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Examination of the Mining of Heavy Oil and Tar Sands by Overburden Substitution

MASTER

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EXAMINATION OF THE MINING OF HEAVY OIL
AND TAR SANDS BY OVERBURDEN SUBSTITUTION

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ABSTRACT

A mining procedure which removes the geologic formations above an oil or tar sand bearing reservoir by strip mining techniques, then floods the upper surface of the reservoir with a pool of water, is examined by computational models and laboratory scale experiments. The results of the studies indicate low production rates are achieved by such a procedure.

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I. INTRODUCTION

A technique has been proposed for recovery of shallow heavy oil and tar sands which involves strip mining of the overburden followed by construction of a pool of water over the hydrocarbon bearing formation. A schematic diagram of such a recovery operation is shown in Figure 1. The water within the pool has a greater density than the oil within the formation which constitutes the conditions for a classical Rayhigh-Taylor instability. The unstable condition is relaxed by reversing the positions such that the lighter liquid is on top, having been displaced by the liquid with greater density. The hydrocarbons, which have moved to the surface, can be easily collected without the need for additional mining. Modifications to enhance the recovery process include using hot water, addition of surfactants, and drilling of penetrating wells. The recovery of heavy oil and tar sands by this process of removal of overburden and replacement with a water pool is analyzed in this report from the view of the properties of the fluids involved and the reaction of these fluids to the applied recovery forces. In addition, bench scale experiments were conducted to test some of the recovery procedures.

II. ANALYSIS OF RECOVERY PROCESSES FOR THE OVERBURDEN SUBSTITUTION TECHNIQUE

The mechanism for bringing the inplace crude oil to the surface of the pool of water is the bouyant force. The forces which oppose the movement of oil from the reservoir to the surface are gravity, flow friction, and interfacial tension between the oil and reservoir matrix materials. The magnitude of the gravitational and bouyant forces are readily expressible in terms of mass density and geometric factors.

Figure 1. Schematic of Overburn Replacement Operation

$$F_b = Vg \rho_w , \quad (1)$$

$$F_g = -Vg \rho_o , \quad (2)$$

where $F_{b(g)}$ is the bouyant (gravitation) force, V is the geometric volume, and g is the gravitational acceleration. The relative magnitudes of these forces are such as to rapidly transport oil which is in a layer below a volume of water to the top surface when the oil is not contained within a rock matrix. In the absence of a rock matrix, the transportation of the oil to the surface is rapid even for comparatively heavy oil.

The inclusion of the effect of flow resistance due to interaction with the reservoir matrix will be determined by two approaches. The first analysis will assume the oil moves through porous channels within the matrix. The second analysis will be based on the Darcy flow through porous media.

A. Channel Flow Model of Production

A model of the flow through a pore channel within the reservoir matrix is diagramed in Figure 2. The resistance to the flow of oil within the centrally located cylinder of radius r and length ΔS is due to stress at the surface of the cylinder.

$$F_\tau = -(2\pi r) (\Delta S) \tau \quad (3)$$

where F_τ is the forces resisting the flow and τ is the shear stress. The balance of forces acting on the cylinder produces the equation

$$(\pi r^2)(\Delta S)g \rho_w - (\pi r^2)(\Delta S)g \rho_o - (2\pi r) \Delta S \tau = 0 \quad (4)$$

where the volume of the cylinder $V = \pi r^2 (\Delta S)$. Solving (4) for the shear stress

$$\tau = \frac{gr}{2} (\rho_w - \rho_o) . \quad (5)$$

The shear stress for Neutronian fluids is defined in terms of the velocity gradient

$$\tau = \mu \frac{dv}{dr} , \quad (6)$$

where μ is the viscosity of the oil and v is the flow velocity. Combining (5) and (6), and solving the resulting differential equation for the velocity distribution

$$v = \frac{g(R^2 - r^2)}{4\mu} (\rho_w - \rho_o) \quad (7)$$

The volumetric flow rate through the channel is

$$Q = \int \vec{v} \cdot d\vec{A} , \quad (8)$$

where A is the vector area of the channel.

Combining (7) and (8)

$$Q = \frac{\pi g R^4}{8\mu} (\rho_w - \rho_o) . \quad (9)$$

The average flow velocity of the oil through the channel is then

$$\langle v \rangle = \frac{Q}{A} = \frac{g R^2}{8\mu} (\rho_w - \rho_o) . \quad (10)$$

Figure 2. Model of Upward Flow of Oil Due to Replacement of Overburn With Water

The rate of production Ω of oil from a pool of area α and porosity ϵ would be of order

$$\begin{aligned}\Omega &= \epsilon \alpha \langle v \rangle \\ &= \frac{\epsilon \alpha g R^2}{8\mu} (\rho_w - \rho_o) .\end{aligned}\quad (11)$$

Consider the properties of 12.5° API from the Kern River field in California.

$$\begin{aligned}\mu &= 130 \text{ Ns/m}^2 \\ g &= 9.8 \text{ m/s}^2 \\ R &= 6 \times 10^{-6} \text{ m} \\ \rho_o &= 975.19 \text{ kgm/m}^3 \\ \rho_w &= 10^3 \text{ kgm/m}^3 \\ \alpha &= 1 \text{ square mile} \\ \epsilon &= 30\%\end{aligned}$$

The predicted production rate would be 3.4 BOPD from a pool with surface area of one square mile.

B. Darcy Flow Model of Production

The application of Darcy's Law to flow in porous media is valid for the range of driving forces normally encountered in oil recovery operations. The Darcy Law loses its validity if the driving force becomes either small enough to be comparable to static forces such as surface tension or large enough to produce flow separation on the micro-scale of the reservoir matrix materials. The effect of static forces on an overburden replacement mining procedure will be considered in the next section; this section will assume Darcy's Law to be a valid description of the flow within the reservoir. The statement of Darcy's Law, applicable to most oil recovery processes, is

$$\vec{v}_m = -\hat{e}_h \frac{K_h}{\mu} (\nabla P) \cdot \hat{e}_h - \frac{K_v}{\mu} \left[(\nabla P) \cdot \hat{e}_v - \rho_o g \right] \hat{e}_v, \quad (13)$$

where $k_{h(v)}$ is the horizontal (vertical) permeability of the reservoir, P is the pressure, $\hat{e}_{h(v)}$ is a unit vector in the horizontal (vertical) direction, and v_m is the porous flow velocity. The driving force for the overburden replacement method is the bouyant force instead of a pressure gradient, for this process

$$\vec{v}_m = - \frac{K_v}{\mu} (\rho_w - \rho_o) g \hat{e}_v. \quad (14)$$

Thus, the driving force for most enhanced oil recovery techniques acts on the reservoir fluids through the horizontal permeability, however, the overburden replacement mining processes act through the vertical permeability. The stratigraphic nature of the sedimentary formations which comprise oil reservoirs results in a horizontal permeability much larger (often by a factor of 5) than the vertical permeability.

The rate of production, based on (14), is

$$\Omega = \frac{\alpha K_v}{\mu} (\rho_o - \rho_w) g. \quad (15)$$

Evaluating the predicted recovery for the conditions equivalent to those examined by the channel flow model

$$\begin{aligned} K_v &= 2 \text{ Darcies} \\ \mu &= 130 \text{ Ns/m}^2 \\ \rho_o &= 975.19 \text{ kg/m}^3 \\ \rho_w &= 10^3 \text{ kg/m}^3 \\ g &= 9.8 \text{ m/s}^2 \\ \alpha &= 1 \text{ square mile}, \end{aligned}$$

the predicted recovery is 4.95 BOPD, which is equivalent to that predicted by the channel flow analysis.

C. Effect of Surface Tension

The applied forces must be much larger than the forces of attraction between the oil molecules and the surface of the rock matrix before the application of Darcy's Law is valid. The equation for a balance of force which includes surface tension within a flow channel is

$$2\pi R\sigma + g\pi R^2 (\rho_w - \rho_o) \Delta S = 0 \quad (16)$$

where σ is the surface tension. Solving (16) for the surface tension

$$\frac{\sigma}{\Delta S} = \frac{2R (\rho_w - \rho_o)g}{2} . \quad (17)$$

Evaluating the magnitude of the ratio of surface tension to length of flow channel for the previously utilized reservoir conditions gives a value of $\frac{\sigma}{\Delta S} = .000367$. Assuming the length of flow channel is the depth of the pay zone, the thickness of the pay zones encountered in most recovery operations are sufficient for a valid application of the porous flow relations presented in the previous two sections.

D. Effect of Temperature

The effect of temperature on the recovery rate in an overburden replacement operation can be determined from equation (14). An increase in temperature can affect the density difference between the crude oil and water, and can affect the oil viscosity. The change of density of a heavy crude oil and water with temperature is given in Figure 3. Figure 3 shows that the increase in density of the oil with

temperature is not significantly greater than that of water. The major effect of heat addition on the recovery rate is therefore the reduction in viscosity of the oil. The effect of temperature on the viscosity of the same heavy oil is graphed in Figure 4.

The rate of production from an overburden replacement operation can be increased by heating the water pool. If the pool is heated to 130°F, the predicted production rate increases from 3-5 BOPD to 780-1300 BOPD. A comparison of the oil production rate achieved by heating the water pool with steam drive in a similar field shows that with an average 2.5 ac. five-spot injection/production well pattern, a production of approximately 25,000 BOPD could be expected. The predicted recovery from the overburden replacement mining procedure is thus more than a factor of ten less than steam drive in situ recovery even allowing for heating of the water pool.

If the pool were heated to 130°F, the heat loss from air convection over the pool surface would be a major problem. The surface heat loss (Γ) is

$$\Gamma = h \alpha (T_p - T_a) \quad (18)$$

where h is the heat transfer coefficient and $T_{p(a)}$ is the temperature of the pool (air). For turbulent convective heat loss to the air, the heat transfer coefficient is¹

$$h = 0.22 \sqrt[3]{T_p - T_a} \text{ (Btu/hr ft}^2 \text{ }^\circ\text{F)}. \quad (19)$$

Combining equations (18) and (19) to calculate the heat loss for a 130°F pool on a 60°F day gives an energy loss equivalent to 7000 BOPD from the pool. The energy loss from

1. Jalcob, M., and G. A. Hanken, Elements of Heat Transfer (John Wiley and Sons, N.Y., 1957) p. 130.

Figure 3. Effect of Temperature on Specific Gravity

Figure 4. Effect of Temperature on Crude Oil Viscosity

the pool without insulative measures is thus greater than the production from the project. The cost of insulation of the surface would be expected to be prohibitive in addition to interfering with the attractive simplicity of the recovery technique.

III. EXPERIMENTAL STUDY OF THE OVERBURDEN REPLACEMENT RECOVERY PROCESS

A series of laboratory-scale recovery experiments were carried out to test the results of the computational analysis of the overburden replacement recovery method. A core sample consisting of an unconsolidated sand matrix (2 Darcy permeability) and 12.5° API crude oil were utilized in the experiments. The cores used in the test had very small quantities of connate water. The permeability of the sand matrix was 20 Darcies. Samples were also prepared which consisted of the same crude oil without the presence of a reservoir matrix. Testing of the recovery of the 12.5° API oil by locating a water pool above the oil without the effect of the reservoir matrix resulted in rapid recovery of 99% of the oil within six hours. The remaining 1% was attached to the glass sides of the vessel containing the experiment. The same test, with a sample containing a reservoir matrix, produced a small amount of oil at a large production rate for the first 24 hour period. The recovery rate was reduced to the rates after this initial large production. The initial production accounted for only .5% of the oil in place. The initial large production was determined to be due to crude oil located at the surface of the core which did not travel through the porous matrix. The oil at the core surface migrated to the container walls, then along the walls to the pool surface. Subsequent tests using vessels with converging walls eliminated the large initial production transient.

Measurement of oil produced in the laboratory experiments averaged over several weeks were $1.5 \times 10^{-8} \text{ m}^3$ of oil per day from vessels with .114 m diameter surfaces at the oil/water

interface. The recovery predicted from equation (15) for the laboratory samples with conditions

$$\begin{aligned}K_v &= 2 \text{ Darcies} \\ \mu &= 130 \text{ Ns/m}^2 \\ \rho_o &= 975.19 \text{ kg/m}^3 \\ \rho_w &= 10^3 \text{ kg/m}^3 \\ g &= 9.8 \text{ m/s}^2 \\ \delta &= 4.08 \times 10^{-2} \text{ m}^2\end{aligned}$$

is $1.3 \times 10^{-8} \text{ m}^3$ of oil per day. The small scale experimental test thus agrees with the mathematically predicted production rate for an overburden replacement mining operation.

IV. RESULTS AND CONCLUSIONS

The application of the mining procedure which removes the formations above an oil or tar sand bearing reservoir and floods the surface of the reservoir has been examined using two computational models and laboratory scale experiments. The computational models consisted of a channel flow model and the application of Darcy's Law. The recovery rate predicted by both models were of the same order. The predicted recovery for a square mile mined area above a reservoir containing 12.5° API crude oil is 3-5 BOPD. The heating of this water pool to 130°F increases production to 780-1300 BOPD; however, convective heat loss from the pool surface is the energy equivalent of 7000 BOPD. Laboratory-scale recovery experiments agree with the computational predictions. This examination of the overburden replacement mining technique indicates that the process is not an effective recovery method for heavy oil or tar sand reservoirs.

NOMENCLATURE

A	Area of pore flow channel
$\hat{e}_h$	Unit vector in horizontal direction
$\hat{e}_v$	Unit vector in vertical direction
F_b	Bouyant Force
F_g	Gravitational force
F_t	Frictional force
g	Gravitational acceleration
h	Heat transfer coefficient
K_h	Horizontal permeability
K_v	Vertical permeability
P	Pressure
Q	Volumetric flow rate
R	Radius of pore flow channel
r	Radial position coordinate
T_a	Air temperature
T_p	Water pool temperature
V	Volume
v	Flow velocity in channel
v_m	Porous flow velocity
$\langle v \rangle$	Average flow velocity
α	Surface area of water pool
Γ	Rate of heat transfer
ΔS	Increment of length along pore flow channel
∇	Del operator
ϵ	Porosity
μ	Crude oil viscosity
ρ_o	Density of oil
ρ_w	Density of water
σ	Surface tension
τ	Shear stress

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