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Geothermal wellbore heat transmission: Stabilization times for "static" and "transient" wellbore temperature profiles

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ABSTRACT

In this work we review the geothermal wellbore heat transmission, particularly the static and transient temperature profiles obtained in production and injection wells. We discuss the fundamental methods and approximations to describe the wellbore heat transmission and compare the results of various approaches in the literature. The objective of this work is to discuss the theory behind the wellbore heat transmission and then further investigate the effect of time on heat transmission. Moreover a new term called the stabilization time is introduced to describe and assess how "static" and "transient" are the static and transient temperature profiles, respectively.

Our purpose here is to present acceptable methods and approaches adequate for engineering considerations. The emphasis is given to the effect of time on wellbore heat transmission. Thus, we wish to find approximate values of the stabilization time which will provide engineering accuracy.

Computed results expressed as simple algebraic expressions and in graphical form and relevant comments are presented to establish the usefulness of approaches provided.

1. Introduction

Static and transient temperature profiles taken along geothermal wells provide very useful information regarding the fluid and petrophysical properties of the reservoir. For example, transient temperature profiles could help identify different zones of water entry (at different temperatures) into the well. Or they could provide insight into how much heat is lost to the surroundings of the well as the fluid is moving in the well. Static profiles on the other hand could be used to identify the top and bottom of the reservoir. In fact multiple entry points may be determined from the static and transient profiles.

When interpreting either the static or transient temperature profiles along the wells, two points are very crucial to consider. The first is that a mathematical model which properly describes the physics of the phenomenon must exist so that various fluid and/or petrophysical properties can be inferred. The second is that during the measurements actual static or transient conditions should be indicated. Failing to do so could result in a mischaracterization of the system. For example after some time of production, if the well is shut in so that a static temperature profile is to be obtained, the well needs to be kept shut for a certain amount of time so that actual static conditions are obtained. Failing to wait for such an amount of time, actual static temperature profiles will not have been reached. The necessary time required to reach stabilized conditions can be assessed through the use of an appropriate mathematical model.

The necessary times required to reach the actual stabilized temperature behavior will be referred to as the stabilization time. The stabilization time is considered for three cases in this study; the stabilization time for reaching transient temperature profiles for a production period, the stabilization time for reaching the transient temperature profiles for an injection period and the stabilization time for the static temperature profiles after a production period. A mathematical model is developed in this study for the above mentioned three periods. The equations derived in this study for the stabilization times serve as an original contribution to the literature.

Before describing the analytical equations for the stabilization times for the different periods, it is crucial to provide some background information regarding the wellbore heat transmission problem. Hence, the following chapter provides a review of the literature regarding the wellbore temperature distribution solutions. In Section 3, the equations for determining the stabilization times are given along with sample applications. Finally conclusions are provided.

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Nomenclature

C	Specific heat capacity of the fluid, J/(kg °C)
k	Thermal conductivity of the formation, J/(ms °C)
L	Total depth of a well, m
Q	Total heat flow rate from a well, J/s
q	Heat flow rate per unit length, J/(s m)
r	Radial distance, m
T	Temperature, °C
t	Time, s
u	Velocity of the fluid in the wellbore, m/s
w	Mass flow rate, kg/s
y	Distance upwards from the bottom of the well, m
z	Distance downward from the top of the well, m
α	Geothermal gradient of the earth, °C/m
β	Polinomial constant, °C/m^2
γ	Euler's constant, 0.57722
κ	Thermal diffusivity of the formation, J/(s °C)
Subscripts	
bh	Bottomhole
D	Dimensionless
e	Earth
if	Inflowing fluid
inj	Injection
p	Production
sh	Shut-in
s	Stabilization
surf	Surface
w	Well
wh	Wellhead

2. Review of wellbore temperature distribution solutions

Generally speaking, methods and models describing the wellbore heat transmission are based on a wellbore heat balance with some assumptions. The most critical assumptions refer to the boundary condition between the wellbore and the surrounding formation. Either a constant heat flux or a constant temperature assumption is used for this purpose. In the case of the general wellbore heat problem, neither heat flux nor the temperature at the wellbore remains constant except in special cases. However, the solutions for the constant flux and constant temperature eventually converge at long times.

Most of the literature on wellbore heat transmission is based on the classical work by Ramey (1962). He derived the temperature distribution in a well used for injecting hot fluid. Ramey (1964) expanded on this to estimate the rate of heat loss from the well to the formation. Horne and Shinohara (1979) reexamined the problem to determine the wellbore heat loss in production and injection wells. Hasan and Kabir (1994) analyzed wellbore heat transfer during two-phase flow. Hagoort (2004) assessed Ramey's classical method for the calculation of temperatures in injection and production wells and showed that Ramey's method is an excellent approximation.

Carslaw and Jaeger (1959) present graphical and analytical solutions for the cases of internal cylindrical sources losing heat at constant flux, constant temperature and the radiation boundary conditions. Solutions converge at long times. This is a sufficiently long time at which temperature is controlled by formation conditions.

For small values of time heat flow in the wellbore is controlled by convection, rather than conduction. Ramey recommends using the constant-temperature cylindrical-source solution if thermal resistance in the wellbore is negligible which is the case when the fluid flow occurs through casing only.

Our study considers only single-phase fluids flowing in the well. The single-phase flow analysis is based on the determination of the fluid temperature as a function of depth and time. Our study deals with the treatment of heat transmission between the fluid in the wellbore and the formation. It is assumed that heat flow in the formation is conductive. For simplicity, we assume a geothermal well with single-phase liquid flowing in a casing without tubing, however it is not difficult to derive the equations and give the expressions for fluid flow within tubing. For most practical purposes, heat transmission between the formation and the fluid may be treated using a constant overall heat transfer coefficient (Garg et al., 2004).

Ramey's solutions for temperature are obtained in terms of depth. However the effects of varying formation temperature as a function of depth in terms of geothermal temperature gradient as well as heat transfer to the surrounding formation by transient conduction are considered in those solutions.

The equation for the evaluation of the temperature in a producing geothermal well is given in Eq. (1) (Ramey et al., 1981):

$$T = T(y) = (T_{bh} - \alpha y) + \alpha A\left(1 - e^{-\frac{y}{A}}\right) + \left(T_{if} - T_{bh}\right) e^{-\frac{y}{A}} \quad (1)$$

where y is the distance upwards from the bottom of the well, T_{bh} is the downhole reservoir temperature, (T_{bh}-αy) is the temperature of the earth (T_e) assuming linear geothermal gradient, α is the geothermal gradient (the increase of formation temperature with increase in depth), and T_{if} is the inflowing fluid temperature. If T_{if} equals T_{bh} then Eq. (1) reduces to Eq. (2):

$$T = (T_{bh} - \alpha y) + \alpha A\left(1 - e^{-\frac{y}{A}}\right) \quad (2)$$

If the geothermal gradient is not constant; that is, temperature does not increase linearly with depth, then the formation temperature/depth profile may be broken into a number of linear segments and the equations applied successively to each segment. If the earth temperature changes according to the following polynomial fit:

$$T_e = T_{bh} - \alpha y - \beta y^2 \quad (3)$$

then the temperature profile in a producing well becomes:

$$T = \left(T_{bh} - \alpha y + \alpha A - \beta y^2 + 2\beta y A - 2\beta A^2\right) + \left(-\alpha A + 2\beta A^2\right) e^{-\frac{y}{A}} \quad (4)$$

In Eq's (1)–(4) A is a group of variables defined in Eq. (5):

$$A = \frac{wCf(t)}{2\pi k} \quad (5)$$

where w is the mass flow rate, C is the thermal heat capacity (specific heat) of the fluid (assumed constant), k is the thermal conductivity of the formation (earth), and $f(t)$ is a dimensionless time function representing the transient heat transfer to the formation.

The function $f(t)$ may be found from Ramey (1962, 1964) and Ramey et al. (1981), or alternatively may be approximated from the line source solution for large flowing times by the equation:

$$f(t) \approx -\ln\left(\frac{r_w}{2\sqrt{\kappa t}}\right) - 0.29 \quad (6)$$

where κ is the thermal diffusivity of the formation and r_w is the radius of the casing. The function $f(t)$ is discussed in detail later.

Heat transfer from the casing to the formation in terms of heat flow rate per unit of length is given by:

$$q = \frac{2\pi k}{f(t)}(T - T_e) \quad (7)$$