International Journal of Thermal Sciences 130 (2018) 457–470

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Temperature transient analysis for bounded oil reservoir under depletion drive

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ARTICLE INFO

Keywords:
Reservoir characterization
Temperature transient analysis
Boundary dominated flow
Analytical solution

ABSTRACT

The significant pressure and temperature signals at wellbores associated with hydrocarbon production can be very useful for reservoir characterization and production analysis purposes. Temperature transient analysis is emerging partly due to the advancement of the downhole temperature monitoring system. Among different flow regimes encountered during the production of a vertical well, the long-lasting boundary dominated flow is crucial since most oil in conventional reservoirs are recovered during this period. The production induced temperature response behaves transient for boundary dominated pressure response and can be analyzed for reservoir property estimation. In this work, we derive a novel temperature transient analytical solution to model sandface temperature signal under boundary dominated flow. Our approach to obtaining the analytical solution from the governing energy balance equation uses Laplace transform with the input of pseudo-steady state pressure equation. This solution can be integrated with previous temperature transient analytical solutions to model the temperature signal from a depletion drived production well. The temperature modeling results acquired from this analytical solution are validated against those from numerical simulation in multiple cases and present distinct behavior under boundary dominated flow. Compared to the heating Joule-Thomson effect in the transient period near the production well, a cooling effect is observed throughout the reservoir after pressure transient reaches the reservoir outer boundary. The magnitude of this cooling effect is proportional to production time. This finding shows the potential of using temperature data at observation wells away from the production well during boundary dominated flow. Further parametric analyses are conducted on eight reservoir, production, and fluid properties to investigate their impacts on the temperature modeling results. These parameters are categorized based on their sensitivities on periods of transient and boundary dominated flow, in which total compressibility and production drainage area are sensitive to the temperature signals under boundary dominated flow only. Unlike the drawdown test, we find that the buildup temperature behavior under boundary dominated flow is identical to that during the transient period. After presenting the forward temperature modeling results, we extend existing reservoir characterization procedures to incorporate the boundary dominated flow. Drainage area and the distance to the closest boundary from the production well can be estimated from the measured temperature data acquired at both production and observation wells. Decent accuracies of the estimations are achieved for the examples presented in this work. The effects of thermal conduction and heat loss may not introduce significant errors in both forward and inverse thermal modeling for the long-lasting boundary dominated flow period.

The temperature transient analytical solution under radial boundary dominated flow introduced in this paper considerably extends the scope for temperature transient analysis. This solution enables observation well temperature transient analysis, which seems promising for field application during the boundary dominated flow period. The analytical solution presented herein helps to advance the temperature transient analysis over the whole well production period and forms a basis for future studies on variable rate temperature transient analysis (rate-temperature transient analysis).

1. Introduction

Temperature monitoring has been an essential part of production logging analysis since 1920's [1]. For reservoir characterization purposes, temperature measurements are not as prevailing as pressure since the main approach for temperature monitoring is through well

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https://doi.org/10.1016/j.ijthermalsci.2018.05.011
Received 21 December 2017; Received in revised form 6 April 2018; Accepted 7 May 2018

logging [2]. Recently, other approaches to monitoring temperature signals during production became viable, including but not limited to permanent downhole gauges: fiber-optic distributed temperature sensors (DTS) [3], and Fiber Bragg Grating (FBG) real-time system [4]. These evolving technologies are cost-effective, with relatively high resolution (as high as 0.01 degC [5]), and profiling the temperature signals both temporally and spatially (DTS and FBG). Meanwhile, the flexibility of DTS and FBG allows their implementations embedded in the cement to minimize the wellbore thermal effects [6,7]. Therefore, reservoir characterization through temperature modeling, referred to as temperature transient analysis (TTA), presents great potential to achieve similar functions as well-established pressure transient analysis (PTA). In addition to its potential for reservoir characterization, temperature monitoring can be beneficial for other applications such as monitoring the injected CO_2 and estimating leakage in CO_2 geological storage projects [8–10]. This work focuses on extending the scope of TTA by incorporating boundary dominated flow (BDF).

Accurate temperature modeling and inversion is vital to estimate reservoir properties from temperature transient data. For complex systems, numerical simulations may be required [11–17]. However, the inversion process based on numerical simulation can be time-consuming and imprecise. To attain prompt temperature inversion and develop the physical understanding of production induced temperature, analytical modeling of TTA has been pursued lately. The analytical temperature modeling mainly focused on the solutions from energy balance equation associated with hydrocarbon production from a vertical fully-penetrating production well [18–21]. Many aspects and applications were considered including build-up temperature modeling [22], the effects of fluid property variations [23] and heat loss to surroundings [24], production of compressible fluid (dry gas) [25], and multilayer reservoirs [26]. However, the full potential of TTA has yet to be realized, and very little is revealed about temperature transient behaviors under BDF. In field cases, pressure transient period is relatively short compared to the BDF period due to limited reservoir boundary and/or restricted drainage area considering surrounding infill wells.

Investigating BDF has been an important aspect of PTA since 1960's [27]. One major application of BDF is to estimate the original oil/gas in place through rate decline analysis [28–32]. If the BDF is in radial flow regime, most of the hydrocarbon is recovered during this period compared to the preceding transient period [33]. Therefore, in this study, we incorporate the radial BDF into the evolving temperature transient analysis, as an emerging reservoir characterization and production analysis technique.

Based on current research state and potential applications, this paper is organized as follows. We first derive an analytical solution for TTA under BDF. This solution is integrated with an existing transient temperature solution under pressure transient period to form an extended temperature transient analytical solution. Next, we validate this analytical solution by comparing the temperature modeling with numerical simulation results. After the verification, parametric analyses are performed on eight reservoir, production, and fluid properties as well as different reservoir shapes to investigate their impacts on the temperature signal. TTA is then extended to explore its potential at observation wells under BDF. Finally, the thermal inversion procedures based on this solution are applied to synthetic temperature measurements at the production and observation wells to estimate the drainage area and reservoir shape. Build-up temperature modeling under BDF and effects of thermal conduction and heat loss to surroundings are also discussed.

2. Problem description and methodology

In this section, we derive an analytical solution to model the transient temperature signal under radial boundary dominated pressure response. The physical model for this solution contains a fully penetrating production well in a single layer and closed boundary reservoir,

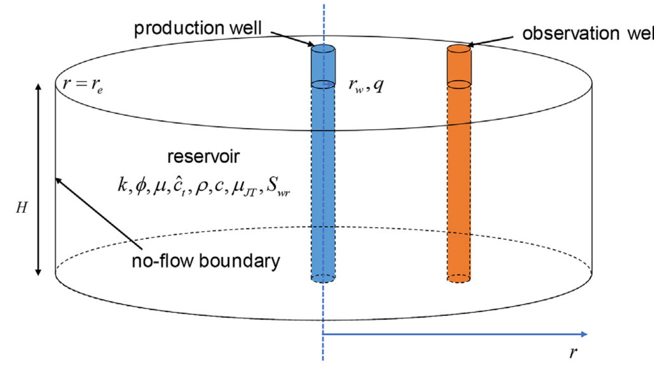

Fig. 1. A schematic of the model description.

where the flow regime is radial before BDF prevails. Also, an observation well is located away from the production well. The reservoir shape is not limited to cylindrical. Temperature modeling results from cubic reservoirs with various ratio of length to width are presented in the results section (§3.1). A model schematic is illustrated in Fig. 1.

The governing equation and boundary conditions to derive this analytical solution are similar to the existing analytical solutions for TTA. In this paper, we apply the single phase energy blance quation in 1D cylindrical porous media provided in Duru and Horne [15], in which their physical implications are extensively discussed:

$$[\phi\rho_f c_f + (1-\phi)\rho_s c_s]\frac{\partial T}{\partial t} + \frac{q\rho_f c_f}{2\pi rH}\frac{\partial T}{\partial r} = \frac{[\phi\lambda_f + (1-\phi)\lambda_s]}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{q\beta T}{2\pi rH}\frac{\partial p}{\partial r} - \frac{q}{2\pi rH}\frac{\partial p}{\partial r} + \phi\beta T\frac{\partial p}{\partial t} + v\rho g \tag{1}$$

Eq. (1) is identical to the governing equations used in Onur and Cinar [22], and the energy balance equation in terms of enthalpy presented by App [34]. This equation can be derived from the fluid and rock energy balance equation [35] with volumetric averaging. Details including Assumptions to develop Eq. (1) are extensively discussed in App [34].

In this work, we assume the conduction and heat loss to surrounding layers can be neglected, the justification of which will be examined in §4.1. Since the reservoir is not tilted as presented in Fig. 1, the gravitational effect can also be ignored. Therefore, the first and last terms on the right hand side (RHS) of Eq. (1) are neglected. Introducing the definition of Joule-Thomson (JT) coefficient (μ_{JT}) from thermal expansion coefficient (β) and the connate water in the fluid system, Eq. (1) reduces to Eq. (2) which was first presented by Chekalyuk [21]:

$$\{\phi[\rho_w c_w S_{wr} + \rho_f c_f(1-S_{wr})] + (1-\phi)\rho_s c_s\}\frac{\partial T}{\partial t} = \frac{q\rho_f c_f}{2\pi rH}\left[\frac{\partial T}{\partial r} - \mu_{JT}\frac{\partial p}{\partial r}\right] + \phi(\rho_f c_f\mu_{JT} + 1)\frac{\partial p}{\partial t} \tag{2}$$

The initial and boundary conditions for TTA under BDF are:

$$T = T_i - \frac{\mu_{JT}\mu q C_1(\ln 2 - \ln C_2)}{2\pi Hk_r k} - \frac{\mu_{JT}\mu q}{4\pi Hk_r k}\ln\left[1 + \frac{2C_2 kk_r t_{pss}}{r^2\phi\mu\hat{c}_t}\right], r \geq r_w, t = 0 \tag{3}$$

$$\frac{\partial T}{\partial t} \doteq T_i + \frac{\phi(\rho_f c_f\mu_{JT} + 1)}{\phi[\rho_w c_w S_{wr} + \rho_f c_f(1-S_{wr})] + (1-\phi)\rho_s c_s}\frac{\partial p}{\partial t}, r = r_e, t > 0 \tag{4}$$

where:

$$C_1 = \frac{\phi(\rho_f c_f\mu_{JT} + 1)}{2\mu_{JT}\{\phi[\rho_w c_w S_{wr} + \rho_f c_f(1-S_{wr})] + (1-\phi)\rho_s c_s\}} \tag{5}$$