Simulation of 1-D heat distribution in heavy oil reservoirs during steam injection process

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Abstract

In this paper, a solution of 1-D energy equation during steam flooding process will be demonstrated in dimensionless form and the effect of conduction and convection terms on temperature propagation and the parameters that controls these effects will be explained as well. Solving this problem is conducted using Mathematics module in Comsol Multiphysics® environment since there is no tackling to this problem using this software.

The results show that at low Darcy's velocity, conduction plays the most significant role during hot fluid injection in cold formations while convection has much less effect on heat propagation in the formation. On the other hand, when the Darcy's velocity increases, the effect of the convective term grows and this can be attributed to the significant role of in situ fluids to increase thermal dispersion within the reservoir. The results also illustrate that the steam injection rate has not always a positive effect on heating up the porous medium.

Keywords: Enhanced oil recovery, heavy oil, thermal, energy equation, steam flooding

Introduction

Enhanced oil recovery (EOR) can be defined as all the methods that can be used after primary and secondary recovery to produce oil from the reservoir and sometimes is referred to as tertiary recovery. As it is well known in petroleum industry that the recovery factor is in best cases between 25-50% of original oil in place during primary and secondary recovery. Moreover, in heavy oil reservoirs the recovery factor may be as low as 5% and in the case of bitumen EOR must start from the very beginning of oilfield life since its viscosity is so high that it is impossible to move within the pore channels without heating.

EOR is expanding worldwide to produce more oil from existing reservoirs to fulfil the demand of the global consumption, which increases on yearly basis. Generally, EOR methods can be classified into thermal and nonthermal methods. The nonthermal methods are applied primarily to light and medium heavy oil reservoirs. Chemical methods, CO_2 injection, and microbial methods are some of the nonthermal EOR techniques. Thermal EOR methods are primarily applied to reduce oil viscosity and increase its mobility. Many technologies are utilized in this regard and the most which are applied or under development are hot water injection, in-situ combustion, electrical heating, and steam injection or steam flooding [1].

Steam injection and its variations is the most famous technology applied in heavy oil and bitumen reservoirs to produce as much as possible oil [2]. Traditional steam injection process depends on two vertical wells, one for steam injection while the other is for production as illustrated in figure 1.

Understanding heat distribution during this process is the keystone to optimize the process and reduce the cost of oil barrel.

Literature is still poor with research related to heat distribution in oil reservoirs during various thermal EOR processes.

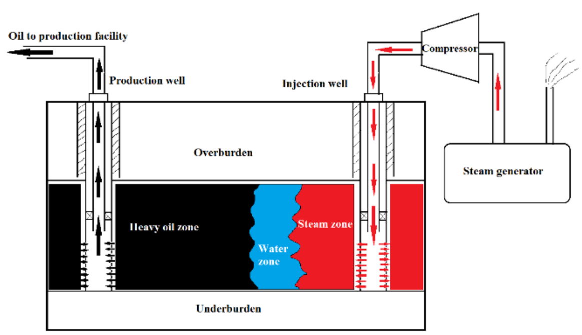

Figure 1. Typical steam injection process in a heavy oil/bitumen reservoir.

Previous studies on steam flooding

Mathematical models and experimental results are very important tools to enable us to understand, evaluate, and optimize steam injection process. Theoretical and experimental investigations on steam flooding started as early as the fifties of the last century. Marx and Langenheim [3] were of the pioneers researchers to report on heat transfer in porous media in 1959 and describe the process

mathematically and calculate produced fluids and heat loss to the overburden and underburden (figure 1). Shutler [4] also was the first to elucidate three-phase simulation of the steam flooding numerically and reported valuable results in the early days, however, with some simplifications. Other researchers developed a mathematical model based on mass and energy balance [5].Temperature propagation in the reservoir has been simulated in one dimension [6], the results illustrates that matrix, and fluid temperature difference is negligible. Moreover, the convection does not have a remarkable effect on heat diffusion in the porous medium. Mozaffari et al [7] explained the mathematical model of steam flooding extensively and solved the governing equations for three phase (steam, oil, and water). They concluded that steam injection increased the recovery up to 60% for a certain Iranian heavy oil reservoir and compared their findings with experimental results from the literature and proved the strength of the mathematical model to describe the process, forecast and optimize the whole operation.
Steam oil ratio (SOR) is one of the key issues to take into consideration during steam flooding since it has a great effect on the total cost of the project. The results from [7] show that there is an optimum steam injection rate for each reservoir and to avoid uneconomic SOR, the ratio should be determined through numerical simulation as a first step in every project. Many numerical studies have been devoted for coupled heat and fluid flow during steam flooding and can be found elsewhere. However, we will limit our study to heat distribution within the heavy oil formation in one dimension to understand in depth the mechanism of heat transfer and the effect of conduction and convection phenomena on heat distribution during the process and the effect of the steam and fluid velocity on temperature propagation.

Governing Equations

Since we are only interested in studying temperature distribution in the porous medium, so our interest is to solve energy equation over a specified domain only. It is well known that energy equation can be written for any porous medium according to the representative elementary volume (REV) approach [8] and in the general case where there is a local thermal nonequilibrium (LTNE) between rock and fluids [9,10]:

In matrix:

$$(1-\varphi)(\rho c_p)_s \frac{\partial T_s}{\partial t} - (1-\varphi)\nabla.(k_s \nabla T_s) - (1-\varphi)\, q_s''' - h\left(T_f - T_s\right) = 0 \ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

and in fluid:

$$\varphi(\rho c_p)_f \frac{\partial T_f}{\partial t} + (\rho c_p)_f\, u\, \nabla T_f - \varphi\nabla.\left(k_f \nabla T_f\right) - \varphi\, q_f''' - h\left(T_s - T_f\right) = 0 \ldots\ldots(2)$$

Where the subscripts (*s*, *f*) refer to solid and fluid respectively, φ porosity, ρ the density, c_p heat capacity, *T* the temperature, *k* thermal conductivity, *h* convective heat transfer coefficient, *u* velocity of the fluid, and q''' heat production by unit volume.
In the reservoir and during steam injection three phases will coexist in the pores of the rock, which are steam, oil and water, so auxiliary equations are required to enable us to solve the system (1) and (2):

$$\sum S_i = S_o + S_w + S_g = 1$$

Where:
S is saturation of phase *i*
o, *w*, and *g* are oil, water, and gas respectively

$$\rho_f = \rho_o S_o + \rho_g S_g + \rho_w S_w$$

$$(\rho c_p)_f = \rho_o c_{po} S_o + \rho_g c_{pg} S_g + \rho_w c_{pw} S_w$$

$$k_f = k_o \varphi\, S_o + k_g \varphi\, S_g + k_w \varphi\, S_w$$

In our model there is no heat generation, which allow for $q''' = 0$ and the following parameters are used to transfer (1) and (2) to nondimensional form:

$$T_f^* = \frac{T_f - T_i}{T_{steam} - T_i},\ T_s^* = \frac{T_s - T_i}{T_{steam} - T_i},\ T^* = \frac{T - T_i}{T_{steam} - T_i},$$

$$t^* = \frac{u_i t}{L},\ x^* = \frac{x}{L},\ u^* = \frac{u}{u_i} \text{ and } p^* = \frac{p}{p_i}$$

Where the subscript *i* refers to the initial value

Thus, (1) and (2) can be written the dimensionless form:

For matrix:

$$\frac{\partial T_s^*}{\partial t^*} - \frac{k_s}{\beta L\, u_i}\frac{\partial^2 T_s^*}{\partial x^{*2}} + \frac{h\, L}{\beta u_i}\left(T_s^* - T_f^*\right) = 0 \ldots\ldots\ldots.(3)$$

Where,

$$\beta = (1-\varphi)\rho_s c_{ps},$$

and for fluid:

$$\frac{\partial T_f^*}{\partial t^*}+\frac{u^*}{\varphi}\frac{\partial T_f^*}{\partial x^*}-\frac{k_f}{\Omega L\, u_i}\frac{\partial^2 T_f^*}{\partial x^{*2}}+\frac{h\,L}{\Omega u_i}\left(T_f^*-T_s^*\right) = 0 \quad \ldots (4)$$

Where:

$$\Omega = \varphi\,\rho_o c_{po} S_o + \varphi\,\rho_g c_{pg} S_g + \varphi\,\rho_w c_{pw} S_w,$$

and L is the total length

The absence of local thermal equilibrium (LTE) usually results from a low heat transfer coefficient ***h***, which appears in equations (3) and (4), [9, 11]. However, fluid flow in petroleum reservoirs is characterised by low velocity of the fluids and according to [10] LTNE is encountered only in highly transient situations and in some steady state problems which are out of the scope of this study.

We will consider local thermal equilibrium (LTE) in our study here where $T_f = T_s = T$, so equations (1) and (2) can be solved simulateously and produce one equation for both fluid and matrix in the following form:

$$m\,\frac{\partial T}{\partial t}+(\rho\, c_p)_f\, u\,\frac{\partial T}{\partial x}-k_m\frac{\partial^2 T}{\partial x^2}=0 \quad \ldots (5)$$

Where:

$$m = (1-\varphi)\rho_s c_{ps} + \varphi\,\rho_o c_{po} S_o + \varphi\,\rho_g c_{pg} S_g + \varphi\,\rho_w c_{pw} S_w$$

And total thermal conductivity:

$$k_m = (1-\varphi)k_s S_s + k_o\varphi\, S_o + k_g\varphi\, S_g + k_w\varphi\, S_w$$

Different researchers have proposed many formulae for thermal conductivity of the porous medium, but we used the above mentioned formula since it represents the contribution of all phases to the total thermal conductivity k_m according to their share in the porous medium.

Equation (5) can be written in dimensionless form also as follows:

$$\frac{\partial T^*}{\partial t^*}+\frac{(\rho\, c_p)_f\, u^*}{m}\frac{\partial T^*}{\partial x^*}-\frac{k_m}{mL\, u_i}\frac{\partial^2 T^*}{\partial x^{*2}}=0 \quad \ldots (6)$$

Darcy's law for fluid flow in porous media is:

$$u = -\frac{k}{\mu}\;\frac{\partial p}{\partial x}$$

Where ***k*** is absolute permeability, ***μ*** viscosity, and ***p*** pressure.

Darcy's equation in dimensionless form becomes:

$$u^* = -\left(\frac{k p_i}{u_i\, L\, \mu}\right)\frac{\partial p^*}{\partial x^*}$$

The above equation is used to calculate u^* in equation (6) and it can also be written in the form $u^*=a\, f\,(t^*)$, where ***a*** is a function of the parameters in the term $\left(\frac{k p_i}{u_i\, L\, \mu}\right)$ and according to [6] the velocity can be treated as a linear function of time, $u^*=a\, t^*$.

Simulation procedure

Consider two wells, one is for injection and the other is for production as shown in figure 2. In the oilfield, the injection well is used to inject steam at a constant temperature and specified quality while the rate can be manipulated during the process according to SOR and operating conditions in the specified field.

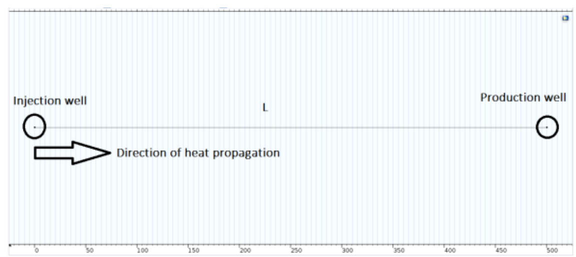

Figure 2. One dimensional simulation domain

Steam forces the fluids to move toward the production well and when the steam is cooling down it condenses into water and forms a hot water bank that drives the oil to move in the formation (figure 1).

The fluid and formation properties that have been applied in the simulation are chosen from the literature [6], which also were used to solve the problem using MATLAB® software and are shown in table 1. Mathematics Module in COMSOL Multiphysics® is used to implement the simulation.

Since we only consider the case of $T_f = T_s = T$ where LTE exists between the fluid and the formation matrix, initial and boundary conditions are chosen carefully as follows:

Initial condition:

$T\,(x, 0) = T_{initial}$

Boundary conditions:

$T\,(0, t) = T_{steam}$

$T\,(L, t) = T_{initial}$

In dimensionless form:

Initial condition:

$T^*(x, 0) = T_{initial} / T_{initial} = 1$

Boundary conditions:

$T^*(0, t) = T_{steam} / T_{initial} = 260/78 = 3.3$

$T^*(L, t) = T_{initial} / T_{initial} = 1$ ……………………………….(7)

Table 1: Physical properties of the fluids and formation matrix [6]

Parameter	Value	
φ	*25 %*	
μ_f	*10*	*Pa. s*
ρ_g	*16.712*	kg/m^3
ρ_o	*800.9*	kg/m^3
ρ_s	*2675*	kg/m^3
ρ_w	*1001*	kg/m^3
C_{pg}	*29.7*	*kJ/kg. C*
C_{po}	*2.1*	*kJ/kg. C*
C_{ps}	*0.88*	*kJ/kg. C*
C_{pw}	*4.2*	*kJ/kg. C*
k_g	*0.00397*	*W/m. K*
k_o	*0.387*	*W/m. K*
k_s	*2.6*	*W/m. K*
k_w	*0.6*	*W/m. K*
S_g	*20 %*	
S_o	*60 %*	
S_w	*40 %*	
Permeability k	$100*10^{-15}$	m^2
T_{steam}	*260*	*C°*
$T_{initial}$	*78*	*C°*
L	*152.5*	*m*

Solving equation (6) along with (7) in a programming language like MATLAB® or C++ (using finite difference or finite volume schemes) is a cumbersome task since choosing the discretisation scheme should be done carefully and the stability depends on time and spatial steps, which must also be chosen carefully. Here appears the advantage of finite element method over other numerical techniques. However, choosing of the shape functions plays an important role in making the solution more stable. Here Lagrange shape function is used along with Quartic element order.

Simulation Results

Simulation has been carried out for various fluid velocities and dimensionless times in the formation. The effect of steam velocity and time are investigated and the effect of convection and conduction phenomena is studied as well.

I- Effect of dimensionless velocity

Figures 3 and 4 illustrate the effect of steam velocity on heat propagation in the reservoir, the higher the velocity of steam the deeper and the faster the temperature of the reservoir is raised and this is because of the amount of energy transferred by the fast steam. Actually high velocity implies high volume of steam. Moreover, time has a primary effect on heat propagation and it can be seen from figures 3 and 4 that, the more time elapsed the deeper the heat propagates into the reservoir.

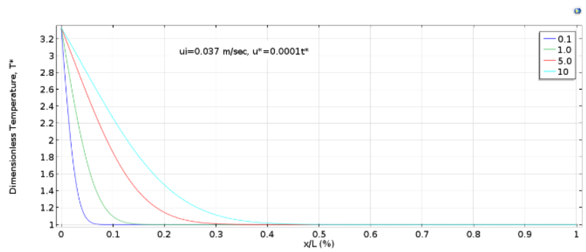

Figure 3. Dimensionless temperature *T** versus dimensionless distance $x^* = x/L$ and $u^* = 0.0001t^*$

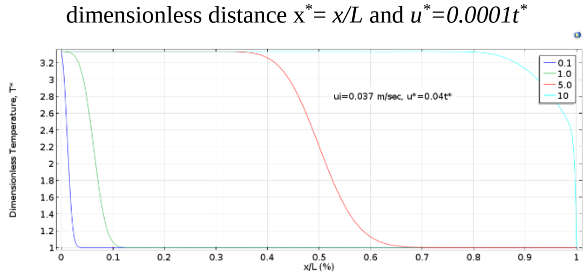

Figure 4. Dimensionless temperature *T** versus dimensionless distance $x^* = x/L$ and $u^* = 0.04t^*$

II- Effect of initial steam velocity

Figure 5 shows heat distribution regime within the formation at initial velocity $u_i = 0.037 m/sec$. When this velocity is decreased to $u_i = 0.0037 m/sec$, the regime is changed and heating up the reservoir is getting faster as it is shown in figure 6 and this can be attributed to conduction effect which must be exploited instead of injecting big amounts of steam. Note that the dimensionless velocity is the same in figures 5 and 6 ($u^* = 0.01t^*$).

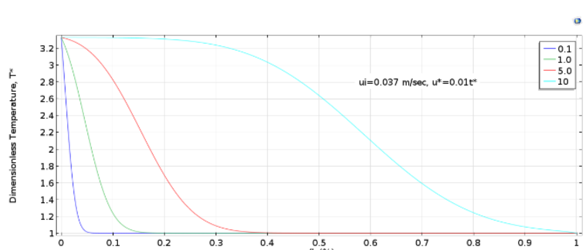

Figure 5. Dimensionless temperature *T** versus dimensionless distance $x^* = x/L$ and $u_i = 0.037 m/sec$

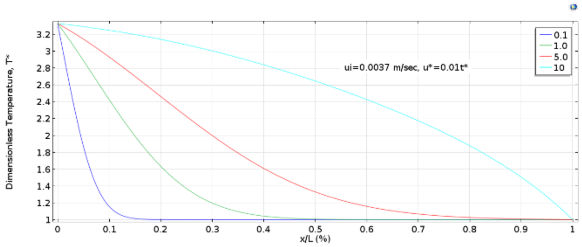

Figure 6. Dimensionless temperature T^* versus dimensionless distance $x^* = x/L$ and $u_i = 0.0037 m/sec$

Peclet number

Peclet number analysis gives a clear idea about the transport-dominated mechanism whether it is convection or conduction (diffusion). Helmig and other researchers [12, 13, and 14] referred to grid Peclet number as stated in the following equation:

$$Pe = \frac{u.\ \Delta l}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (8)$$

Where $\underline{\boldsymbol{u}}$ is Darcy flow velocity, $\underline{\boldsymbol{D}}$ is diffusion coefficient, and $\underline{\boldsymbol{\Delta l}}$ is characteristic length and here it is referred to as element length.

Two constant terms can be recognized from equation (6):

- Diffusion constant $\frac{k_m}{m\, L\, u_i}$
- Thermal convection velocity $\frac{(\rho c_p)_f\ u^*}{m}$

Diffusion constant is responsible for the conduction effect, the convection term controls convection phenomena, and as the velocity of the fluids in the porous medium is very low, the effect of convection is limited to fluids' velocity. On the other hand, thermal conductivity of the rock is much more than that of fluids in the pores based on that it transfers heat by conduction and releases it to the fluids, which contributes to heat propagation away from the steam front. Applying equation (8) for low velocities in the range $0.0001t^*$-$0.01t^*$ results in values close to zero which confirms diffusion dominated process.

Conclusions

Steam flooding and its variations is one of the most efficient methods to enhance the recovery of heavy oil and bitumen reservoirs and it is expanding globally very fast. To understand heat distribution during this process, energy equation has been solved in one dimension and in dimensionless form and the following conclusions can be drawn from the numerical experiments:

- Time plays important role in heating up the formation, the more time elapsed; the deeper the steam penetrates into the reservoir and the better the propagation of heat inside the reservoir.
- The more the volume of steam injected, the deeper the heat penetrates inside the formation; however, at low steam velocity the heat penetrates the reservoir due to conduction effect.
- Conduction is superior to convection in steam injection process.

In the future LTNE in heavy oil/bitumen reservoirs will be studied using equations (3) and (4) to determine the situations where LTE assumption is not valid.

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