usually susceptible to a substantial influence from portions of the reservoir outside the vicinity of the well pair being investigated.

FIGURE 1 shows the effect of the viscosity of reservoir fluids upon pulse velocity and amplitude. The indicated relationships of pulse amplitude and velocity to the viscosity of reservoir fluids are based upon an initial pulse amplitude of 1,000 barrels per day, and a duration of 2 hours, generated in a reservoir having an average permeability-thickness product of 4.0×10^4 md.-ft. and a porosity-thickness product of 1.0 ft. The responsive pressure change and pulse velocity are determined in a well spaced 1320 feet from the pulsed well. The compressibility of reservoir fluids is assumed to remain constant for this particular example.

FIGURE 2 shows the effect of the compressibility of reservoir fluids upon pulse velocity and amplitude. As in FIGURE 1, the indicated relationships are based upon the propagation of a 1,000 barrel per day input pulse, of 2 hours duration, through a reservoir having an average permeability-thickness product of 4.0×10^4 and a porosity-thickness product of 1.0; and the measurement of a responsive differential pressure change in a well spaced 1320 feet from the pulse well. In FIGURE 2 the viscosity of reservoir fluid is assumed to remain constant.

Thus it can readily be seen that changes in pulse amplitude and velocity are indicative of the movement of a fluid interface, provided only that the fluids which form the interface have a significantly different viscosity and/or compressibility. In the event movement of the interface results in both a decreased viscosity and a decreased compressibility of reservoir fluids between the input and responsive wells, then the increased amplitude and velocity caused by the decreased viscosity (FIGURE 1) are added to the increase in amplitude and the increase in velocity caused by the decreased compressibility (FIGURE 2).

As an example of the invention, in pattern waterflooding, consider an inverted five-spot pattern wherein each of the four production wells is spaced 1320 feet from the injection well, in a reservoir having the characteristics designated in connection with FIGURES 1 and 2. The initial injection of flood water is controlled to generate a 1,000-barrel per day pulse of two hours duration. The velocity and amplitude of the resulting pressure disturbance is measured at each of the production wells. The flooding of the pattern is then begun and continued in a conventional manner, based upon whatever experience and information are available as to the best engineering practice in flooding the given reservoir. After a period of three months, for example, a pulse having the same initial amplitude and duration as before is again propagated from the central well to each of the four production

wells. The pulse velocity and amplitude observed between each well pair is then compared with the original pulse velocity and amplitude observed at the beginning of the flood. If, in each of three quadrants, the change in pulse velocity and amplitude caused by the progress of the flood front is substantially the same, but in the fourth quadrant the pulse amplitude and velocity has not undergone a comparable change, it will be apparent that the flood front is not progressing as rapidly in the fourth quadrant as in the remaining three. Therefore, upon resuming the flood, an increased flow rate is maintained from the production well of the fourth quadrant in order to favor a more rapid frontal advance in the fourth quadrant, as a means of compensating for whatever heterogeneity may have initially retarded the progress of the flood front in the fourth quadrant. As an equivalent alternative, a decreased production flow rate may be maintained from the other three quadrants.

Curves such as presented in FIGURES 1 and 2 may readily be prepared for use in connection with the application of the invention to a reservoir having different permeability and porosity characteristics, for different well spacing, and for different input pulses, by using the following solution to the diffusivity equation:

$$\Delta p \frac{Q\mu}{Kh} - Ei(-u), \text{ where } u = \frac{\phi ch^2}{Kt}$$

and:

Δp = Pressure change in the responsive well

Q = Rate of flow at pulsed well

μ = Viscosity of reservoir fluids

K = Permeability

h = Reservoir thickness

ϕ = Porosity

c = Compressibility

r = Distance between wells

t = Time,

and by using the superposition principle (Mathematics of Physics and Modern Engineering, Sokolnikoff and Redheffer, McGraw-Hill Book Co., Inc. (1958) p. 766) to determine the velocity and amplitude of the pulses for various values of reservoir transmissibility (Kh/μ) and storage (ϕch). Changes of viscosity cause a corresponding change in the value for transmissibility and, assuming a constant value of storage, corresponding changes in received pulse amplitude and velocity can be determined. Similarly, a progressive change in compressibility causes a predicted change in storage and, assuming a constant transmissibility, the progressive change in received pulse amplitude and velocity can be calculated. A progressive change in both compressibility and viscosity can also be calculated in this manner.

What is claimed is:

1. A method for tracing the movement of a fluid interface located between two wells in a porous subterranean reservoir which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at one of said wells, timing the arrival of a corresponding pressure transient at the other of said wells, measuring the amplitude of the resulting pressure transient at the other of said wells, subsequently generating a second fluid flow-rate pulse by changing the volume flow rate at one of said wells, timing the arrival of the resulting pressure transient at the other of said wells, and measuring the amplitude of the second pressure transient at the other of said wells, whereby the viscosity and compressibility of reservoir fluids at the time of said first measurement of pulse velocity and amplitude, and the viscosity and compressibility of reservoir fluid at the time of said second measurement of pulse velocity and amplitude may be determined, any difference between the first and second determinations of reservoir fluid viscosity and compressibility being a measure of change in the position of the interface.

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2. A method of tracing the movement of a fluid interface located between two wells in a porous subterranean reservoir which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at one of said wells, determining the velocity of the resulting pressure transient in traversing the reservoir between the wells, measuring the amplitude of said resulting transient at the other of said wells, and subsequently determining the velocity and amplitude of a second fluid flow-rate pulse generated by changing the volume flow rate at one of said wells, said pulse having substantially the same initial character as said first pulse, whereby any difference between the first and second determinations of pressure transient velocity and amplitude is a measure of the change in position of the fluid interface.

3. A method for tracing the movement of a fluid interface located between two wells in a porous subterranean reservoir which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at one of said wells at a time when the position of the interface is known, determining the velocity of the resulting pressure transient in traversing the reservoir between wells, measuring the amplitude of said pressure transient at the other of said wells, and subsequently generating a second fluid flow-rate pulse by changing the volume flow rate at one of said wells, said pulse having substantially the same initial character as said first pulse, determining the velocity of the pressure transient resulting from said second pulse in traversing the reservoir between the wells, and measuring the amplitude of said second pressure transient at the other of said wells, whereby any difference between the first and second determinations of velocity and amplitude is a measure of the change in position of the fluid interface.

4. A method for following the progress of a pattern waterflood which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at one well of said pattern, determining the velocity and amplitude of the resulting pressure transient at a second well of said pattern, injecting flood water into at least one injection well of said pattern, and during the progress of flood generating at least one additional fluid flow-rate pulse by changing the volume flow rate at one of the wells involved in said first determination of pressure transient velocity and amplitude, measuring the velocity and amplitude of said pressure transient at the other well involved in the first determination of pressure transient velocity and amplitude, whereby any difference in transient velocity and amplitude between said first and second determinations is a measure of the extent to which the water-oil interface has progressed between the two wells.

5. A method for following the progress of a pattern waterflood which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at an injection well of said pattern, measuring the velocity and amplitude of the resulting pressure transient in an adjacent production well of said pattern, injecting flood water and during progress of the flood propagating, by changing the volume flow rate at one of said wells at least one additional fluid flow-rate pulse between the same two wells of said pattern, whereby any difference between the initial and subsequent determinations of pressure transient velocity and amplitude in a measure of the extent to which the water-oil interface has progressed from the injection well toward the production well.

6. A method for following the progress of a pattern waterflood which comprises propagating a first fluid flow-rate pulse between an injection well of said pattern and an adjacent production well of said pattern by changing the volume flow rate at one of said wells, measuring the

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velocity of the resulting pressure transient in traversing the reservoir between said wells, measuring the amplitude of said pressure transient upon arrival at the responsive well of said pair, injecting flood water and during the progress of the flood propagating a second fluid flow-rate pulse between the same two wells of said pattern by changing the volume flow rate at one of said wells, measuring the velocity of the pressure transient resulting from said second fluid flow-rate pulse in traversing the reservoir between said wells, measuring the amplitude of said second pressure transient upon its arrival at the responsive well of said pair, whereby any difference between the velocity and amplitude of the first pressure transient compared with the velocity and amplitude of the second pressure transient is a measure of the extent to which the water-oil interface has progressed from the injection well toward the production well.

7. A method for following the progress of a pattern waterflood which comprises propagating a first fluid flow-rate pulse between an adjacent production-injection well pair by changing the volume flow rate at one of said wells, determining the velocity and amplitude of the resulting pressure transient upon its arrival at the responsive well of said pair, injecting flood water and during the progress of the flood propagating a second fluid flow-rate pulse by changing the volume flow rate at one of said wells, said pulse having an initial amplitude and duration substantially equal to the amplitude and duration of said first pulse by changing the volume flow rate, determining the velocity and amplitude of the pressure transient resulting from said second pulse on its arrival at the responsive well of said pair, any difference between the velocity and amplitude of the first and second transients being a measure of the extent to which the water-oil interface has progressed from the injection well toward the production well.

8. An improved method for minimizing irregular advances in the flood front of a pattern waterflood which comprises generating a first fluid flow-rate pulse by changing the volume flow rate at an injection well, timing the arrival of the resulting pressure transient at each production well adjacent said injection well, measuring the pressure transient amplitude at each of said production wells, injecting flood water at said injection well and during the progress of the flood generating a second fluid flow-rate pulse by changing the volume flow rate at said injection well, said second pulse having an initial amplitude and duration substantially equal to the amplitude and duration of said first pulse, timing the arrival of the pressure transient resulting from said second pulse in each of said production wells, measuring the amplitude of said second pressure transient in each of said production wells, determining from said measurements of velocity and amplitude any differences between the rate of frontal advance toward the respective production wells, and readjusting the rates of production at a selected number of production wells in order to off-set any initial tendency of the flood to advance irregularly.

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