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Inclusion of Memory Concept to Describe Rock/fluid Rheology and Heat Transfer during Thermal Operations

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Abstract

The temperature distribution in a reservoir formation is becoming a very important issue due to its utilization in detecting water or gas influx or type of fluid entering into the wellbore. This information is necessary for better reservoir management. This information is subject to reservoir rock/fluid rheologies that are a continuous function of time. These highly complex characteristics of rock/fluid interaction during thermal operation play a vital role in heat transfer within the rock matrix and flowing hydrocarbon. This heat transfer mainly governs the temperature propagation of the reservoir formation. Prediction of temperature distribution behavior during steam injection process is significant for production evaluation of field operations. Such a prediction can be used in the case of hot water injection into a reservoir and also applies in some other thermal recovery processes, such as in-situ combustion. This study developed mathematical models in terms of Nusselt number, Peclet number, and Prandtl number with the inclusion of “memory” concept to describe these rheological phenomena. The model equations describe how the fluid and rock properties are dependent on continuous time function and investigates the temperature propagation during thermal operation. The proposed models are capable of handling the variable rock and fluid properties with time and space during enhanced oil recovery (EOR). The effects of temperature on different reservoir parameters can also be investigated using the proposed mathematical tool.

Keywords: Steam injection, temperature distribution, variable rock/fluid properties, reservoir characterization, and reservoir modeling.

Nomenclature

A_{yz}	Cross sectional area of rock perpendicular to the flow of flowing fluid, m^2
c	Single phase reservoir fluid compressibility, pa^{-1}
c_p	Specific heat capacity of single phase fluid or rock matrix, $kj/kg-k$
g	Gravitational acceleration in x direction, m/s^2
h_c	Convection heat transfer coefficient, kj/hm^2k
k	Variable permeability of the reservoir system, m^2
k_{pi}	Permeability at initial condition, m^2
k_e	Effective thermal conductivity, $kj/h\,m\,k$
L	Distance between production and injection well along x direction, m
M	average volumetric heat capacity of the fluid-saturated rock, kj/m^3k
p	Pressure of the system, pa
q_i	$=Au=$ Initial volume production rate, m^3/s
q_x	fluid mass flow rate per unit area in x-direction, kg/m^2s
q_{inj}	$=Au=$ injection volume flow rate of steam, m^3/s
q_{prod}	$=Au=$ production volume flow rate of oil, m^3/s
S	Saturation, m^3/m^3
t	Time, s
T	Temperature in the formation, k
T_f	Temperature of injected fluid, k
T_r	Reference temperature of injected fluid, k
T_s	Average temperature of solid rock matrix, k
u	fluid velocity in porous media in the direction of x axis, m/s
x	Flow dimension at any point along x-direction,m

Greek Symbols

α	Fractional order of differentiation, dimensionless
μ	Fluid dynamic viscosity, $pa.s$
η	ratio of the pseudopermeability of the medium with memory to fluid viscosity, $m^3s^{1+\alpha}/kg$
ξ	A dummy variable for time i.e. real part in the plane of the integral, s
ρ	Single phase mass density, kg/m^3
Γ	Gamma function
ϕ	Porosity of the rock matrix, m^3/m^3

Subscripts

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f	Reservoir fluid (i.e. $g+o+w$)
g	Injected steam
o	Reservoir oil
s	Solid reservoir rock matrix
t	Total rock and fluid (i.e. $s+f$)
w	Reservoir water
wi	Initial reservoir water
i	Initial condition
ref	Reference point
x	Flow direction along x-in a Cartesian coordinate

Non-dimensional Numbers

L^*	Dimensionless length of the reservoir
T^*	Dimensionless temperature
N_u	Nusselt number, $[\frac{h_c L}{k_e}]$
P_e	Peclet number, $[\frac{L\,\rho_f\, c_{pf}\, u_x}{k_e}]$
P_r	Prandtl number, $\frac{\mu\, c_{pf}}{k_e}$
t^*	Dimensionless time
u^*	Dimensionless velocity
x^*	Dimensionless distance

1. Introduction

The current worldwide petroleum industries are facing a great problem from mature reservoirs. Many of these wells are producing oil or gas where a high ratio of produced water volume to produced hydrocarbon volume is coming out. In such a situation, the economic hydrocarbon production rates are difficult to achieve due to water-coning and critical flow rates. If the oil (or gas) production rate exceeds this critical flow-value, water breakthrough occurs [1]. Thus, water may take part the major factor in the total production rate. To prevent water breakthrough due to coning phenomenon, the oil/gas industry uses several technologies such as reducing permeability to water by the injection of resins, polymers or gels, keeping production rates below the critical value, periodical production and by other means [1].

Water coning or breakthrough depends on the rock/fluid properties with time. During the steam injection of an EOR scheme, the alterations of rock/fluid properties are well established in the literature especially by Hossain and coauthors [2 – 8]. This alteration of rock/fluid properties guides the temperature profile within the reservoir formation. The temperature propagation tells us the information about the water influx in the permeable zone. Therefore, the understanding of temperature propagation through a formation is important in the design of production management. Temperature profile can be applied to identify water or gas entries in the reservoir. It may be used to find out the fracture characteristics in the reservoir. It is also important to guide the action of sliding sleeves or other downhole flow control devices. Therefore, it is useful to investigate the pattern of temperature propagation and heat exchange between fluid and rock in the formation.

Spillette's model [9] is based on the assumption that the heat is transferred by two mechanisms: 1) the physical movement of the injected fluids and 2) thermal conduction. Convective heat transfer between the injected fluid and the original reservoir fluids and the permeable reservoir rock is assumed to be accounted for by the additional assumption of instantaneous thermal equilibrium in the reservoir. Hossain et al. [4 – 5, 8] investigated temperature propagation pattern and its dependence on various parameters during thermal operations. They have completed an extensive review of temperature propagation and its dependence on several parameters. The model equations have been solved for temperature distribution throughout the reservoir for different cases. It is found that the fluid and rock matrix temperature difference is not significant. Moreover, results show that formation fluid velocity, steam injection velocity, and time have an impact on temperature profiles behavior. They identified that temperature distribution is much more sensitive to time, and formation fluid velocity. It is also sensitive to steam or hot water injection rate or velocity. They assumed a linear function for fluid velocity in the formation. They did not consider the thermal effects in terms of Nusselt number, Peclet number and Prandtl number. Recent investigation shows that due to temperature variation in the formation, the porosity, permeability and the rheology of reservoir may also change as a result of continuous heat transfer within the fluid and rock matrix [7 – 8]. This continuous alteration of fluid and pore space properties may greatly be influenced by the fluid memory especially in some geothermal area [4, 10 – 11].

Therefore, the present study includes the effects of fluid memory in the fluid flow behavior during the steam injection at the formation of reservoir. As we came to know that the fluid velocity, time have strong effects on temperature propagation pattern, it is very important to investigate the effects of fluid memory as well as the rheology of rock/fluid based on heat transfer. In this study we are focusing how to model the complex heat transfer phenomena and alteration of temperature between rock and fluid and its influence on temperature propagation in terms of Nusselt number, Peclet number and Prandtl number. The main objective of this study is to develop temperature profiles which is sensitive to time dimension and which will give advance information on any change or anomaly of temperature profile due to water entry or breakthrough.

2. Model Description

Steam flooding is a process whereby steam is injected into a number of wells while the oil is produced from adjacent wells (Figure 1). It is taken into account a porous media of uniform cross sectional area and homogeneous along x-axis. It is normal practice to consider that the fluid flow in porous media is governed by Darcy's law. Since the media is homogeneous, the pressure along x-direction may be considered to be varied based on initially Darcy diffusivity equation.

In this study, we have used modified Darcy's law which represents the notion of fluid memory. It is also considered that the thermal conductivity of fluid and solid rock matrix is not a function of temperature and constant along the media. In the initial stage of the reservoir, there is a uniform distribution of pressure and temperature throughout the reservoir. The computations are carried out for different fluid velocities. The initial and boundary conditions are defined as:

$$T_f(x,0) = T_s(x,0) = T_i,$$
$$In\ dimensionless\ form: T_f^*(x,0) = T_s^*(x,0) = 1$$

$$T_f(0,t) = T_s(0,t) = T_{steam},$$
$$In\ dimensionless\ form: T_f^*(0,t) = T_s^*(0,t) = \frac{T_{steam}}{T_i}$$

$T_f(L,t) = T_s(L,t) = T_i,$
$In\ dimensionless\ form: T_f^*(L,t) = T_s^*(L,t) = 1$

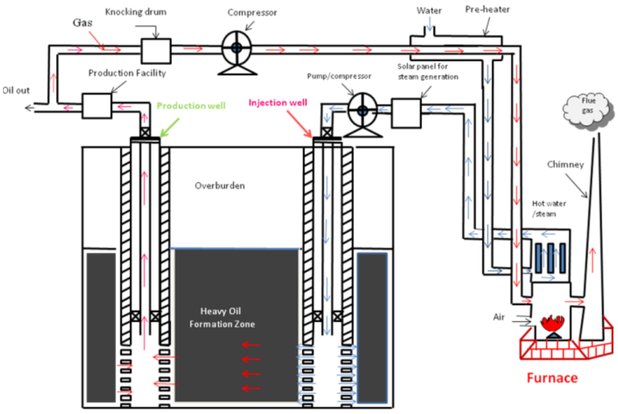

Fig. 1. Mechanism of Oil recovery scheme using injection and production wells in an oil field reservoir [4]

3. Mathematical model Development

The energy balance equation is considered as the governing equation for both rock and fluid separately. The partial differential equations have a familiar form because the system has been averaged over representative elementary volumes (REV). A right handed Cartesian coordinate system is considered where x-axis is along the formation length. The mass flow rate and conservation energy equations are considered to develop the model for temperature distribution in porous medium. In such situation, the momentum equation of fluid phase in the system can be written as [12 – 13]:

$$\frac{\partial p}{\partial x} = \rho_f\, g - \frac{\mu_i}{K_i} u - \frac{\rho_f}{\phi}\frac{\partial u}{\partial t} \tag{1}$$

It is assumed that there is no gravitational acceleration effect and a horizontal flow along the axis x. Therefore Eq. (1) reduces to:

$$u_{x_1} = \frac{K_i}{\mu_i}\left(\frac{\partial p}{\partial x} + \frac{\rho_f}{\phi}\frac{\partial u_{x_1}}{\partial t}\right) \tag{2}$$

The notation $u_{x_1}$is used instead of u to separate the fluid velocity which is representing without the dependency and inclusion of memory.

To determine temperature distribution with space and time, energy balance equation is considered as the governing equation for both rock and fluid separately. The inclusion of time dependent rock/fluid properties is a great deal for petroleum industry because the most uncertain situation for this industry is the true prediction of production performance and management. Therefore, the consideration of time dependent phenomena is very important for a well managed petroleum project. To introduce the notion of time dependency in temperature distribution, the use of “memory” concept is the recent well established phenomena [8, 10 – 11]. The inclusion of “memory” concept is introduced using the modified Darcy’s law as the flow rate equation which may be written as [4 – 5, 10 – 11]:

$$u = -\eta\left[\frac{\partial^\alpha}{\partial t^\alpha}\left(\frac{\partial p}{\partial x}\right)\right] \tag{3}$$

where, $\frac{\partial^\alpha}{\partial t^\alpha}\left(\frac{\partial p}{\partial x}\right) = \frac{\int_0^t (t-\xi)^{-\alpha}\left[\frac{\partial^2 p}{\partial \xi\, \partial x}\right]\partial \xi}{\Gamma(1-\alpha)}$ with $0 \le \alpha < 1$.

The above equation can be written for 1D system as:

$$u_{x_2} = -\frac{\eta}{\Gamma(1-\alpha)}\int_0^t (t-\xi)^{-\alpha}\left[\frac{\partial^2 p}{\partial \xi\, \partial x}\right]\partial \xi \tag{4}$$

The notation $u_{x_2}$is used instead of u to separate the fluid velocity which is representing time dependency and inclusion of memory. Hossain et al. [11, 14] defined the composite variable, η (function of permeability and viscosity) as:

$$\eta = \frac{k}{\mu_{ab}}(t)^\alpha = \frac{[3.0\,(p/6894.76)^{-0.31} + 10.5] \times 10^{-12}}{\mu_{ob} e^{8.422\times 10^{-5}(p-p_b)}}(t)^\alpha \tag{5}$$

where,

$$\mu_{ob} = 6.59927 \times 10^5 R_s^{-0.597627} T^{-0.941624}\gamma_g^{-0.555208} API^{-1.487449} \tag{6}$$

$$p_b = -620.592 + 6.23087\frac{R_s\gamma_o}{\gamma_g B_o^{1.38559}} + 2.89868\,T \tag{7}$$

$$B_o = B_{ob} e^{-C_o(p-p_b)} \tag{8}$$

$$B_{ob} = 1.122018 + 1.410 \times 10^{-6}\frac{R_s T}{\gamma_o^2} \tag{9}$$

$$c_o = \frac{\left(\begin{array}{c}-70603.2 + 98.404\,R_s + 378.266\,T - 6102.03\,\gamma_g \\ +755.345\,API\end{array}\right)}{(p+3755.53)} \tag{10}$$

The above equations (Eqs. 5 – 10) are based on oil field units such as oil formation volume factor (B_o), rb/stb; oil compressibility (C_o), psi^{-1}; oil formation volume factor at bubble point(B_{ob}), rb/stb; oil viscosity at the bubble point(μ_{ob}) , cp; oil viscosity above the bubble point(μ_{ab}), cp; solution gas oil ratio (R_s), scf/stb; temperature of crude oil (T), ^{0}F; specific gravity of gas (γ_g), lb_m/ft^3; specific gravity of oil(γ_o), lb_m/ft^3; and API oil gravity (*API*), ^{0}API.

To analyze the heat transfer and temperature propagation in the formation, a 1D energy balance equations can be written for both solid rock matrix and fluid flow as [8, 11, 15]:

$$k_s\frac{\partial^2 T_s}{\partial x^2} = (1-\phi_i)\rho_s c_{ps}\frac{\partial T_s}{\partial t} + \frac{h_c}{L}(T_s - T_f) \tag{11}$$

$$k_f\frac{\partial^2 T_f}{\partial x^2} - \rho_f c_{pf}\, u_x\frac{\partial T_f}{\partial x} = \phi_i\,\rho_f c_{pf}\frac{\partial T_f}{\partial t} + \frac{h_c}{L}(T_f - T_s) \tag{12}$$

where,

$$\rho_f c_{pf} = \rho_w c_{pw} S_w + \rho_o c_{po} S_o + \rho_g c_{pg} S_g \tag{13}$$

$$k_f = k_w + k_o + k_g \tag{14}$$

$$k_e = \phi_i k_f + (1-\phi_i)\,k_s \tag{15}$$

$$\rho_f = \rho_w S_w + \rho_o S_o + \rho_g S_g \tag{16}$$

$$S_w + S_o + S_g = 1 \tag{17}$$

$$M = (1-\phi_i)\rho_s c_{ps} + \phi_i\rho_w c_{pw} S_w + \phi_i\rho_o c_{po} S_o + \phi_i\rho_g c_{pg} S_g \tag{18}$$

Two cases such as different and same rock and fluid temperature are considered during the formulation and computation of the temperature profile.

3.1. Case I

Conservation of energy equations (Eqs. 11 – 12) for both solid rock and fluid can be written in dimensionless form when different rock and fluid temperature are considered. To transform those equations into dimensionless form, Eq. (19) has been considered where use of the non-dimensional parameters defined as:

$$T^* = \frac{T}{T_i},\ T_s^* = \frac{T_s}{T_i},\ T_f^* = \frac{T_f}{T_i},\ x^* = \frac{x}{L},\ p^* = \frac{p}{p_i},\ q^* = \frac{q}{q_i},\ t^* = \frac{k_{pi}\, t}{\phi_i\, \mu\, c_t L^2},\ \xi^* = \frac{k_{pi}\, \xi}{\phi_i\, \mu\, c_t L^2} \qquad (19)$$

Substituting the above non-dimensional parameters into Eq. (11) yields:

$$k_s \frac{T_i}{L^2}\frac{\partial^2 T_s^*}{\partial x^{*2}} = (1-\phi_i)\rho_s c_{ps} \frac{T_i\, k_{pi}}{\phi_i\, \mu\, c_t\, L^2}\frac{\partial T_s^*}{\partial t^*} + \frac{h_c}{L}\left(T_s^* T_i - T_f^* T_i\right)$$

$$\frac{k_{pi}(1-\phi_i)\rho_s c_{ps}}{\phi_i\, \mu\, c_t\, k_s}\frac{\partial T_s^*}{\partial t^*} - \frac{\partial^2 T_s^*}{\partial x^{*2}} + \frac{L\, h_c}{k_e}\frac{k_e}{k_s}\left(T_s^* - T_f^*\right) = 0$$

$$\frac{k_{pi}(1-\phi_i)\rho_s c_{ps}}{\phi_i\, \mu\, c_t\, k_s}\frac{\partial T_s^*}{\partial t^*} - \frac{\partial^2 T_s^*}{\partial x^{*2}} + \frac{k_e}{k_s}N_u\left(T_s^* - T_f^*\right) = 0$$

$$\frac{k_{pi}\, \rho_f}{\mu^2\, c_t}\frac{\mu c_{pf}}{k_e}\frac{(1-\phi_i)}{\phi_i}\frac{\rho_s c_{ps}}{\rho_f c_{pf}}\frac{\partial T_s^*}{\partial t^*} - \frac{k_s}{k_e}\frac{\partial^2 T_s^*}{\partial x^{*2}} + N_u\left(T_s^* - T_f^*\right) = 0$$

$$E_n P_r \frac{(1-\phi_i)}{\phi_i}\frac{\rho_s c_{ps}}{\rho_f c_{pf}}\frac{\partial T_s^*}{\partial t^*} - \frac{k_s}{k_e}\frac{\partial^2 T_s^*}{\partial x^{*2}} + N_u\left(T_s^* - T_f^*\right) = 0$$

$$E_n P_r M_1 \frac{\partial T_s^*}{\partial t^*} - \frac{k_s}{k_e}\frac{\partial^2 T_s^*}{\partial x^{*2}} + N_u\left(T_s^* - T_f^*\right) = 0 \qquad (20)$$

Where,

$E_n = \frac{k_{pi}\, \rho_f}{\mu^2\, c_t}$, a new proposed non-dimensional number

$M_1 = \frac{(1-\phi_i)}{\phi_i}\frac{\rho_s c_{ps}}{\rho_f c_{pf}}$

Again substituting the non-dimensional parameters of Eq. (19) into Eq. (12) yields:

$$k_f \frac{T_i}{L^2}\frac{\partial^2 T_f^*}{\partial x^{*2}} - \rho_f c_{pf} u_x \frac{T_i}{L}\frac{\partial T_f^*}{\partial x^*} = \phi_i \rho_f c_{pf}\frac{T_i\, k_{pi}}{\phi_i\, \mu\, c_t\, L^2}\frac{\partial T_f^*}{\partial t^*} + \frac{h_c}{L}\left(T_f^* T_i - T_s^* T_i\right)$$

$$\frac{k_f}{k_e}\frac{\partial^2 T_f^*}{\partial x^{*2}} - \frac{L\, \rho_f c_{pf} u_x}{k_e}\frac{\partial T_f^*}{\partial x^*} = \frac{\phi_i \rho_f c_{pf}}{k_e}\frac{k_{pi}}{\phi_i\, \mu\, c_t}\frac{\partial T_f^*}{\partial t^*} + \frac{h_c\, L}{k_e}\left(T_f^* - T_s^*\right)$$

$$\frac{k_f}{k_e}\frac{\partial^2 T_f^*}{\partial x^{*2}} - P_e\frac{\partial T_f^*}{\partial x^*} = \frac{\mu\, c_{pf}}{k_e}\frac{k_{pi}\, \rho_f}{\mu^2\, c_t}\frac{\partial T_f^*}{\partial t^*} + N_u\left(T_f^* - T_s^*\right)$$

$$\frac{k_f}{k_e}\frac{\partial^2 T_f^*}{\partial x^{*2}} - P_e\frac{\partial T_f^*}{\partial x^*} = P_r E_n\frac{\partial T_f^*}{\partial t^*} + N_u\left(T_f^* - T_s^*\right) \qquad (21)$$

Equation (20) and Eq. (21) represent the energy balance equations in terms of Nusselt number, Peclet number, Prandtl number [16] and a new definition of non-dimensional number, E_n. In Peclet number, u_x is representing for the cases; u_{x_1} and u_{x_2}. During the numerical computation, both u_{x_1} and u_{x_2} are used the find out the impact of "memory" during temperature distribution by Peclet number and will be used Eq. (4). These two partial differential equations should be solved simultaneously to find the temperature distribution and heat transfer for fluid temperature T_f^*, and rock matrix, T_s^* in the formation.

In solving Eqs. (20 – 21), the initial and boundary conditions are subjected to:

$T_f(x,0) = T_s(x,0) = T_i$
$T_f(0,t) = T_s(0,t) = T_{steam}$
$T_f(L,t) = T_s(L,t) = T_i$

In dimensionless form

$T_f^*(x^*,\ 0) = T_s^*(x^*,\ 0) = 1$
$T_f^*(0,\ t^*) = T_s^*(0,\ t^*) = T_{steam}/T_i$
$T_f^*(1,\ t^*) = T_s^*(1,\ t^*) = 1$

3.2. Case II

If we consider the temperature of the fluids and rock matrix are the same, the energy balance equations can be combined together. Now, combine Eq. (11) and Eq. (12) and substitute Eq. (13) and Eq. (18) into the combined form, the energy balance takes the form as a single equation [8, 11, 15]:

$$M\frac{\partial T}{\partial t} + \rho_f c_{pf} u_x \frac{\partial T}{\partial x} - \left(k_s + k_f\right)\frac{\partial^2 T}{\partial x^2} = 0 \qquad (22)$$

Using the dimensionless parameters defined in Eq. (19) and substituting the above transformation in to Eq. (22) yields:

$$M\frac{T_i\, k_{pi}}{\phi_i\, \mu\, c_t\, L^2}\frac{\partial T^*}{\partial t^*} + \rho_f c_{pf} u_x \frac{T_i\, \partial T^*}{L\, \partial x^*} - \left(k_s + k_f\right)\frac{T_i}{L^2}\frac{\partial^2 T^*}{\partial x^{*2}} = 0$$

$$\frac{k_{pi}\, \rho_f}{\mu^2\, c_t}.\frac{M\mu}{\phi_i\, \rho_f}\frac{T_i}{L^2}\frac{\partial T^*}{\partial t^*} + \frac{L\, \rho_f c_{pf} u_x}{k_e}.k_e.\frac{T_i}{L^2}\frac{\partial T^*}{\partial x^*} - \left(k_s + k_f\right)\frac{T_i}{L^2}\frac{\partial^2 T^*}{\partial x^{*2}} = 0$$

$$E_n\frac{\partial T^*}{\partial t^*} + P_e\frac{k_e}{M_2}\frac{\partial T^*}{\partial x^*} - \frac{\left(k_s + k_f\right)}{M_2}\frac{\partial^2 T^*}{\partial x^{*2}} = 0 \qquad (23)$$

where,

$M_2 = \frac{M\mu}{\phi_i\, \rho_f}$

Equation (23) represents the energy balance equations in terms of Peclet number, and the new non-dimensional number, E_n. This equation gives the dimensionless temperature profile and heat transfer along the formation length when the rock and fluid temperature are considered to be same. The initial and boundary conditions are:

$T(x,0) = T_i$

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

$T(L,t) = T_i$

In dimensionless form

$T^*(x^*,\ 0) = 1$

$T^*(0,\ t^*) = T_{steam}/T_i$

$T^*(1,\ t^*) = 1$

3. Conclusions

The variable rock and fluid properties with the inclusion of "memory" are captured in this article through dimensionless groups. The developed temperature propagation prediction models are highly non-linear in nature due to the continuous time and space function as variables. These models can be used to interpret the temperature changes along injected and produced fluid flow direction. A new dimensionless number has been introduced to handle gravity force by viscous force ($E_n = \frac{k_{pi}\,\rho_f}{\mu^2\,c_t}$) . The proposed models are useful to simulate the rock/fluid properties with time. These models can be applied more accurately during reservoir simulation and well testing.

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