Applied Energy 183 (2016) 837–852

Contents lists available at ScienceDirect

Applied Energy

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

Geothermal exploitation from depleted high temperature gas reservoirs via recycling supercritical CO_2: Heat mining rate and salt precipitation effects

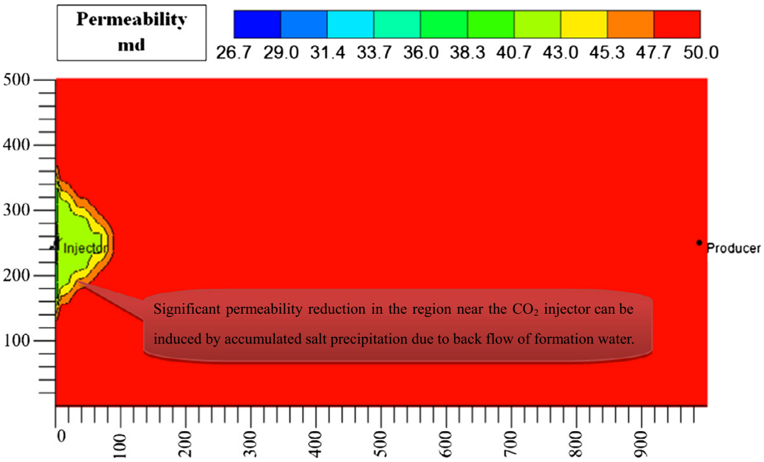
Guodong Cui [a], Liang Zhang [a], Bo Ren [b], Chioma Enechukwu [a], Yanmin Liu [a], Shaoran Ren [a,*]

[a] College of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China
[b] Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX 78712, USA

HIGHLIGHTS

- Depleted high temperature gas reservoirs have high geothermal potential.
- Geothermal recovery via CO_2 injection can improve heat mining rate.
- Salt precipitation induced by CO_2 flow can cause reservoir damage.
- Back flow of water can cause an accumulated salt precipitation near injector.
- Injection of low salinity water can effectively reduce reservoir damage.

GRAPHICAL ABSTRACT



Significant permeability reduction in the region near the CO_2 injector can be induced by accumulated salt precipitation due to back flow of formation water.

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 8 September 2016
Accepted 10 September 2016

Keywords:
Depleted gas reservoir
Supercritical CO_2
Geothermal exploitation
Water evaporation and salt precipitation
Back flow of formation water

ABSTRACT

The geothermal energy in depleted high temperature gas reservoirs can be developed using existing wells and surface facilities via recycling water or supercritical CO_2 after natural gas production. For a typical medium-size gas field, the recoverable geothermal energy can be equivalent to over 10 million tons of standard coal. The injection of CO_2 can improve the heat mining rate, and it can also enhance gas recovery at the early stage of the process and achieve geological storage of CO_2. However, a big concern in the injection of CO_2 is the salt precipitation induced by the interactions between the injected CO_2 and the formation water, which might cause reservoir damage and subsequently affect the flow behavior and the heat mining rate. In this paper, a comprehensive model of geothermal exploitation from gas reservoirs via CO_2 injection was established, in which the processes of formation water evaporation, salt dissolution and precipitation, and their effects on formation porosity and permeability were incorporated. The influences of various parameters on geothermal recovery and salt precipitation were investigated by using this model, including the saturation and salinity of formation waters, injection-production pressure difference, and the permeability and porosity of the gas reservoirs. The results show that, for the gas reservoir studied at a temperature of 130 °C (i.e. with a volume of 1000 m × 500 m × 50 m), the heat mining rate of one injector-producer pair can be maintained at about 5 MW with a CO_2 recycling rate of 3000 t/day for 30 years. The effect of salt precipitation is moderate, and it is dependent on the reservoir

---

* Corresponding author.
E-mail address: rensr@upc.edu.cn (S. Ren).

http://dx.doi.org/10.1016/j.apenergy.2016.09.029

Nomenclature

Symbols

c_{NaCl}	the apparent quantity of NaCl (in water phase) in unit pore volume, mol/m^3
C_s	the concentration of precipitated salt in unit pore volume, mol/m^3
$C_s{}^0$	the initial concentration of precipitated salt in unit pore volume, mol/m^3
C_{salt}	the theoretical quantity of the precipitated salt per unit pore volume when water has been completely evaporated, mol/m^3
C_ϕ	the compressibility of rock, 1/kPa; P is the real-time reservoir pressure, kPa
E_a	the activity energy, J/mol
k	the current reservoir permeability, md
k^0	the initial reservoir permeability, md
M_W	the molar mass of water, kg/mol
N	an index, integer
P	the real-time reservoir pressure, kPa
P^0	the initial reservoir pressure, kPa
R	the universal gas constant, J/(mol °C)
s_w	the saturation of the water phase, dimensionless unit
T_{abs}	the reference temperature, °C
v	the rate of salt precipitation or dissolution in unit pore volume, mol/(s m^3)
x_i	the mole fraction of component i in the oil phase
x^0	the initial concentration of NaCl in the formation water, mole fraction
x_{NaCl}	the NaCl concentration calculated after water evaporation (or brine water dilution), mole fraction
x_{satu}	the NaCl saturation concentration in the water phase (i.e. the solubility of NaCl), mole fraction

Greek letters

κ	the reaction constant, s^{-1}
ρ_s	the mole density of precipitated salt, mol/m^3
ρ_{wm}	the mole density of the water phase, mol/m^3
ρ_w	the mass density, kg/m^3
ϕ	the real-time reservoir porosity after salt dissolution/-precipitation and pressure changes
ϕ^0	the initial reservoir porosity

conditions. Especially, salt precipitation occurs severely in the near well region when the remaining water saturation is higher than the irreducible water saturation. Meanwhile, water evaporation induced by CO_2 injection may cause a back flow of formation water due to the effects of gravity and capillarity, which can intensify the evaporation and increase the salt precipitation and enrichment in the region. This can cause a reduction of permeability which therefore decreases the heat mining rate. Different methods for reducing salt precipitation was proposed and evaluated accordingly, including injection of low salinity water prior to CO_2 injection and co-injection of CO_2 and fresh water.

1. Introduction

Geothermal energy is abundant and it is not affected much by weather conditions (e.g. sunshine, wind speed and temperature changes) in comparison with other renewable energy sources, and it can be exploited continuously and serve as a baseload or dispatchable power resource without requiring energy storage [1]. All these advantages make geothermal energy one of the promising supplement to fossil energy [2,3]. In general, vapor and hot water-dominated reservoirs, such as hot-water springs, are classified as conventional geothermal resources, while hot dry rocks, deep saline aquifer, magma systems and geo-pressured reservoirs are classified as unconventional resources [4,5], which have been recognized to have high potentials for geothermal development [5,6].

It has also been indicated that high temperature natural gas reservoirs possess huge geothermal energy [7,8], but it has been neglected by the geothermal community. Table 1 shows the predicted geothermal potential of some high-temperature gas reservoirs collected from around the world [9–16]. The geothermal energy contained in a typical medium size gas reservoir (e.g. the Xushen gas reservoir with original gas in place (OGIP) of 10 billion Sm^3) at a temperature of 150 °C could be equivalent to 19 million tons of standard coal. It should be noted that the heat transfer from the nearby formations to the gas reservoir is ignored in the calculation, so the actual recoverable geothermal energy should be higher than the calculated in Table 1.

For geothermal production from the high-temperature depleted gas reservoir [6,7], the existing wells and surface facilities can be easily adapted for heat mining, which would significantly reduce the investment and meanwhile extend the economic life of the gas reservoir [17]. There are some advantages of heat mining via CO_2 injection. Firstly, the high mobility of CO_2 can increase the injectivity of the heat carrying fluid, which is particularly important for the reservoirs with low permeability. Secondly, the injection of CO_2 can enhance the ultimate natural gas recovery via pressure maintenance and displace natural gas due to gravity effect [18,19], and which has been proven to be feasible technically and economically [20–23]. Thirdly, the injection of CO_2 into such gas reservoirs could achieve the permanent sequestration of CO_2 as the reservoir integrity and containment of gas have been proven in the geological framework [23,24].

For these deep high temperature gas reservoirs with low permeability, the injectivity of water is poor and high water injection rate will cause wellbore and formation damage [25,26]. Therefore, use of water as a heat transmission fluid as practiced in the conventional geothermal exploitation is not applicable. Supercritical CO_2 ($SCCO_2$) has been proposed as an alternative heat transmission fluid because of its unique thermal properties and good mobility for geothermal production from deep and high temperature gas reservoirs [27–29]. $SCCO_2$ has many advantages when it is used for geothermal exploitation. Under normal reservoir conditions, CO_2 will be in its supercritical state with low viscosity, high density and high heat capacity, which can increase injectivity and heat mining rate [14]. $SCCO_2$ has larger compressibility than water, which can increase buoyancy force in the wellbore and result in a thermo-siphon effect that can reduce the parasitic power consumption in fluid circulation systems [1,28].