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Some Features afferent to the Screening Calculation of Steam-Flood Oil Recovery

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Abstract

This paper presents, beside the classical model introduced by Marx and Langenheim, several analytical methods for estimating the performance of oil recovery from reservoir by steam-flood. Both the advantages and limitations in use of each method are evidenced. For exemplification purposes, a case study which illustrates the algorithm of determining the performance parameters afferent to a continuous steam injection into an oil reservoir process, using the Marx-Langenheim model, is included.

Key words: *oil recovery, steam-flood, screening calculation, heat transfer.*

Introduction

The preliminary calculations for forecasting the behavior of a steam-flooding process into an oil reservoir may be done using various analytical models which substantially simplify the mechanisms of heat and fluid mass transfer associated to any reservoir oil recovery by steam-flooding. The successful use of these models largely depends on the user's ability of understanding the essential assumptions and of using, in a specific situation, the most realistic model available. The failure in achieving this objective frequently leads to overlapping pessimistic and optimistic estimations of both oil recovery and steam amount. All these models endorse only the continuous steam-flood and are essentially consider the heat transfer as being one-dimensional. These models are summarized here.

The Marx-Langenheim model [1, 2, 3, 4, 7] is based on the supposition that the steam front exhibits a piston-like advance and uses an original heat transfer equation for estimating the steam-invaded region volume. This method considers that the oil is displaced from the steam-invaded region until the residual oil saturation in the swept region is attained.

The Myhill-Stegemeier model [5] is similar to the Marx-Langenheim procedure, but the Mandl-Volek equations are used to compute the steam-invaded zone volume [6], so that the extent of this area is defined more accurately.

The van Lookeren model [7] may be used to get a reasonable estimation of the vertical sweep efficiency in steam-flood processes.

The Vogel [10] and Miller [11] models presume the complete superposition of the steam above a thick oil-saturated sand layer which is heated by downward conduction from the steam.

The models introduced by Butler [8] and Edmunds [9] describe the velocity at which high-viscosity oil or bitumen can be heated with steam and mobilized in two specific situations. Butler's equation is intended for calculating the bitumen production rate from the steam-swept region by gravity drainage, while Edmunds' equation refers to the bitumen mobilization by stripping from the walls of a fissure heated with steam.

Case Study for the Marx-Langenheim Model

Although the Marx-Langenheim procedure requires piston-like oil displacement by steam and a unity value of the vertical sweep efficiency, this model has a good applicability even when the suppositions mentioned above are not accomplished.

The case study considers a steam flood project involving the steam injection through a well, at the depth H = 500 m. The input data are: producing layer thickness h = 15 m, absolute permeability k = 0.8 D, porosity m = 0.3, initial oil saturation (in stock-tank conditions) s_{oi}/b_{oi} = 0.60, oil density ρ_o = 920 kg/m^3, original reservoir temperature T_r = 35 °C, pressure in the steam-swept region p = 5 MPa (which corresponds to the steam temperature T_s = 264 °C), reservoir rock effective permeability for steam $k_s = 0.25k$, residual oil saturation in the steam-swept region s_{ors}/b_{os} = 0.10, residual oil saturation in the hot water-swept region s_{orw}/b_{ow} = 0.25, net thickness equal to the gross thickness, thermal diffusivity of the layers bounding upward and downward the producing layer $a_s = 10^{-6}$ m^2/s, average thermal capacity per unit volume of the adjacent layers $(\rho\, c)_l$ = 2,450 kJ/(m^3·K), average thermal capacity per unit volume of the heated region $(\rho\, c)_r$ = 2,200 kJ/(m^3·K), steam flow rate M = 2,200 kg/hr, steam quality at generator's outlet (where the pressure is p_g = 7 MPa), x_g = 0.82, generator's thermal efficiency, based on the net calorific power of the combustible $(\rho_o\, P_{on})$ = 38,700 MJ/m^3, η_g = 0.845, average temperature of the generator's feeding water T_{wg} = 20 °C, steam quality at the wellhead x_{wh} = 0.80 (at the pressure p = 5 MPa), area of the five-spot well element with central injector A_p = 14,000 m^2.

It is required to determine the areas of the steam-swept and heated regions, supposing that: (1) 15% of the injected heat is taken over by the produced fluids, (2) the steam is injected through the tubing, and (3) the annular pressure is atmospheric. It is also required to estimate the amount of oil produced, considering that the cumulative oil production at time t equals the displaced oil volume at time $t - t_t$, where the threshold time t_t equals the time needed to inject into the reservoir a volume of steam (expressed in cold water equivalent) equal with 0.14 reservoir pore volumes.

Table 1. The casing temperature and heat flux dissipated into the well variations with the injection time

t, yrs.	T_{ac}, K	q_{sdw}, W/m
1	459	479
2	463	459
3	465	449
4	466	440
5	467	436

The heat flux dissipated into the injection well is expressed as

$$q_{dw} = M\, l_v \left(x_{wh} - x_r\right), \tag{1}$$

where l_v is the water's latent heat of vaporization-condensation per unit mass, and the steam quality in reservoir conditions can be calculated with the formula

$$x_r = x_{wh} - \frac{q_{dw}}{M\, l_v}\, . \tag{2}$$

The heat flux per unit length dissipated into the well is defined as

$$q_{sdw} = \frac{q_{dw}}{H}\, , \tag{3}$$

and has the values listed in Table 1, together with the casing temperature, as functions of the injection time t.

Observing that, according to the q_{sdw} values in Table 1, the average heat loss per unit length of casing, for the 5 life years of the steam flood process, has the mean value q_{sdw} = 0.46 kW/m, relation (2) in which l_v = 1,693 kJ/kg (from Table 2 in reference [1]) leads to the average quality of the steam injected into the reservoir $x_r = 0.55$.

The heated region thickness, h_s, may be estimated with the formula

$$\frac{h_s}{h} = 1{,}7\,\psi \ , \tag{4}$$

applicable for $\psi < 0.59$, where ψ is defined as

$$\psi = \left[\frac{\mu_v\, M\, x_r}{\pi(\rho_o - \rho_v)\rho_v\, g\, k_v\, h^2}\right]^{0,5} \ , \tag{5}$$

ρ_v, μ_v are the density and dynamic viscosity of water vapor, ρ_o – oil density, g – gravity acceleration, and k_v – producing layer effective permeability for steam. The liquid and vapor phase properties for saturated steam are listed in Table 2.

Table 2. Liquid and vapor phase properties for saturated steam

T_v, °C	p_v, kPa	ρ_l, kg/m^3	μ_l, 10^{-6} Pa·s	c_{pl}, kJ/(kg·K)	λ_l, W/(m·K)	ρ_v, kg/m^3	μ_v, 10^{-6} Pa·s	c_{pv}, kJ/(kg·K)	λ_v, W/(m·K)
1	2	3	4	5	6	7	8	9	10
0	0.6108	999.8	1.792	4.217	56.5	0.004847	8.84	1.856	1.67
20	2.337	998.3	1.003	4.182	60.2	0.01729	9.52	1.866	1.74
40	7.375	992.3	654	4.179	61.7	0.03037	9.86	1.875	1.90
60	19.920	983.2	466	4.185	65.2	0.1302	10.88	1.916	2.12
80	47.36	971.6	354	4.197	66.9	0.2933	11.65	1.962	2.31
100	101.33	958.1	282	4.216	67.9	0.5977	12.37	2.028	2.50
120	198.54	942.9	233	4.245	68.5	1.122	13.04	2.120	2.68
140	361.4	925.8	197	4.285	68.6	1.497	13.37	2.176	2.80
160	618.1	907.3	170	4.339	68.3	3.260	14.36	2.398	3.25
180	1,002.7	886.9	150	4.408	67.6	5.160	15.06	2.596	3.55
200	1,554.9	864.7	134	4.497	66.4	7.864	15.74	2.843	3.88
220	2,319.8	840.3	122	4.613	64.7	11.62	16.44	3.150	4.30
240	3,347.8	813.6	111	4.769	62.6	16.76	17.18	3.536	4.80
260	4,694.3	783.9	102	4.983	60.2	23.73	17.90	4.047	5.40
280	6,420.2	750.5	94	5.290	57.8	33.19	18.65	4.767	6.15
300	8,592.7	712.2	85.6	5.762	54.7	46.19	19.53	5.863	7.32
320	11.289	666.9	77.6	6.565	51.2	64.60	20.8	7.722	9.2
340	14.605	610.2	69.5	8.233	47.0	92.76	22.5	12.21	11.9
360	18.675	527.5	59.7	14.58	42.5	144.0	25.7	25.12	17.4
374.15	22.120	315.5	40.6	–	91.4	315.5	40.6	–	91.4

For p_v = 5 MPa, from Table 2 ρ_v = 25.4 kg/m^3 and $\mu_v = 18\cdot10^{-6}$ Pa·s are read, which are introduced in equation (5) yielding ψ = 0.42, then from relation (4) the value $h_s = 0.7h$ is obtained. In the following calculations, we will consider that $h_s \cong h$.

The available heat flux into the reservoir has the expression

$$q_r = M\, i_{st} \ , \tag{6}$$

with

$$i_{st} = x_r\, l_v + i_l - i_{wr} \ , \tag{7}$$

where i_{st} is the enthalpy per unit mass of the steam in the state conditions p_s, T_s related to the initial reservoir conditions p_r, T_r, and i_l, i_{wr} – enthalpies per unit mass of the liquid water at the temperatures T_s and T_r, respectively. From Table 2 [1], i_l = 1,155 kJ/kg at T_s = 264 °C and i_{wr} = 147 kJ/kg at T_r = 35 °C are read, then equation (6) leads to q_r = 1,061 kW, which corresponds to a net flux of heat injected $q_{rn} = (1 - 0.15)q_r$ = 901 kW.

The Marx-Langenheim procedure is applicable if, between the net flux of heat injected and the sum of heat-loss flux in the adjacent layers, q_s, and variation of latent heat content in the heated region, the following inequality exists:

$$M\, x_r\, l_v \geq q_s + m\, \rho_v\, s_v\, l_v\, h \frac{\mathrm{d}A}{\mathrm{d}t} \;, \tag{8}$$

where s_v is the average saturation in water vapors, which may be considered as time independent.

Consequently, the heat balance equation of the heated region at a given time can be written as

$$q_r = (\rho c)_r (T_s - T_r) h \frac{\mathrm{d}A}{\mathrm{d}t} + q_s(A) \,, \tag{9}$$

where, according to the Marx-Langenheim method [1, 3], the heated region area has the expression

$$A(t) = \frac{q_r (\rho c)_r\, h\, a_s}{4 \lambda_s^2\, \Delta T} \left[\mathrm{e}^{u^2} \operatorname{erfc}(u) + \frac{2u}{\sqrt{\pi}} - 1 \right] , \tag{10}$$

in which

$$\operatorname{erfc}(u) = 1 - \operatorname{erf}(u) \,, \tag{11}$$

$$\operatorname{erf}(u) = \frac{2u}{\sqrt{\pi}} \int_0^u \mathrm{e}^{-y^2} \mathrm{d}y \;, \tag{12}$$

$$u = \frac{2\lambda_s}{(\rho c)_r\, h} \sqrt{\frac{t}{a_s}} \;, \tag{13}$$

$$(\rho c)_r = m(\rho_o\, c_o\, s_o + \rho_w\, c_w\, s_w) + (1-m)\rho_{ro}\, c_{ro} \;. \tag{14}$$

Discrete values of the functions $\mathrm{e}^{u^2} \operatorname{erfc}(u)$ and $F(u) = \mathrm{e}^{u^2} \operatorname{erfc}(u) + \frac{2u}{\sqrt{\pi}} - 1$ are listed in Table 1 from reference [1].

By deriving equation (10) the following expression is obtained

$$\frac{\mathrm{d}A}{\mathrm{d}t} = \frac{q_r}{(\rho c)_r\, h\, \Delta T} \mathrm{e}^{u^2} \operatorname{erfc}(u) \tag{15}$$

and relation (9) becomes

$$\frac{q_s}{q_r} = 1 - \mathrm{e}^{u^2} \operatorname{erfc}(u) \,. \tag{16}$$

If expressions (15) and (16) are introduced into relation (8), the following condition results:

$$M\, x_r\, l_v \geq q_r \left\{ 1 - \left[1 - \frac{m\, \rho_v\, s_v\, l_v}{(\rho c)_r\, \Delta T} \right] \mathrm{e}^{u^2} \operatorname{erfc}(u) \right\} . \tag{17}$$

As the term containing s_v is much less than unity, it may be neglected, so that equation (17) becomes

$$M\, x_r\, l_v \geq q_r \left[1 - \mathrm{e}^{u^2} \operatorname{erfc}(u) \right] , \tag{18}$$

or

$$M\, x_r\, l_v \geq q_s \;. \tag{19}$$

When the heat flux delivered by the injected steam becomes equal with the heat-loss flux in the adjacent layers, the velocity at which the heated area increases will be negligible. The time corresponding to this situation is called critical time, t_{cr}, and the parameter u takes a critical value u_{cr} which can be calculated from equation (18) written as

$$\mathrm{e}^{u_{cr}^2}\operatorname{erfc}(u_{cr}) = 1 - \frac{M\,x_r\,l_v}{q_r}\ . \tag{20}$$

Based on relation (6), equation (20) becomes

$$\mathrm{e}^{u_{cr}^2}\operatorname{erfc}(u_{cr}) = 1 - \frac{x_r\,l_v}{x_r\,l_v + i_l - i_{wr}}\ , \tag{21}$$

which must be corrected for the net flux of heat injected as follows

$$\mathrm{e}^{u_{cr}^2}\operatorname{erfc}(u_{cr}) = 1 - v\ , \tag{22}$$

where

$$v = \frac{x_r\,l_v}{x_r\,l_v + i_l - i_{wr}}\,\frac{q_r}{q_{rn}}\ , \tag{23}$$

$$q_{rn} = q_r - \sum_{j=1}^{n} M_j\left(i_{jo} - i_{jr}\right), \tag{24}$$

M_j is the rate of phase j produced by wells, i_{jo} – enthalpy per unit mass of phase j at reservoir outlet, and i_{jr} – enthalpy per unit mass of phase j at the initial reservoir temperature T_r.

For calculating the area A_s of the steam-swept region at time values greater that the critical time t_{cr}, Hearn [12] proposed a thermal balance expressed by equation (19) written as

$$M\,x_r\,l_v \cong q_s(A_s)\,,\quad t > t_{cr}\ . \tag{25}$$

This formula shows that the flux of latent heat injected is used to compensate the heat losses $q_s(A_s)$ over the surface of area A_s. Considering that the heat exchange from the heated area of the reservoir to the adjacent formations may be calculated based on a equivalent hot region having an uniformly distributed temperature T_s and an area $A > A_s$, Hearn derived the equation

$$\frac{A_s}{A} \cong \left[\frac{v}{1 - \mathrm{e}^{u^2}\operatorname{erfc}(u)}\right]^{1,05}\left[2 - \frac{v}{1 - \mathrm{e}^{u^2}\operatorname{erfc}(u)}\right], \tag{26}$$

for $u > u_{cr}$ and v expressed by relation (23).

The volume N_d of oil displaced at time t from the steam-swept region or the heated region is

$$N_d = m\,h_n\left[A_s\left(\frac{s_{oi}}{b_{oi}} - \frac{s_{ors}}{b_{os}}\right) + \left(A - A_s\right)\left(\frac{s_{oi}}{b_{oi}} - \frac{s_{orw}}{b_{ow}}\right)\right], \tag{27}$$

if $A_s < A$, corresponding to $t > t_{cr}$, or

$$N_d = m\,A\,h_n\left(\frac{s_{oi}}{b_{oi}} - \frac{s_{ors}}{b_{os}}\right), \tag{28}$$

when $A_s = A$, corresponding to $t \le t_{cr}$.

The steam-flood process efficiency is commonly characterized by the oil-steam ratio R_{os} defined as

$$R_{os} = \frac{\rho_w\,N_p}{\int_0^t M\,\mathrm{d}t}\ , \tag{29}$$

where N_p is the cumulative volume of produced oil and ρ_w – water density at temperature T_{wg}.

If a threshold time t_t exists between the start of the steam-flood process and the increase of the producing wells oil rate, the cumulative oil production at time t is defined by equation (28) particularized for $A(t) = A(t - t_t)$ when $t - t_t \le t_{cr}$, or by relation (27) modified by substituting the areas A and A_s at time t with the same areas at time $t - t_t$, when $t - t_t > t_{cr}$.

To measure the performance of a steam-flood process, beside the oil-steam ratio, the performance coefficient P can be used. This coefficient is defined as the ratio between the net calorific power P_{on} of the produced oil and the heat consumed by the boiler to produce the steam injected, namely

$$P = \eta_g \frac{\rho_o P_{on}}{i_{sg} - i_{wg}} R_{os} , \tag{30}$$

where i_{sg} is the enthalpy per unit mass of steam at generator's outlet, and i_{wg} – the enthalpy per unit mass of the steam generator feeding water.

The performance of the steam-flood process calculated with this algorithm is listed in Table 3.

Table 3. The calculated performance of the steam-flood process in a five-spot element for the case study data

t, years	A, m^2	A_s, m^2	$A\,h$, m^3	N_d, m^3	N_p, m^3	R_{os}, m^3/m^3	P
0,5	1.295	1.295	19.420	2.913	0	0,000	0,00
1	2.268	2.268	34.014	5.102	2.913	0,166	2,25
2	3.851	3.790	57.769	8.623	6.973	0,201	2,72
3	5.174	4.967	77.608	11.502	10.120	0,193	2,60
4	6.338	5.965	99.076	14.009	12.793	0,183	2,47
5	7.393	6.847	110.890	16.265	15.164	0,173	2,34

Conclusions

The apparently insurmountable difficulties concerning the simultaneous solution of the microscopic equations describing the material and thermal balances, in order to determine the fields of velocities, densities, phase pressures and temperature, in the case of a steam-flood into an oil reservoir, impose the use of the method of decoupling these two sets of equations, although a series of physical parameters of the fluid phases depend on the temperature distribution in time and space.

Marx and Langenheim performed this decoupling by completely neglecting fluid flow into the reservoir and assuming that the injected thermal energy is confined by the producing layer in the steam-invaded region, at a constant temperature, and partially delivered to the neighboring layers. Thus, they formulated the law of variation in time of the heated region, considering that the steam front realizes a piston-like displacement, and the vertical-sweep efficiency is unity, while the temperature variation into the reservoir is step-like.

The Myhill-Stegemeier model [5] constitutes a more advanced version of the Marx-Langenheim procedure which appeals to the Mandl-Volek algorithm to calculate the volume of the steam-swept region.

The van Lookeren model [7] involves, complementarily, the estimation of the vertical sweep efficiency. Based on the segregated motion principles, this model is the only analytical method which accounts for the effects of oil collector inclination, ratio of gravity and viscous forces, as well as level of liquid in the injection well on oil production rate. The influence of buoyant forces on the approximate shape of the steam region is also included.

The model proposed by Vogel [10] is based on the supposition that the injected steam segregates immediately in the upper side of the oil bearing formation and ensures the vertical heat transfer by upward conduction to the layers bounding the collector in the top and by downward conduction through the oil column.

Miller [11] extended the Vogel's model to make a complete estimation of the flow rate vs. time dependency, accepting that oil viscosity reduction is entirely due to the conductive heating of the oil layer above which the steam region is uniformly distributed.

Butler's model [13] refers to a process of production of very viscous oil by gravity drainage from an expanding steam zone. In this process of producing a bitumen layer, the communication gap between the vertical wells situated at a relatively long distance is surmounted by using a horizontal well located at the bottom of the collector, as a producing drain. The steam is delivered to the drain by vertical injectors drilled in several locations situated at (1.5…6) m above the horizontal well.

The model introduced by Edmunds [9] is intended for estimating tar recovery from a preheated reservoir with steam flowing through a fissure, a thin water layer or a gas-saturated region. Some possibilities of increasing the performance of a tar or bitumen reservoir steam-flooding process, suggested by Edmunds, are: (1) retrieving the heat contained by the produced fluids; (2) decreasing steam mobility by using foams; (3) increasing bitumen mobility in the heated region by using solvents, carbon dioxide etc.

The case study presented in this paper, concerning the consistency of the Marx-Langenheim method based on the comparison between the flux of latent heat injected into the reservoir and the flux of heat losses to the adjacent layers, reflects the particularities of this procedure. The oil-steam mass ratio and the performance coefficient provide additional information on the performance of the oil recovery process.

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Unele particularități ale metodelor de calcul simplificat al recuperării țițeiului prin injecție continuă de abur

Rezumat

În lucrare suni prezentate, alături de modelul, devenit clasic, preconizat de Marx şi Langenheim, câteva metode analitice de estimare a performanței recuperării țițeiului din zăcământ prin spălare cu abur. Sunt puse în evidență atât avantajele cât şi limitele de aplicabilitate ale fiecărei metode. Spre exemplificare, este inclus un studiu de caz care ilustrează modul de determinare a parametrilor de performanță aferenți unui proces de injecție continuă de abur într-un zăcământ de țiței, folosind modelul Marx-Langenheim.