



Formation heating by steam circulation in a horizontal wellbore



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ABSTRACT

A two-dimensional transient heat conduction model is developed that predicts heat transfer from a horizontal wellbore to the formation during a steam circulation process. The model takes into account the partial penetration of the wellbore, which is not included in previously developed analytical models applicable for reservoir heating. This inclusion makes the problem mathematically challenging as the inner boundary condition of the problem becomes non-homogenous. The governing heat conduction equation is solved for an infinite acting reservoir and semi-analytical solutions for the heat flux from the wellbore and temperature distribution in the formation are obtained using a combination of Laplace and finite Fourier cosine transforms. The average formation temperature and the heat flow across the wellbore are calculated and the results are presented. This analysis has applications in thermal stimulation of oil wells with low injectivity, where it is required to preheat the formation prior to steam injection.

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1. Introduction

It has been shown that formation heating by steam injection can significantly increase production rate and ultimate oil recovery from heavy oil reservoirs [8,14]. Thermal stimulation of oil formations has been widely used to either improve characteristics of fluid [5,6,7,9,17] or to remove or prevent the formation of wax and asphaltene build up in near wellbore regions [10,11,19].

During a process of steam drive, usually a large quantity of steam is needed to move the steam front through the reservoir particularly in thick pay zones. The steam zone movement is also reduced by heat loss to the under and overburden strata. Therefore, the steam drive process can take a long time and turn uneconomical especially when well spacing is not close or a low steam injection rate is used. Moreover, the steam drive process cannot be implemented in many heavy oil reservoirs due to viscous nature of crudes.

Wellbore heating of heavy oil reservoirs through conduction may overcome the above-mentioned disadvantages since formation heating significantly reduces the viscosity of heavy oils [1]. Depending on the type of heating process, various mathematical models have been proposed to predict heat transfer in near wellbore regions. For instance, Thomas [18] analytically studied a heating formation process in cylindrical coordinate and reported a solution for injection of non-condensing flue gases into a fracture

by incorporating the variation of thermal conductivity with temperature. He showed that the effect of thermal conductivity is very significant in oil shale reservoirs. Satter [15] followed similar approach and investigated the injection of saturated or under-saturated steam through a fracture or a thin highly permeable zone. However, Satter's analysis differs since he presented a theoretical analysis of conduction heating beyond the time of heat breakthrough at the producing wells. He provided a solution for estimating steam injection rate after heat breakthrough and investigated several parameters such as steam injection rate, temperature, pay thickness, and well spacing. Lesser et al. [12] numerically studied the temperature history of an impermeable formation heated by hot condensing gases through a set of horizontal equally spaced fractures. Connaughton and Crawford [3] developed a mathematical model that predicts formation heating by steam injection through a horizontal fracture or a thin channel using the analogy of conduction heating of an infinite cylinder with a disk source. Although conduction heating in a reservoir through fractures and channels has been studied extensively, development of analytical solutions for formation heating through a horizontal well has not received much attention.

The process of wellbore heating for initiation of steam stimulation process from a horizontal well located in immobile tar sand was originally proposed by Sanchez [13]. This is a process for pre-treating a reservoir prior to initiation of a steam drive process. In this process, first steam is injected into a horizontal wellbore at a pressure slightly higher than the reservoir pressure but below the fracture pressure to avoid fracturing. Steam is then allowed

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Nomenclature

α	thermal diffusivity, m ² /s	q	heat flux, W/m ²
A	area of the conducting surface, m ²	Q	cumulative thermal energy, W s
I	modified Bessel's functions of 1st kind	r_w	wellbore radius, m
k	thermal conductivity, W/m C	s	Laplace transform variable
K	modified Bessel's functions of 2nd kind	t	time, s
L_e	length of domain, m	T	temperature, °C
L_p	length of perforated wellbore, m	T_R	reservoir temperature, °C
M	number of segments	T_S	down-hole steam temperature, °C
n	finite Fourier cosine transform variable		

to circulate in wellbore for a sufficient time that preheats the formation by transient heat conduction to a desired temperature at a desired distance from the wellbore. As a result, the immobile viscous hydrocarbons in near wellbore regions become mobile and can be produced to the surface by stopping the steam circulation.

Numerical problems have been traditionally used to estimate the formation temperature around the wellbores. The disadvantage of numerical models is the computation time associated with the simulation of heat conduction problem. Therefore, development of analytical models allows fast and accurate estimation of formation temperature and thermal energy required to heat up the formation to a temperature that is necessary for mobilization of heavy and viscous oils.

The objective of this paper is to find an analytical solution for the temperature distribution in the near wellbore region during steam circulation that allows fast estimation of heat required for mobilization of viscous oil around the wellbore. A two-dimensional transient heat conduction model is developed to address the formation heating process by steam circulation in a wellbore. The model incorporates the effect of partial penetration of the horizontal well in radial coordinate. It is worth noting that previously developed analytical models applicable for reservoir heating did not include the effect of partial penetration of the wellbore. This inclusion makes the problem mathematically challenging as the inner boundary condition of the problem becomes non-homogeneous. The solution for the dimensionless temperature, at any point and time, is obtained using combination of Laplace and finite Fourier cosine transforms, which has been extensively used in the solutions of diffusive problems [4]. The average reservoir temperature to a desired distance from the wellbore, heat flux across the wellbore and cumulative heat flow are calculated.

2. Mathematical model

We assumed a horizontal well drilled at the center of an oil formation and employ the element of symmetry to define the extent of the formation in horizontal direction (L_e) and perforated section ($0 < x < L_p$), as shown in Fig. 1. As steam is being circulated in the wellbore, there is conduction heat transfer from the wellbore to the reservoir. Note that the heat conduction is the main heating mechanism during the start-up stage in a thermal stimulation process. Compared with oil production stage, heat transfer by convection during start-up stage is insignificant and can be ignored.

We assumed that the circulated fluid does not invade the formation and the thermal diffusivity and conductivity of the formation are invariant with temperature. In addition, since the wellbore is partially perforated, there is no direct contact between steam and formation for $L_p < x < L_e$.

Under the assumption of local thermal equilibrium between the formation fluids and the reservoir rock, the governing heat conduction equation is given by

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}, \quad (1)$$

where α is the thermal diffusivity. In the horizontal direction, $x = 0$ and $x = L_e$ are the no flow boundaries, which can be mathematically expressed by

$$\left. \frac{\partial T}{\partial x} \right|_{x=0} = \left. \frac{\partial T}{\partial x} \right|_{x=L_e} = 0. \quad (2)$$

We assumed that the wellbore is always maintained at a constant temperature, which is equal to the down-hole steam temperature, T_S . In the radial direction, beyond the wellbore, there is a radial symmetry and the net heat flux is zero. This is mathematically shown by

$$T|_{r=r_w} (0 < x < L_p) = T_S, \quad (3a)$$

$$\left. \frac{\partial T}{\partial r} \right|_{r=r_w} (L_p < x < L_e) = 0. \quad (3b)$$

The temperature far from the wellbore is same as the initial reservoir temperature during the heating period; thus $T(x, \infty, t) = T_R$. Initially, at $t = 0$, the formation is assumed to be at a reservoir temperature, T_R , which offers $T(x, r, 0) = T_R$. In order to nondimensionalize the governing equation and the system under consideration, we used the following dimensionless parameters

$$T_D = \frac{T - T_R}{T_S - T_R}, \quad (4)$$

$$r_D = \frac{r}{r_w}; \quad x_D = \frac{x}{L_p}, \quad (5)$$

$$t_D = \frac{\alpha t}{r_w^2}. \quad (6)$$

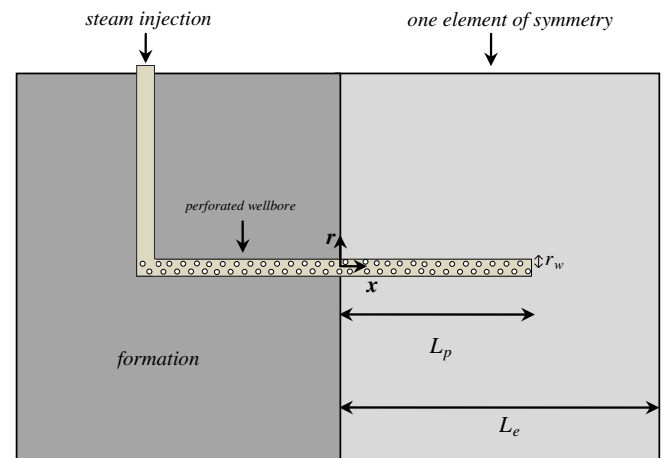


Fig. 1. A cross-section schematic of the model geometry with the element of symmetry.

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