Journal of Petroleum Science and Engineering 166 (2018) 842–849

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Energy efficiency and greenhouse gas emissions of current steam injection process and promising steam based techniques for heavy oil reservoirs

Yanyong Wang[a,**], Shaoran Ren[a,*], Liang Zhang[a], Changhao Hu[b]

[a] School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, Shandong, 266580, People's Republic of China
[b] Research Institute of Petroleum Exploration and Development, PetroChina Liaohe Oilfield Company, Panjin, Liaoning, 124000, People's Republic of China

ARTICLE INFO

Keywords:
Heavy oil
Steam injection process
Greenhouse gas emissions
Energy efficiency

ABSTRACT

Steam injection process has been the prevailing technique for heavy oil and bitumen extraction in the past decades, but the recovery performance and energy efficiency are poor, especially in oil reservoirs with harsh conditions and severe heterogeneity. With global requirements on energy conservation and emission reduction, it is of great significance to improve current techniques or find new techniques to promote the energy efficiency of steam injection process and mitigate associated greenhouse gas emissions. In this study, the energy efficiency and CO_2 emissions of current steam injection processes were evaluated, along with sensitivity analysis of various influencing factors. Cyclic steam stimulation (CSS) process was taken as an example to study the production and energy efficiency performance of steam injection. The results show that the steam to oil ratio, energy intensity and CO_2 emissions all rise with the increasing crude oil viscosity, but fall with the increase of oil saturation, reservoir temperature, bottom hole steam quality and reservoir heat efficiency. Field history analysis about CSS process shows that the production performance of CSS process was dominated by different factors with the proceeding of oil production, and gas injection assisted CSS process can effectively enhance oil recovery, improve energy efficiency and mitigate CO_2 emissions. Finally, the improved steam injection techniques are discussed to shed some lights on the efficient exploitation of heavy oil reservoirs.

1. Introduction

As the reserves of conventional light oil become depleted and more difficult to find, heavy oil and bitumen resources have attained much interests from oil industry in recent years, due to their wide distribution and abundant reserves (Xu et al., 2001). The exploitation methods for heavy oil and bitumen can be classified into surface mining (for oil sands) and in situ recovery process, such as cold production techniques (Istchenko and Gates, 2014) and thermal recovery methods (Al Adasani and Bai, 2011; Dutt and Mandal, 2012; Shah et al., 2010). The poor mobility of heavy oil and bitumen at original reservoir conditions is the greatest challenge for their exploitation, but oil viscosity is very sensitive to temperature, which can be reduced by several orders of magnitudes if the reservoir temperature is raised to 200 °C or even higher (Gates and Larter, 2014). Therefore, thermal recovery methods, including steam injection process, in situ combustion (ISC) and electrical heating based techniques, have been widely investigated and/or employed in the past several decades. Technically, steam injection process can be considered as one of the most prevailing techniques in field application due to the high heat content, availability and moderate cost of steam. At present, the steam injection process widely adopted on the site includes cyclic steam stimulation (CSS, or the so-called steam huff-*n*-puff), steam flooding and steam assisted gravity drainage (SAGD) (Nasr and Ayodele, 2005; Zhou et al., 2015, 2016). However, it usually consumes a large quantity of energy for each barrel of heavy oil produced, and requires great amounts of water and fossil fuels (e.g., natural gas, coal, crude oil and agricultural residue) for steam generation, which can lead to expensive produced water treatment and considerable greenhouse gas emissions. With global requirements on energy conservation and emission reduction, it is reasonable and necessary to evaluate the performance of current steam injection processes (or thermal recovery techniques) using different criteria, including oil recovery, energy efficiency and greenhouse gas emissions (Yang and Gates, 2009). In addition, at the low oil price scenario, it is also practically significant to improve current steam injection processes or apply new techniques which can not only enhance heavy oil recovery, but also be less energy intensive and more environmentally friendly.

In this study, the energy efficiency and greenhouse gas emissions of current steam injection process were quantified and evaluated using an improved model, with sensitivity analysis of different factors, including

* Corresponding author.
** Corresponding author.
E-mail addresses: wangyy@s.upc.edu.cn (Y. Wang), rensr@upc.edu.cn (S. Ren).

https://doi.org/10.1016/j.petrol.2018.03.094
Received 25 November 2017; Received in revised form 4 March 2018; Accepted 27 March 2018
Available online 28 March 2018
0920-4105/

Nomenclature

Acronyms

CER	cumulative energy requirements
cSOR	cumulative steam to oil ratio
CSS	cyclic steam stimulation
ER	energy return
ERR	energy return ratio
ISC	in situ combustion
LHV	lower heating value
OOIP	original oil in place
SAGD	steam assisted gravity drainage
SOR	steam to oil ratio
tCOR	theoretical carbon dioxide to oil ratio
tEOR	theoretical energy to oil ratio
tSOR	theoretical steam to oil ratio

Symbols

C_{ng}	carbon intensity of natural gas, kg of CO_2/GJ LHV
c_{po}	specific heat capacity of oil phase, kJ/(kg °C)
c_{pr}	specific heat capacity of rock, kJ/(kg °C)
c_{pw}	specific heat capacity of water phase, kJ/(kg °C)
E_{elec}	electric energy consumed per unit heavy oil produced, GJ/m^3
H_{fw}	specific enthalpy of feed water, kJ/kg
H_l	specific enthalpy of liquid phase, kJ/kg
H_o	energy intensity of heavy oil, MJ/kg
$H_{s,bh}$	specific enthalpy of steam at bottom hole, kJ/kg
$H_{s,sg}$	specific enthalpy of steam at the outlet of steam generator, kJ/kg
$H_{s,x}$	specific enthalpy of steam, kJ/kg
$H_{w,r}$	specific enthalpy of hot water in reservoir, kJ/kg
H_v	specific enthalpy of vapor phase, kJ/kg
Q_{bulk}	energy required to heat a bulk volume of oil formation, kJ
Q_{unit}	energy required to heat a unit volume of heavy oil, kJ/m^3
S_o	oil saturation, fraction
S_{or}	residual oil saturation, fraction
S_w	water saturation, fraction
T_e	effective flow temperature of heavy oil, °C
T_r	original reservoir temperature, °C
V_{bulk}	bulk volume of oil formation, m^3
v_s	specific volume of water, m^3/kg
x	steam quality, fraction

Greek letters

ϕ	formation porosity, fraction
η_{er}	reservoir heat efficiency, fraction
η_{sg}	thermal efficiency of steam generator, fraction
ρ_o	oil density, kg/m^3
ρ_r	rock density, kg/m^3
ρ_w	water density, kg/m^3

crude oil viscosity, reservoir properties and operation conditions. Field case analysis in terms of CSS process was taken as an example to study the production and energy efficiency performance of steam injection. In addition, promising steam based methods for the development of heavy oil resources were discussed. The results of this study are expected to provide some insights into the efficient exploitation of heavy oil reservoirs.

2. Mathematical models

2.1. Specific enthalpy of steam

Steam with high temperature high pressure is the most effective heat exchange medium due to its high sensible and latent heat. The specific enthalpy of steam can be evaluated as a function of temperature and quality,

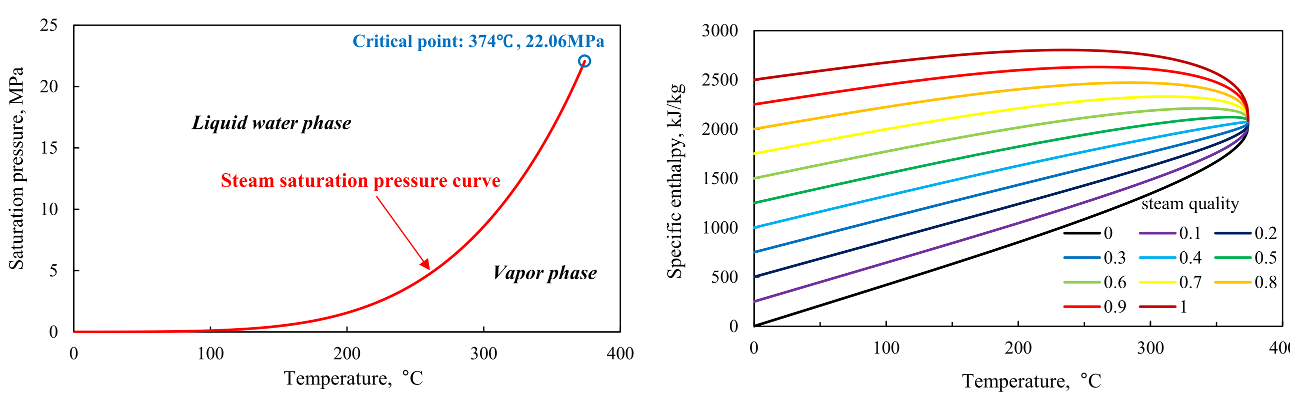
$$H_{s,x} = (1 - x)H_l + xH_v \tag{1}$$

where $H_{s,x}$ is the specific enthalpy of steam, kJ/kg, H_l and H_v are the respective specific enthalpy for liquid and vapor phase, kJ/kg, and x is the steam quality, fraction.

The steam saturation pressure curve and its specific enthalpies at different temperatures and qualities are presented in Fig. 1. The thermophysical data used in the calculation were obtained from the NIST (National Institutes of Standards and Technology) Chemistry WebBook, SRD 69. We can clearly see that the specific enthalpy of steam below 374 °C can be significantly increased via elevating its quality.

2.2. Energy intensity of steam injection process

On account of the poor mobility of heavy oil at original reservoir conditions, especially for extra or ultra heavy oils, the natural productivity of heavy oil reservoir will be low. In steam injection process, the oil viscosity in steam swept region can be effectively reduced by the heating of steam, and thus the oil mobility will be improved significantly. The theoretical amount of energy required to heat a certain



(a) (b)

Fig. 1. Saturation pressure of steam and its specific enthalpy. (a) Steam saturation pressure curve. (b) Specific enthalpy of saturated steam at different qualities.