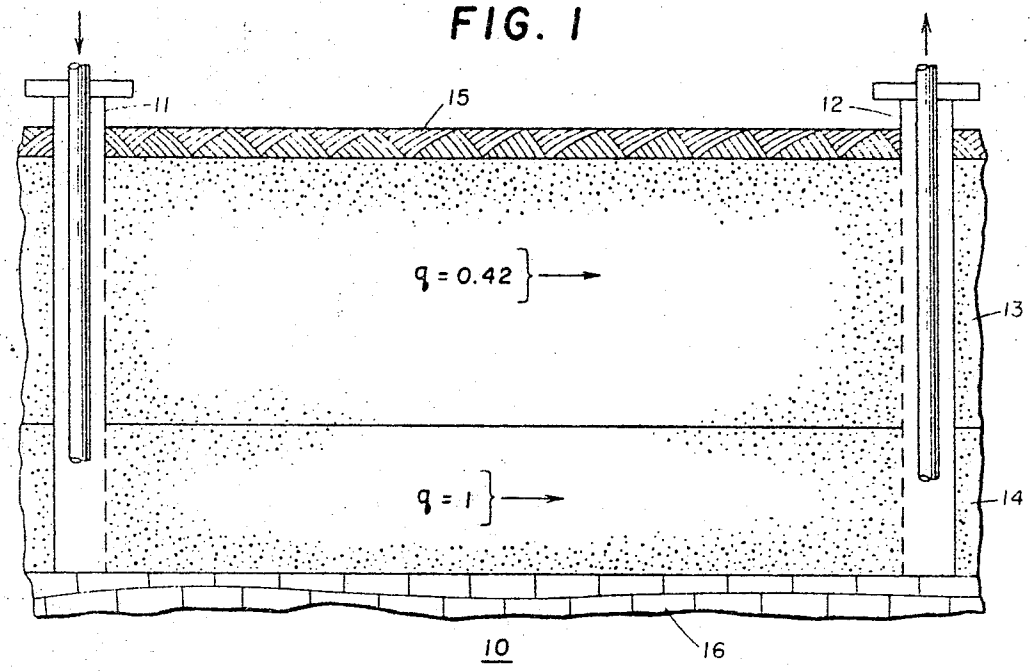
Feb. 7, 1967 A. S. ODEH 3,302,710

METHOD FOR RECOVERING HYDROCARBONS

Filed Feb. 7, 1964 2 Sheets-Sheet 1

FIG. 1



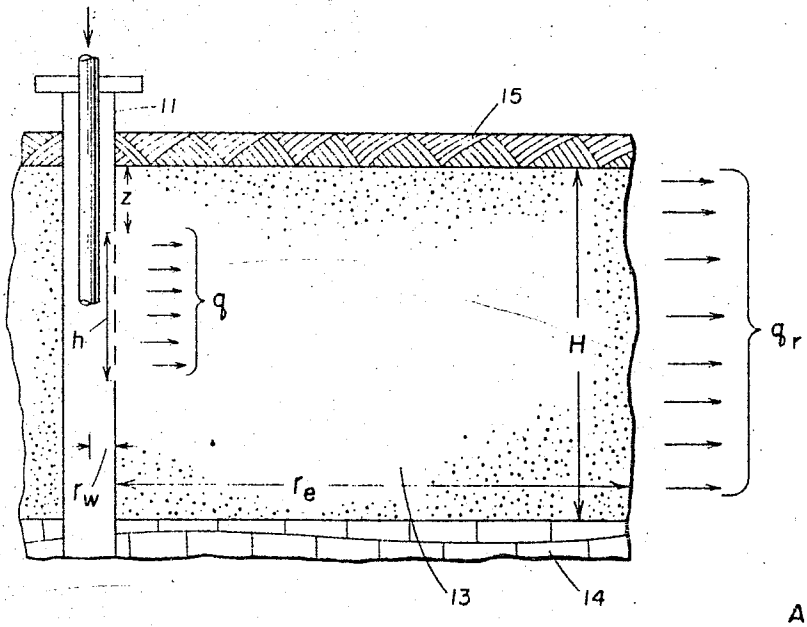


FIG. 2

AZIZ S. ODEH
INVENTOR.

BY Emil J. Bednar
ATTORNEY

METHOD FOR RECOVERING HYDROCARBONS

Filed Feb. 7, 1964 2 Sheets-Sheet 2

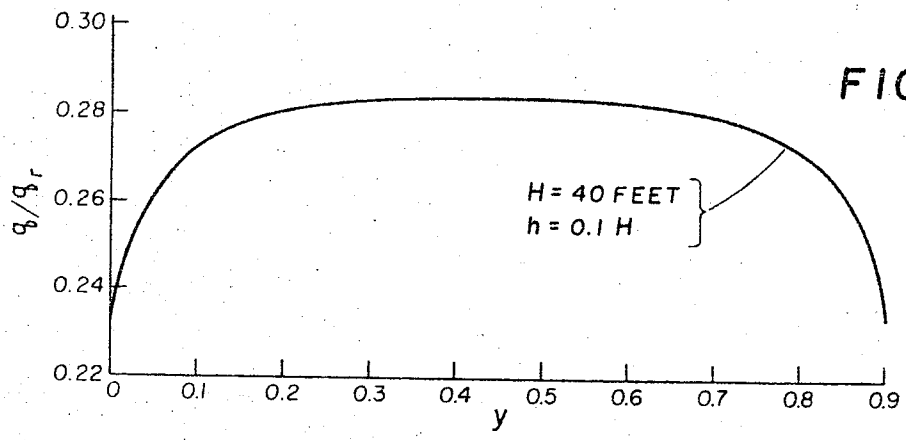


FIG. 3

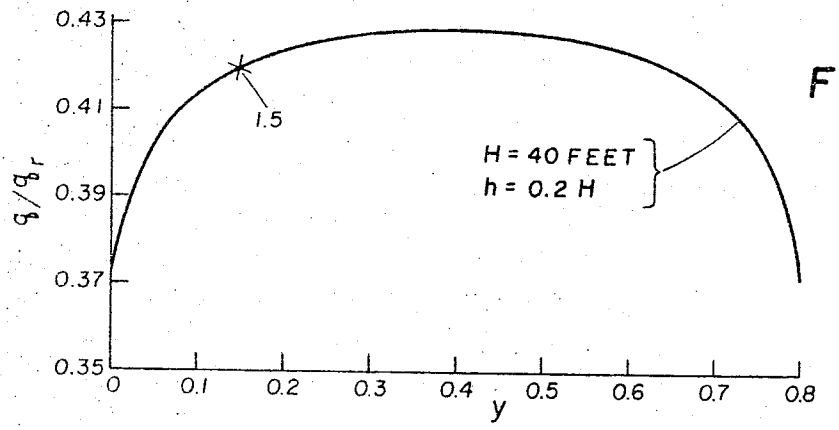


FIG. 4

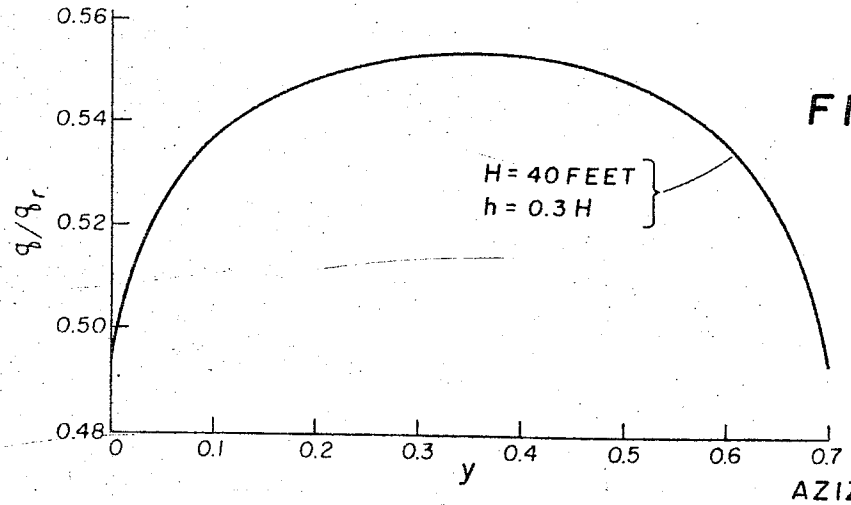


FIG. 5

AZIZ S. ODEH
INVENTOR.

BY Emil J. Bednar
ATTORNEY

United States Patent Office

3,302,710
Patented Feb. 7, 1967

3,302,710

METHOD FOR RECOVERING HYDROCARBONS

Aziz S. Odeh, Dallas, Tex., assignor to Mobil Oil Corporation, a corporation of New York

Filed Feb. 7, 1964, Ser. No. 343,280
6 Claims. (Cl. 166—9)

This invention relates to a method for recovering hydrocarbons from subterranean reservoirs. More particularly, it relates to such method for recovering hydrocarbons from a formation or strata in fluid communication, over less than its thickness, with a wellbore.

In many situations in the production of hydrocarbons, it is necessary to provide fluid communication between a wellbore and a strata of a hydrocarbon reservoir over less than the entire vertical thickness of such strata. For example, the selective perforation of a casing in a wellbore over a distance less than the entire vertical interval of the strata it penetrates may be used to restrict the rate of fluid flow between the wellbore and such strata. Such arrangement may be utilized at the wellbore contact to each of several adjacent strata having different fluid flowing characteristics to produce fluid flows at an equal velocity through all the strata. More particularly, such partial perforations of a wellbore adjacent to each of several strata can be utilized in various procedures employing injected or natural displacing fluid to assist in the optimum recovery of hydrocarbons. This arrangement is utilized to provide a more uniform movement of the fluids at the same velocity in each strata of the reservoir to secure a better recovery of hydrocarbons. The nonuniform and unequal movement of fluids in the various strata of the reservoir leads to inefficient recovery of hydrocarbons as a result of the bypassing of hydrocarbons in the reservoir by the displacing fluid. Additionally, such unequal movement of displacing fluid leads to premature breakthrough of the fluid into the wellbore. This fluid may be of any type, such as carbon dioxide, natural gas, or water, injected into, or resident in, the strata to assist in producing the hydrocarbons from the reservoir.

Restricting fluid communication between a wellbore and an adjacent strata to less than its thickness has other useful applications. For example, it may be desirable not only to restrict the fluid flow to a certain rate but to establish such flow only through a certain interval at the wellbore. One utility of such arrangement is to reduce water or gas coning. Another utility is to control the flow of a relatively high pressure fluid existing in such strata.

As will be apparent to those skilled in the art, the use of such an interval of fluid communication at a wellbore creates problems in the optimum production of fluids from the adjacent strata. With the flow between the wellbore and strata through an interval of fluid communication, the flow potential distributions are of a spherical nature adjacent the interval of the wellbore and do not become radial until a substantial distance away from the wellbore in the formation. It is well known that with an interval of fluid communication extending from one horizontal boundary of the strata less than about 50 percent of its vertical dimension, fluid flow of a radial nature is not obtained until at about a distance from the wellbore twice the strata thickness. Radial flow is not obtained until a much greater distance in the strata from the wellbore where the mentioned interval extends for a much shorter distance into the strata from one of its horizontal boundaries. Radial flow is similarly delayed where the mentioned interval is positioned intermediate the horizontal boundaries of the strata. Of course, the preferred conditions of fluid flow are obtained where the interval of fluid communication extends substantially

through the entire thickness of the strata. Under these circumstances radial flow is obtained immediately adjacent the wellbore.

The distance through which fluids must flow through a selectively positioned interval of fluid communication between the wellbore and the strata before radial flow is established is one factor controlling the efficiency in the recovery of hydrocarbons from such strata. One reason for this result is that hydrocarbons in the strata where nonradial flow exists are bypassed and remain unproduced. Another reason for this result exists where a displacing or driving fluid used for displacing the hydrocarbons in the strata undergoes premature breakthroughs at areas of nonradial flow and thereafter more fluid is used to displace the hydrocarbons. Thus, the use of an interval of fluid communication to obtain a fluid flow between a wellbore and a given portion of a strata is well known. Similarly, it is known to restrict the fluid flow through such interval to obtain a desired rate of fluid flow therethrough. However, the problems relating to fluid flow through such interval have not been solved.

It has been discovered that an interval of fluid communication less than strata thickness can be placed at a desired position in a wellbore relative to a strata for any given set of fluid flowing conditions therein to produce optimum flow conditions in the strata. More particularly, by using this discovery, the radial flow of fluid is obtained under a given set of fluid flowing conditions in the strata as closely adjacent the wellbore as is possible with less than the entire strata thickness exposed for fluid communication to the wellbore. Of course, such discovery provides for optimum fluid flowing conditions in such strata in the effective production of hydrocarbons at the greatest efficiency.

It is therefore an object of the present invention to provide a method for recovering hydrocarbons under optimum fluid flowing conditions from reservoirs having strata exposed to fluid flow at a wellbore over an interval of less than the thickness of such strata. Another object is to provide in such method a definite relationship between the factors concerning fluid flow in a reservoir and the interval of fluid communication between a strata and wellbore so that the efficient recovery of hydrocarbons may be obtained. Another object is to provide in such method for an interval of fluid communication less than the thickness of the strata at a position in a wellbore where radial flow is obtained in the strata more closely adjacent the wellbore than has heretofore been obtained. Another object is to provide for the utilization of at least one positioned interval of fluid communication in a wellbore adjacent to each strata with the fluid flow restricted through some of the intervals such that optimum fluid flowing conditions are obtained through the uniform and aligned movement of fluids in each of the strata for the maximum recovery of hydrocarbons from each such strata. Another object is to provide for the recovery of hydrocarbons from a reservoir in accordance with the preceding objects where all factors concerning the flow of fluid in each strata in the reservoir have a definite relationship and which relationship may be correlated to any particular strata and any set of fluid flowing conditions encountered in the production of hydrocarbons in a steady state flow.

These and other objects will be readily apparent from the following description of the present invention when taken in reference to the appended claims and the attached drawings, wherein:

FIGURE 1 is a vertical section through a reservoir in the earth containing hydrocarbons in which the method of this invention can be practiced;

FIGURE 2 is a partial view of the reservoir shown in

FIGURE 1 to illustrate one application of the method of this invention; and

FIGURES 3, 4, and 5 are graphic illustrations of the physical relationship between factors of the fluid flowing conditions in a reservoir as established by the method of this invention to the recovery of hydrocarbons.

Generally, the present invention resides in a method for producing hydrocarbons by obtaining optimum fluid flowing conditions in a reservoir having strata containing hydrocarbons which strata is in fluid communication with a wellbore over an interval less than its total thickness; and which interval is located at a certain intermediate position in the strata in order that, for a given flow of fluid through such interval between the wellbore and the strata responsive to a given velocity potential, radial flow is produced in the strata more closely adjacent to the wellbore than at any other arrangement where complete radial flow does not exist by the step of producing hydrocarbons in a definite relationship, a specific definition of which will be fully presented hereinafter, to the fluid flowing conditions in the reservoir.

In one aspect, the present invention is a method for producing hydrocarbons from a production well by obtaining maximum invasion efficiency at breakthrough of an injection fluid which is passed from an adjacent injection well into an intervening stratified reservoir. Invasion efficiency may be defined as the hydrocarbon pore space invaded, or contacted, by the injected fluid for each hundred units of hydrocarbon pore space enclosed by the injection fluid, through the full reservoir thickness, at the leading edge of the injection front. Maximum invasion efficiency at breakthrough is obtained where the injection fluid front advances at the same rate through all of the stratified reservoir.

Referring to FIGURE 1, a reservoir **10** is shown as penetrated by an injection well **11** and by a production well **12**. The reservoir **10** is comprised of dissimilar oil-bearing sands **13** and **14**. The injected fluid is water, but other fluids may be used, if desired. In this description it will be assumed that the sands **13** and **14** are horizontally enclosed by an impervious overburden **15** and supporting strata **16**. It is further assumed that the sand **44** has such characteristics as to limit a water injection front rate of advance, for the same injection conditions, below that obtainable in the sand **13**. The well **11**, provided with means for injecting water, is completed throughout the sand **14** and the well **12**, provided with means for producing hydrocarbons, is completed throughout both the sands **13** and **14**.

The sands **13** and **14** can be assumed to have the following properties:

	Sand 13	Sand 14
Permeability, md.	500	200
Porosity	0.18	0.18
Thickness, ft.	40	30
Residual Oil Saturation, percent	30	32
Original Water Saturation, percent	20	20

The sands **13** and **14** in the reservoir **10** have different physical characteristics, such as thickness and permeability; and, therefore, the rates of water injection, at the same driving pressure into the sands **13** and **14** of the reservoir **10**, will be dissimilar. The water injection front will have a rate of advance in the sand **13** greater than in the sand **14**. Thus, the water injected throughout the vertical interval of the sand **13** will break through into the well **12** sooner than from the sand **14**. This reduces the invasion efficiency of water at breakthrough. One important feature of this invention is to insure that the injected fluid-hydrocarbon interface, or the water injection front, advances at a constant rate through all strata of the reservoir, i.e., sands **13** and **14**. For purposes of this description, the mobility ratio of the injected water to the connate reservoir hydrocarbons is 1:1. Further, no cross flow of significant merit occurs vertically between the sands **13** and **14** of the reservoir **10** and the conditions of fluid injection are in a steady state.

The velocity potential $\Delta\phi$ which drives the waterflood through the reservoir **10** is the difference between the velocity potentials at the injection well **11**, and production well **12**, i.e., $\phi_w - \Delta_e$. The injection rate, q in the sand **14** for radial flow is defined by the equation:

$$q=\frac{2\pi H\Delta\phi}{\ln\frac{r_e}{r_w}}=\frac{2\pi kH}{\mu}\frac{\Delta p}{\ln\frac{r_e}{r_w}} \tag{1}$$

wherein:

H is the thickness of the sand **14**,
r_e is the distance in the reservoir **10** between the wells **11** and **12**,
r_w is the radius of the well **11**,
μ is the viscosity of injected fluid, water,
k is the permeability of the sand **14** to water, and
Δp is the pressure differential between the wells **11** and **12**.

The injection rate per unit thickness V is defined by the equation:

$$\frac{q}{H}=V=2\pi\frac{\Delta\phi}{\ln\frac{r_e}{r_w}} \tag{2}$$

Thus, the rate of injection front advance R is defined the equation:

$$R=\frac{V}{(\text{Porosity})(1-\text{original water saturation}-\text{residual oil saturation})} \tag{3}$$

In the sand **14** with the whole interval of strata receiving the injection of fluid from the well **11**, the rate of injection front advance R is defined by the equation:

$$R=\frac{V}{0.18\times0.48}=\frac{2\pi\Delta\phi}{0.0864\ln\frac{r_e}{r_w}}=\frac{2\pi k}{0.0864\mu}\frac{\Delta p}{\ln\frac{r_e}{r_w}} \tag{4}$$

In the same manner, the rate of injection front advance R′ in the sand **13** with the whole interval of strata receiving the injection of fluid from the well **11** is defined by the equation:

$$R'=\frac{V}{0.18\times0.5}=\frac{2\pi}{0.09}\frac{\Delta\phi}{\ln\frac{r_e}{r_w}}=\frac{2\pi k}{0.09\mu}\frac{\Delta p}{\ln\frac{r_e}{r_w}} \tag{5}$$

wherein the terms were previously defined with respect to the Equation 1 but having the numerical values of the physical characteristics of the sand **13**.

If both the sand **13** and **14** were open throughout their entire intervals to the well **11**, the ratio of the injection front advances between the sand **13** and **14** under the same injection pressure would be defined by the equation:

$$\frac{R'}{R}=\frac{\text{Equation 5}}{\text{Equation 4}}=\frac{\dfrac{2\pi(500)\Delta p}{0.09\mu\ln\frac{r_e}{r_w}}}{\dfrac{2\pi(200)\Delta p}{0.0864\mu\ln\frac{r_e}{r_w}}}=2.4{:}1 \tag{6}$$

Thus, the injection front would advance at a rate 2.4 times as fast in the sand **13** as in the sand **14**. Severe premature breakthrough of the injected fluid would occur in the sand **13**.

Obviously, to obtain the same rate of injection front advance in both sands **13** and **14**, the sand **13** is not open throughout its interval at the well **11** to fluid communication. The sand **13** is only opened to fluid communication over an interval to the extent required to limit the full interval rate of flow q_r to be reduced by a factor of 2.4. Thus, the desired restricted rate of flow q, i.e., the injection rate, into the sand **13** is $q/q_r=1/2.4=0.42$. Simply stated, the rate of flow q into the sand **13** to reduce the

rate of flow q_r to 42 percent of its value is obtained by an interval of fluid communication less than the thickness of the sand **13** at the well **11**. This arrangement is necessary to make the injection front advance in the sands **13** and **14** at the same velocity. One means to obtain such restricted injection or flow rate q of water from the well **11** into the sand **13** is by exposing to the well **11** only an interval of the sand **13** to fluid communication. Where a casing is cemented within the well **11**, the use of perforations to establish fluid communication between the well **11** and adjacent strata may be utilized. For example, the casing is perforated throughout the sand **14**. The casing is also perforated, at the same density of opening per unit length, over an interval adjacent the sand **13** less than its thickness to provide the reduced rate of flow, 0.42 q_r. Thus, only the lengths of the perforated areas of the casing vary adjacent the sands **13** and **14**. Other means to restrict fluid flow to an interval of the sand **13** exposed at the well **11** will be obvious to those skilled in the art, for example, the procedures disclosed in the United States Letters Patents 2,352,834 and 2,973,039.

Where a fluid is injected into a strata-like sand **13** through an area less than the total strata interval and such area is not correctly positioned adjacent the strata, several undesired results can be produced. One result is that the injected fluid may travel as spherical flow for a substantial distance from the injection well **11** before becoming radial flow. This will cause some area of the sand **13** to be bypassed by the injected fluid. Another result is that a considerable vertical misalignment of the injection fronts can occur before the flood front of injection water in the sand **13** is stabilized at substantially a constant rate, the same as in the sand **14**. This will produce a premature arrival of the injection front of water from the sand **13** into the well **12** before arrival from the sand **14**. For example, placing the interval or opening for injecting fluid from the well **11** at the top, or bottom, of the sand **13** will produce a fluid flowing condition the same as obtained by partially penetrating wells in similar isotropic formations. Reference may be had to the text "Physical Principles of Oil Production" by Muskat, edition of 1949, at pages 205 to 219, inclusive, for examples of such fluid flowing conditions.

It is the purpose of the present method to place the interval of fluid communication to the sand **13** at a location in the well **11** spaced from the horizontal boundaries of the sand **13** and also specifically positioned therein where the priorly mentioned undesired results are minimized and the invasion efficiency is maximized. Referring now to FIGURE 2, the sand **13** and the well **11** are shown in detail with an interval h of fluid communication to provide the flow rate ratio, $q=0.42q_r$, of the injected water. The sand **13** is of thickness H adjacent the well **11**. The interval h is spaced from the horizontal boundaries of the sand **13**. The interval h is positioned in the well **11** spaced at a distance z from one horizontal boundary, such as the top, of the sand **13**.

The pressure in a steady state flow does not vary with time at any one point in the sand **13**. If the potential is ϕ at any distance r from the well **11** with the mobility ratio of 1:1, then for steady state flow, ϕ is described by the following equation:

$$\delta^2\phi/\delta r^2+1\delta\phi/r\delta r+\delta^2\phi/\delta z^2=0 \qquad (7)$$

As is apparent, ϕ, the velocity potential, is defined by the equation:

$$\phi=k/\mu(P-\rho gz) \qquad (8)$$

wherein:

P is the pressure,
ρ is the density of water,
k is the permeability of the sand **13** to water,
g is the acceleration of gravity, and
μ is the viscosity of the injected water.

Equation 7 is to be solved for the boundary conditions:

(a) $\phi=\phi_e$, the potential at the production well **12**, i.e., at $r=r_e$, and

(b) $q=-2\pi hr\delta\phi/\delta r|_{r=r_w}$, where q is the rate of fluid injection which is constant, and

(c) $\delta\phi/\delta z=0$ at $z=0$ and H.

The boundary conditions (a) and (b) are that the potential is constant at the producing well, and the fluid injection is at a constant rate, respectively; and the boundary condition (c) is the requirement that no fluid passes vertically across the horizontal boundaries of the sand **13**.

If it is recalled that $\Delta\phi=\phi_w-\phi_e$ for injection in the well **11**, then Equation 7 as applied thereto resolves to the equation:

$$\delta^2\Delta\phi/\delta r^2+1\delta\Delta\phi/r\delta r+\delta^2\phi/\delta z^2=0 \qquad (9)$$

The Equation 9 is readily solved by the finite cosine transform:

$$\overline{\Delta\phi}=\int_0^H \Delta\phi\cos\alpha z dz, \text{ wherein } \alpha=n\pi/H$$

After transforming and performing the usual algebraic steps, the Equation 9 solution for the before-mentioned boundary conditions is obtained as the equation:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2R_w\bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right] \qquad (10)$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, and $\bar{h}=h/H$.

Those skilled in the art will recognize that the latter portion of the Equation 10 contains Bessel Functions which include modified Bessel Functions of the first kind, zero order, modified Bessel Functions of the second kind, zero order, modified Bessel Functions of the first kind, first order and modified Bessel Functions of the second kind, first order. The general definition $y=z/H$ is fractional as to the position of the interval h. The term z is a coordinate defining the distance from one horizontal boundary of the sand **13** to one horizontal boundary of the interval h. The coordinates z_1 and z_2 then mathematically define the top and bottom boundaries of the interval h. Substitution of these coordinates into the general definition $y=z/H$ provides:

$$y_1=z_1/H, \text{ and } y_2=z_2/H$$

The y_1 and y_2 are then particular expressions for defining the specific locations of the top and bottom of the interval h in the sand **13** as mathematically derived from the general definition $y=z/H$.

In practicing the method of this invention, Equation 10 defines the relationship between the fluid flowing conditions providing for the optimum production of hydrocarbons from the sand **13** and the sand **14**.

For example, with the sands **13** and **14** open to flow throughout their thicknesses at the well **11**, the Equation 10 becomes reduced to the equation:

$$\Delta\phi=\frac{q_r}{2\pi H}\ln\frac{r_e}{r_w}, \text{ or } q_r=\frac{\Delta\phi 2\pi H}{\ln\frac{r_e}{r_w}} \qquad (11)$$

Thus, for a certain velocity potential $\Delta\phi$, the rates of flow q_r from the well **11** into each of the sands **13** and **14** can be calculated. Therefore, for the same $\Delta\phi$ the ratio of these rates of flow becomes an index to the necessary restriction of flow to provide the restricted rate of flow q

into the sand 13 from the well 11. Usually, the ratio of these rates of flow is through the perforated interval adjacent to the sand 13 to the flow through the entire casing perforated adjacent to the sand 14. If desired, the absolute magnitudes of the rates of flow into each of the sands 13 and 14 through the perforations may be determined from FIGURE 5:15 at page 218 in the cited reference to Muskat.

With reference to Equation 10, it is clearly seen that there is a definite relationship for any strata between q and $\Delta\phi$ in respect to $\overline{h}$, y, z, and H. Returning to our specific example of the sands 13 and 14, the relationship of these terms in the method of this invention is as follows. A finite solution of the Equation 10 by applying the terms H=40 feet and q/q_r=0.42 with well 11 assumed as having a radius of .25 foot (r_w) and spaced from well 12 a distance of 660 feet (r_e) (the usual arrangement of well spacing) provides that the interval h extends 0.2 of the thickness, or 8 feet, of the sand 13 and that the top of the interval h is positioned 0.15 of the thickness or a z of 6 feet, in the sand 13 below its upper horizontal boundary.

Although the Equation 10 can be solved manually with the above fluid flowing conditions through the use of the "Tables of Vessel Functions," a better method is by the use of a computer, such as the Control Data Corporation Model 1604 for performing the desired solutions.

A suitable graphic display may also be prepared to provide a visual record of the solution of Equation 10 to simplify its future applications to a variety of reservoir conditions since r_w and r_e are the most common well parameters encountered. For this purpose with a certain $\Delta\phi$, Equations 10 and 11 were subject to computation to provide the rates of flow from each of the sands 13 and 14 over their entire thickness. The ratio of these flow rates is the index to restriction of flow of fluid previously mentioned for the sand 13, i.e., q/q_r at the $\Delta\phi$. For each ratio of q/q_r, the interval h and $y=z/H$ were determined by holding all but one of the terms constant and computing the remaining term with r_e and r_w being assumed as 660 feet and .25 foot, respectively. In FIGURES 3, 4, and 5 are graphic illustrations of these computed terms h and y where for each strata thickness H of 40 feet, for a given interval h of integer tenths of H, 0.1H, 0.2H and 0.3H, positioned at a distance y from one horizontal boundary of the sand 13, there is a finite value of q/q_r. Similar curves can be determined for other perforated intervals h and other sand thickness H.

The curves of FIGURES 3, 4, and 5 can be used for any strata 40 feet in thickness to provide the magnitude of the interval h of fluid communication at the sand 13 exposed to the well 11 and its position z from the top of the sand 13, both of which were previously computed from the Equation 10 where r_e and r_w are reasonably similar to the stated values. Where H=40 feet and q/q_r=0.42, reference to the FIGURES 3, 4, and 5 shows that only the curve of FIGURE 4 yields a solution. With particular reference to FIGURE 4, it is seen that for a q/q_r=0.42 that the interval h is 0.2H and its position z is 0.15 of the thickness H of the sand 13 from its top horizontal boundary. Obviously, prior computation of the curves like that of FIGURES 3, 4, and 5 for varied strata thickness and well spacings simplifies and expedites the solution to the problem of determining the perforated interval h and its location z adjacent the sand 13 in the well 11.

Thus, water is injected from the well 11 into the sands 13 and 14 with the interval h of fluid communication to the sand 13 having the dimension and position above set forth. Under these conditions, the waterflood front advances at the same velocity in the sands 13 and 14. Additionally, radial flow is obtained closely adjacent the well 11 in the injected water so that the waterflood front is substantially aligned along the vertical in both the sands 13 and 14. These conditions are most apparent to produce the optimum production and recovery of petroleum from the well 12.

Another aspect of the method of this invention is the application of Equation 10 to the production of reservoir fluids from the sands 13 and 14 into the well 11 responsive to an artificial or natural water drive under a steady state from the region of the well 12. The water drive should advance at a constant rate through the reservoir 10 to the well 11. The method is applied in the same manner as for water injection at the well 11 with

$$\Delta\phi=\phi_e-\phi_w$$

i.e., the velocity potential $\Delta\phi$ driving hydrocarbons into the well 11 is the difference between the velocity potential ϕ_c, at the radial extremity of the reservoir $10r_e$, less the velocity potential ϕ_w at the radial boundary, r_w, in the well 11.

Yet another aspect of the method of this invention is the optimum production of hydrocarbons by arrangement of the physical characteristics which as a group provide the fluid flowing characteristics of a formation for the optimum production of hydrocarbons. In a single strata, for example the sand 13, the effect of mud damage in the sand 13 adjacent the well 11 on the production of fluids into the well 11 through the perforated interval h can be readily determined. For this determination, assume the previously defined dimensions, H=40 feet, h=8 feet, z=6 feet, and the ratio of rates of flow, q/q_r, through the interval h to the entire strata to be 0.42, etc. For example, from the Equation 11, the potential flow rate of reservoir fluids, q_r, through the entire sand 13 into the well is determined. By calculations from the Equation 10, the optimum flow rate of reservoir fluids, q, through the interval h at a position z into the well 11 from the sand 13 is determined. Experimental measurement is made of the actual rate of flow of reservoir fluids, q, into the well 11 from the sand 13 through the interval h. Comparison of the measured and calculated rates of flow will clearly show the existence and magnitude of any mud damage to the sand 13 adjacent to the well 11. Thus, expensive and sometimes harmful acidizing, fracturing, and similar remedial measures are found unnecessary where the restricted flow rate q is a result of using an excessively small interval h. Even if such remedial remedies were applied, they may not improve the production of reservoir fluids through the interval h since they would not solve the basic problem. Obviously, under such condition adequate remedy by this invention resides in providing a lengthened interval h of fluid communication as a method of well completion and producing petroleum by this method as defined by Equation 10. Where mud damage, or other formation defects, restricts the production of petroleum through an adequate interval h, acidizing, fracturing, and the like would be proper, followed by producing petroleum by this method as defined by Equation 10.

It will be apparent that by the method of this invention fluid flow between the well 11 and the sand 14 may be through only an interval of fluid communication less than its thickness. Thus, in a plurality of strata forming a hydrocarbon reservoir, all, or only some, of the strata may employ the interval of fluid communication applied in accordance with the Equation 10.

From the foregoing, it will be apparent that there has been provided herein a novel method for producing hydrocarbons from subterranean reservoirs under optimum fluid flowing conditions. Further, these objects are accomplished through the use of a method in which optimum fluid flowing conditions are obtained by having these conditions arranged in a definite relationship so as to obtain the efficient recovery of hydrocarbons. Although it will be apparent to those skilled in the art to make various changes to the method of this invention without departing from its scope to conform to certain situations, it is intended that these changes, other alterations, and

related variations are considered as part of the present invention and within the scope of the appended claims. It is further intended that the foregoing description is to be taken as a means of illustration and not as a means of limitation. The only limitations to be applied to this invention are in the following claims.

What is claimed is:

1. A method for the production of hydrocarbons by obtaining optimum fluid flowing conditions in a reservoir having a strata of thickness H penetrated by a wellbore of radius r_w, which wellbore is in fluid communication with the strata over an interval of height h with said interval disposed at a distance z from one horizontal boundary of the strata responsive to a differential velocity potential $\Delta\phi$ existing in the strata between the wellbore and a radial boundary r_e of the strata comprising the steps of:

(a) flowing fluids at a fluid flow rate q through the interval between the wellbore and the strata in the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w \bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression $y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(b) producing hydrocarbons by such flowing fluids until substantial quantities of the hydrocarbons are recovered from the reservoir.

2. A method for the production of hydrocarbons by obtaining optimum fluid flowing conditions in a reservoir having a strata of thickness H penetrated by a wellbore of radius r_w, which wellbore is in fluid communication with the strata through an interval of height h with said interval positioned at a distance z from one horizontal boundary of the strata and where a differential velocity potential $\Delta\phi$ exists between the wellbore and a radial boundary r_e of the strata to provide a fluid flow rate q through the interval by the steps comprising:

(a) completing the wellbore in the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w \bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression $y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(b) producing hydrocarbons by such flowing fluids until substantial quantities of the hydrocarbons are recovered from the reservoir.

3. A method for the production of hydrocarbons through wellbore penetrating a reservoir having at least two strata of different fluid flowing characteristics by the steps comprising:

(a) flowing fluid between the wellbore and one of the strata at a given magnitude of velocity of fluid flow in such strata, which velocity is not greater than can be obtained in any other strata in fluid communication with the wellbore in response to a differential velocity potential $\Delta\phi$ which exists between the wellbore of radius r_w and a radial boundary r_e of the reservoir,

(b) flowing fluid between the wellbore and each of the strata of thickness at an adjusted fluid flow rate q responsive to said differential velocity potential $\Delta\phi$ to obtain the same magnitude of velocity of fluid flow as mentioned in said one of the strata in each of the other strata by restricting the fluid flow to an interval h in the wellbore between the wellbore and each such other strata with the interval positioned at a distance z from a horizontal boundary in each such other strata in the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w \bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression $y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(c) producing hydrocarbons from the strata by such flowing fluid at the same magnitude of velocity of fluid flow in all the strata until substantial quantities of hydrocarbons are recovered from the reservoir between the wellbore and the radial boundary r_e.

4. A method for the production of hydrocarbons through a wellbore penetrating a reservoir having at least two strata of different fluid flowing characteristics by the steps comprising:

(a) injecting a driving fluid from a first wellbore with a radius r_w into one of the strata at a velocity potential ϕ_w to establish a given velocity of the driving fluid front advance toward a second wellbore spaced from the first wellbore a radial distance r_e and producing hydrocarbons displaced by the driving fluid into the second wellbore at a velocity potential ϕ_e, the differential velocity potential $\Delta\phi$ is $\phi_w-\phi_e$ between the wellbores to move fluids through the strata,

(b) injecting the driving fluid from the first wellbore into each of the other strata at a limited flow rate q to obtain the same velocity of driving fluid front advance toward the second wellbore in each of the other strata responsive to the velocity potential $\Delta\phi$ by restricting the fluid flow to an interval h in the first wellbore at each such other strata of thickness H with the interval positioned at a distance z from a horizontal boundary in each such other strata in the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w \bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w\bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

$y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(c) producing hydrocarbons from the strata through the second wellbore by continuing the injecting of driving fluid from the first wellbore into each of the strata to advance the driving fluid front at a constant velocity of fluid flow in each of said strata until substantial quantities of hydrocarbons are recovered from the strata of the reservoir between the first and second wellbores.

5. A method for the production of hydrocarbons through a wellbore penetrating a reservoir having at least two strata of different fluid flowing characteristics by the steps comprising:

(a) passing a driving fluid front through the strata of the reservoir toward a wellbore with a radius r_w to produce hydrocarbons at a velocity potential ϕ_w into the wellbore, the driving fluid front initially located in the strata at a radial distance r_e from the wellbore and having a velocity potential ϕ_e at such initial location, the differential velocity potential $\Delta\phi$ advancing said driving fluid front is $\phi_e-\phi_w$,

(b) producing hydrocarbons from each of the strata containing the driving fluid front into the wellbore, the produced fluids from the strata restricted to a rate of fluid flow q into the wellbore to obtain a constant velocity of driving fluid front advance equal to the advance through one of the strata responsive to the differential velocity potential $\Delta\phi$, the production of hydrocarbons through an interval h in the wellbore at such strata of thickness H where an adjusted rate of flow is provided with the interval positioned at a distance z from one horizontal boundary of each such strata in the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w\bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression $y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(c) producing hydrocarbons from the strata through the wellbore responsive to the driving fluid front advancing at the same velocity in each strata until substantial quantities of hydrocarbons are recovered from the reservoir.

6. A method for the production of hydrocarbons through a wellbore penetrating a reservoir having at least two strata of different fluid flowing characteristics by the steps comprising:

(a) flowing hydrocarbons from the wellbore of radius r_w from each of the strata of thickness H at individual rates of flow q by exposing the wellbore at each strata to fluid flow for an interval h disposed a distance z from one horizontal boundary of each such strata, the fluid flow being responsive to a differential velocity potential $\Delta\phi$ present between the wellbore and a radial boundary r_e in the reservoir, each rate of flow q for each strata having a magnitude that the velocity of fluid flow in the strata is the same and in each strata for each rate of flow q the terms h, z, and y have the relationship:

$$\Delta\phi=\frac{q}{2\pi H}\left[\ln\frac{r_e}{r_w}+\frac{2}{\pi^2 R_w\bar{h}}\sum_1^\infty\frac{[I_0(n\pi R_e)K_0(n\pi R_w)-K_0(n\pi R_e)I_0(n\pi R_w)]\cos n\pi y\,[\sin n\pi y_2-\sin n\pi y_1]}{n^2[K_0(n\pi R_e)I_1(n\pi R_w)+K_1(n\pi R_w)I_0(n\pi R_e)]}\right]$$

wherein $R_e=r_e/H$, $R_w=r_w/H$, $y=z/H$, y_1 and y_2 are particular expressions, of the general expression $y=z/H$, for the specific coordinate locations of the top and bottom of said interval, $\bar{h}=h/H$, and

(b) recovering the flowing hydrocarbons from the reservoir through the wellbore.

References Cited by the Examiner

UNITED STATES PATENTS

2,019,418	10/1935	Lang	166—10
2,227,539	1/1941	Dorton	166—10 X
2,352,834	7/1944	Hassler	166—10 X
2,973,039	2/1961	Payne	166—224

OTHER REFERENCES

Muskat, Physical Principles of Oil Production, 1st edition, McGraw-Hill Book Co. Inc., 1949, New York, pages 205–210 and 259 to 266.

ERNEST R. PURSER, *Primary Examiner.*

CHARLES E. O'CONNELL, *Examiner.*

S. J. NOVOSAD, *Assistant Examiner.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,302,710 February 7, 1967

Aziz S. Odeh

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 3, line 42, for "44" read -- 14 --; column 4, line 7, for "ϕ_w-Δ_e" read -- ϕ_w-ϕ_e --; line 29, before "the" insert -- by --; column 10, line 9, after "the", second occurrence, insert -- other --; line 10, after "thickness" insert -- H --.

Signed and sealed this 10th day of October 1967.

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents