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Evaluation of working fluids for geothermal power generation from abandoned oil wells

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HIGHLIGHTS

- Geothermal power generation model based on transient formation heat conduction of abandoned oil wells is presented.
- Geothermal energy from abandoned oil wells with well depth less than 3000 m is worthless to be exploited.
- DPGS efficiency of supercritical working fluids at outlet is higher than FPGS efficiency of subcooled working fluids.
- R134a and R245fa are more suitable than R600a, etc. for geothermal power generation using abandoned oil wells.

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ABSTRACT

Geothermal power generation from abandoned oil wells is a new way to utilize geothermal energy. The organic Rankine cycle is used for exploiting geothermal energy from abandoned oil wells efficiently. The investigation on influences of working fluids on the power generation efficiency is significant. An analysis model for geothermal power generation based on the transient formation heat conduction of abandoned oil wells is presented in this paper. For abandoned oil wells with different kinds of well depths and geothermal gradients, the power generation performances using various organic fluids are analyzed. Direct power generation system (DPGS) is compared with flashing power generation system (FPGS). The results show that the geothermal energy from the abandoned oil wells with well depth less than 3000 m is worthless to be exploited due to low power generation efficiency. For the abandoned oil wells with well depths larger than 3000 m and geothermal gradients higher than 0.04 K/m, DPGS efficiency of supercritical working fluids leaving the recovery well is higher than FPGS efficiency of subcooled working fluids. R134a and R245fa are more suitable than R600a, R600, propylene, R290 and R143a for the geothermal power generation using abandoned oil wells.

1. Introduction

Geothermal energy is a renewable, clean and sustainable energy stored in the form of heat beneath the earth's surface [1]. It is evaluated that approximately 44 TW of heat power is transferred from the interior to the surface of the Earth [2]. Geothermal energy will become an important part of the new energy in the future with gradually running out of the traditional energy such as coal and oil [3]. Dry steam or high-temperature liquid water extracting from geothermal wells has been utilized to generate electricity for decades. The geothermal power plants are established in 24 countries and the total installed capacity of geothermal facilities worldwide is more than 10,000 MW in 2010 [4,5]. However the development of geothermal power is restricted by the expensive cost of drilling [6]. Meanwhile 20–30 millions oil wells are abandoned around the world and there are serious pollution problems caused by the leak [7]. However, several scholars suggested that abandoned oil wells can be changed into geothermal wells for power generation [8–12]. In this way the cost of drilling will not only be reduced, but also pollution problems will be solved. It may become a new way to utilize geothermal energy.

The existing methods of geothermal power generation mainly can be divided into two categories: (1) single cycle and (2) binary cycles. Single cycle includes direct power generation system (DPGS) and flashing power generation system (FPGS). Water is used as the working fluid for traditional geothermal power generation by single cycle. However organic fluids are used as working fluid for geothermal power generation from abandoned oil wells by single cycle because geothermal energy obtained from abandoned oil wells is the medium and low quality sources. The organic Rankine cycle (ORC) is a promising process for conversion of the

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Nomenclature

Variables

A_{inj}	flow area of injection well, m^2
a	geothermal gradient, K m^{-1}
c_p	specific heat capacity of fluid, J kg^{-1} K^{-1}
dQ/dz	rate of heat flow over dz, W m^{-1}
dz	length of well segment, m
d_e	hydraulic diameter of injection well, m
f	friction factor, Eq. (6)
$f(t)$	transient heat-conduction time function, dimensionless
h	well depth, m
h_1	specific enthalpy of fluid in the state 1, J kg^{-1}
h_2	specific enthalpy of fluid in the state 2, J kg^{-1}
$h_{1'}$	specific enthalpy of fluid in the state 1′, J kg^{-1}
$h_{1''}$	specific enthalpy of fluid in the state 1″, J kg^{-1}
h_g	specific enthalpy of fluid in the state g, J kg^{-1}
h_w	convective heat transfer coefficient, W m^{-2} K^{-1}
J_0	zero-order Bessel function of the first kind
J_1	first-order Bessel function of the first kind
M	mass flow rate of fluid, kg s^{-1}
$M_{1''}$	mass flow rate of gas produced by flashing chamber, kg s^{-1}
P	actual power generated by system, W
P_{net}	net power produced, W
P_{pump}	electricity consumed by pump, W
Pr	Prandtl number
p_{in}	inlet pressure of fluid, MPa
Q	total heat obtained, kW
Re	Reynolds number
R_{inj}	external radius of injection well, m
R_{rec}	external radius of recovery well, m
r_{inj}	internal radius of injection well, m
r_{rec}	internal radius of recovery well, m
T_0	surface temperature of formation, K
T_{op}	optimum flashing temperature, K
T_c	condensing temperature, K
T_{ei}	formation temperature at the infinite distance from well axis, K
T_f	fluid temperature, K
T_g	temperature of fluid entering the flashing chamber, K
T_w	heat exchanger/formation interface temperature, K
T_{in}	temperature of fluid entering injection well, K
T_{out}	temperature of fluid leaving recovery well, K
u	dummy variable for integration
u_f	fluid flow velocity, m s^{-1}
u_{in}	inlet velocity of fluid entering injection well, m s^{-1}
Y_0	zero-order Bessel function of the second kind
Y_1	first-order Bessel function of the second kind
z	variable well depth from surface, m

Greek letters

α_e	thermal diffusivity of formation, m^2 s^{-1}
η_{ge}	generator efficiency
η_m	turbine mechanical efficiency
η_{oi}	turbine relative internal efficiency
η_{pump}	pump efficiency
λ_e	thermal conductivity of formation, W m^{-1} K^{-1}
λ_f	thermal conductivity of fluid, W m^{-1} K^{-1}
μ_f	viscosity coefficient of fluid, N s m^{-2}
ρ_f	density of the fluid, kg m^{-3}
$(\rho c)_e$	formation heat capacity, J m^{-3} K^{-1}
$(\rho c)_w$	wellbore heat capacity, J m^{-3} K^{-1}
ω	ratio of formation heat capacity and wellbore heat capacity, dimensionless
τ	operating time, d
τ_D	dimensionless time $(= \alpha_e\tau/r_{inj}^2)$
τ_f	friction-loss gradient, Pa/m

Subscripts

1	state 1 in Fig. 1
2	state 2 in Fig. 1
1′	state 1′ in Fig. 2
1″	state 1″ in Fig. 2
c	condensing
e	formation
f	fluid
g	state g in Fig. 2
in	inlet
inj	injection well
rec	recovery well
out	outlet
w	interface of heat exchanger and formation

low and medium temperature heat to electricity and enables the cost efficient power generation [13]. The power generation efficiency of organic Rankine cycle is greatly influenced by working fluids [14]. Hence the investigation on influences of working fluids on the power generation efficiency is significant. Saleh et al. [15] presented thermal cycle efficiencies of ORC for 31 pure component working fluids at the temperature of 373 K or somewhat higher for geothermal energy applications and concluded that fluids with low critical temperatures are suitable. Zhang et al. [16] investigated the parameter optimization and performance comparison of the fluids in subcritical organic Rankine cycle and transcritical power cycle in low-temperature binary geothermal power system. The result was that the R125 in transcritical power cycle showed excellent economic and environmental performance and could maximize utilization of the geothermal energy. Roy et al. [17] analyzed non-regenerative organic Rankine cycle using working fluids such as R-12, R-123, R-134a and R-717 with superheating at a constant pressure of 2.50 MPa as well as under employed heat source temperature at two different conditions: 550 K and 15 K above the turbine inlet temperature. Guzovic et al. [18] investigated that binary plants worked with ORC or with the Kalina cycle utilizing medium-temperature geothermal sources in Croatia for electricity production and concluded that ORC had better thermal efficiency in case of geothermal source Lunjkovec–Kutnjak (140 °C). Tempesti et al. [19] presented two micro CHP ORC plants using solar and low temperature geothermal and investigated three different fluids (R134a, R236fa, R245fa). The result was that R245fa showed the best cycle efficiency and R134a released the highest heat. Yin et al. [20] studied thermodynamic cycles using mixtures of SF_6–CO_2 for geothermal power plants and found that SF_6 15 and 20 mol% yielded the highest Brayton and Rankine cycle efficiencies.

At present few investigations are performed on working fluids for geothermal power generation from abandoned oil wells. Davis and Michaelides [10] investigated geothermal power generation from abandoned wells using isobutane as working fluid and concluded that the maximum power depended largely on the temperature of the well bottom and the injection pressure. Ebrahimi and Torshizi [12] studied the optimization of power generation from a