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# Steam injection for heavy oil recovery: Modelling of wellbore heat efficiency and analysis of steam injection performance

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ABSTRACT

The aims of this work are to present a comprehensive mathematical model for estimating wellbore heat efficiency and to analyze performance of steam injection for heavy oil recovery. In this paper, we firstly introduce steam injection process briefly. Secondly, a simplified approach of predicting steam pressure in wellbores is presented and a complete expression for steam quality is derived. More importantly, both direct and indirect methods are adopted to determine the wellbore heat efficiency. Then, the mathematical model is solved using an iterative technique. After the model is validated with measured field data, we study the effects of wellhead injection rate and wellhead steam quality on steam injection performance reflected in wellbores. Next, taking cyclic steam stimulation as an example, we analyze steam injection performance reflected in reservoirs with numerical reservoir simulation method. Finally, the significant role of improving wellbore heat efficiency in saving water and fuels is discussed in detail. The results indicate that we can improve the wellbore heat efficiency by enhancing wellhead injection rate or steam quality. However, high wellbore heat efficiency does not necessarily mean satisfactory steam injection performance reflected in reservoirs or good performance of heavy oil recovery. Moreover, the paper shows that using excellent insulation materials is a good way to save water and fuels due to enhancement of wellbore heat efficiency.



## 1. Introduction

Heavy oil, one of the most important petroleum resources, is widely distributed in many countries, especially in Canada, Venezuela, USA, China, and so on [1–3]. However, it is not always easy to recover high-viscosity oil economically and efficiently. Firstly, the commonly-used thermal recovery methods, such as CSS (cyclic steam stimulation), steamflooding and SAGD (steam-assisted gravity drainage) [4,5], are put into use at the cost of consuming lots of water and fuels. In addition, the above thermal-based techniques all involve steam injection, which, however, is a complex process. Moreover, poor performance of steam injection has direct and negative effects on that of heavy oil recovery. Usually, bad steam injection performance reflects in at least two aspects. On one hand, it reflects in wellbores. For example, in Liaohe Oilfield, northeast of China, the bottomhole steam qualities and wellbore heat efficiencies of many steam injection wells are very low, especially for deep wells. The immediate cause is that as high-temperature steam flows along the wellbore, much heat carried by steam/water mixture is lost from the fluid to surrounding formation on account of temperature difference [6–8]. It should be stressed that low bottomhole steam quality and wellbore heat efficiency can cause many other problems, mainly including: (1). Unsatisfactory performance of heavy oil recovery. (2). High production cost. (3). More water consumption. (4). More environmental pollutants due to more consumption of fuels, such as coal, natural gas or residual oil. On the other hand, poor steam injection performance also reflects in reservoirs. For instance, in CSS, the heated area or the radius of heated zone is small [9–11], and the viscosity of heavy oil still cannot be lowered effectively and extensively, although much steam is injected into the reservoir along the wellbore. The reasons are various, such as too high initial oil viscosity, excessive overburden heat loss [12], much water stored in the neighborhoods of steam injection wells [13], unreasonable time interval for soaking, and so on.

The wellbore heat efficiency can be estimated based on accurate prediction of profiles of steam pressure, temperature, quality and wellbore heat loss rate. The four parameters depend on each other and the steam pressure has an obvious effect on the predicted results of other three parameters. Therefore, accurately predicting steam pressure distribution in wellbores is of great significance to

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**Nomenclature**

| | |
|---|---|
| $a$ | geothermal gradient (K/m) |
| $C_1$ | the Euler's constant $C_1 = 0.5772$ |
| $C_{Jm}$ | Joule–Thomson coefficient of mixture fluid (K/Pa) |
| $C_{pL}$ | heat capacity of liquid water at constant pressure (J/(kg K)) |
| $C_{pm}$ | heat capacity of mixture fluid at constant pressure (J/(kg K)) |
| $dQ/dz$ | wellbore heat loss or rate of heat flow from fluid to the surrounding formation (W/m) |
| $D$ | total depth of the wellbore (m) |
| $f$ | friction factor, dimensionless |
| $f(t)$ | transient heat-conduction time function, dimensionless |
| $g$ | gravitational acceleration (m/s$^2$) |
| $h_c$ | convective heat transfer coefficient (W/(m$^2$ K)) |
| $h_f$ | forced-convection heat transfer coefficient on inside of inner tubing (W/(m$^2$ K)) |
| $h_L$ | specific enthalpy of liquid water (J/kg) |
| $h_m$ | specific enthalpy of mixture fluid (J/kg) |
| $h_r$ | radiative heat transfer coefficient, W/(m$^2$ K) |
| $h_s$ | specific enthalpy of dry steam (J/kg) |
| $h_w$ | specific enthalpy of saturated water (J/kg) |
| $i$ | $i$th segment, dimensionless |
| $J_0$ | first kind Bessel functions of zero order |
| $J_1$ | first kind Bessel functions of first order |
| $L_v$ | latent heat of vaporization of steam (J/kg) |
| $m$ | number of segment, dimensionless |
| $p$ | pressure (Pa) |
| $\bar{p}$ | average fluid pressure (Pa) |
| $p_{inj}$ | wellhead injection pressure (Pa) |
| $\Delta p$ | pressure drop (Pa) |
| $q_g$ | in-situ volumetric flow rate of gas phase (m$^3$/s) |
| $q_L$ | in-situ volumetric flow rate of liquid phase (m$^3$/s) |
| $Q_t$ | total wellbore heat loss (J) |
| $r_{ci}$ | inside radius of casing (m) |
| $r_{co}$ | outside radius of casing (m) |
| $r_{di}$ | inside radius of outer tubing (m) |
| $r_{do}$ | outside radius of outer tubing (m) |
| $r_h$ | radius of drill hole (m) |
| $r_{ti}$ | inside radius of inner tubing (m) |
| $r_{to}$ | outside radius of inner tubing (m) |
| $t$ | injection time (s) |
| $T$ | temperature (K) |
| $\bar{T}$ | average fluid temperature (K) |
| $T_0$ | surface temperature of the formation (K) |
| $T_{ei}$ | initial temperature of the formation (K) |
| $T_h$ | cement/formation interface temperature (K) |
| $T_{inj}$ | temperature of injected fluid (K) |
| $\Delta T$ | temperature drop (K) |
| $u$ | dummy variable for integration, dimensionless |
| $U_{to}$ | over-all heat transfer coefficient between fluid and cement/formation interface (W/(m$^2$ K)) |
| $v_L$ | velocity of liquid water (m/s) |
| $v_m$ | velocity of mixture fluid (m/s) |
| $v_{sg}$ | superficial gas velocity (m/s) |
| $v_{sL}$ | superficial liquid velocity (m/s) |
| $w_t$ | mass flow rate or wellhead steam injection rate (kg/s) |
| $x$ | steam quality (dimensionless) |
| $x_0$ | wellhead steam quality (dimensionless) |
| $x_D$ | bottomhole steam quality (dimensionless) |
| $\Delta x$ | steam quality drop (dimensionless) |
| $y$ | dependent variables |
| $Y_0$ | the second kind Bessel functions of zero order |
| $Y_1$ | the second kind Bessel functions of first order |
| $z$ | variable well depth from surface, m |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity of the formation (m$^2$/h) |
| $\eta$ | wellbore heat efficiency (dimensionless) |
| $\theta$ | well angle from horizontal |
| $\lambda_{cas}$ | thermal conductivity of casing (W/(m K)) |
| $\lambda_{cem}$ | thermal conductivity of cement sheath (W/(m K)) |
| $\lambda_e$ | thermal conductivity of formation (W/(m K)) |
| $\lambda_{ins}$ | thermal conductivity of insulation materials (W/(m K)) |
| $\lambda_{tub}$ | thermal conductivity of tubing wall (W/(m K)) |
| $\rho_L$ | density of liquid water (kg/m$^3$) |
| $\rho_m$ | density of mixture fluid (kg/m$^3$) |
| $\rho_s$ | density of steam (kg/m$^3$) |
| $\tau_D$ | dimensionless time |
| $\omega$ | ratio of the formation heat capacity to the wellbore heat capacity, dimensionless |

the estimation of wellbore heat efficiency. However, it is found that previous classic methods [14–16] for calculating pressure drop of gas/liquid flow in pipes are a little complicated. Because before we can successfully use these methods, we firstly must be able to precisely divide flow patterns and determine transition criteria based on a large number of experiments, which, however, are not easy to achieve. Moreover, many main flow parameters for each flow pattern are controlled by complex governing equations, and solving these equations is always difficult and time-consuming.

The objectives of this work are to present a comprehensive mathematical model for estimating the wellbore heat efficiency and to analyze the steam injection performance reflected both in wellbores and in reservoirs. In this article, we firstly introduce steam injection process briefly. Secondly, a simplified approach of predicting steam pressure distribution in wellbores is presented and a complete expression for steam quality is derived. Moreover, both direct and indirect methods are adopted to determine the wellbore heat efficiency. Then, the mathematical model is solved using an iterative technique. After the model is validated with measured field data, we study the effects of wellhead injection rate and wellhead steam quality on steam injection performance reflected in wellbores. Next, taking CSS as an example, we analyze steam injection performance reflected in reservoirs with numerical reservoir simulation method. Finally, the significant role of improving wellbore heat efficiency in saving water and fuels is discussed in detail.

## 2. Steam injection process

The viscosity of heavy oil (between 10° and 20° API) can range up to ten thousands of cP under initial reservoir conditions [17]. Consequently, it would be difficult and uneconomic to produce heavy oil if we do not take some measures to lower the oil viscosity or to improve the oil mobility. Since one of the most important properties of heavy oil is that its viscosity drops rapidly with temperature, we often recover heavy oil reservoirs by raising the reservoir temperature. And at present, there are two ways to achieve this goal. The first one is injecting heat from surface into pay zones, namely, injecting hot fluid, such as hot water, wet steam, superheated steam, multi-thermal fluids, and so on [1,18]. The other one is generating heat within the reservoirs, such as