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Studies on geothermal power generation using abandoned oil wells

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ABSTRACT

In this paper, abandoned "dry hole" oil wells are simulated as a source of geothermal power for generating electricity. Isobutane is chosen as the working fluid. It is heated by the geothermal energy from geologic formation and drives the turbine to generate electricity. A model based on transient formation heat transfer is presented. Furthermore, a numerical simulation for an abandoned well with a depth of 6000 m is performed. The result shows that the outlet temperature of fluid leaving the recovery well gradually decreases with the system operating time increasing and ultimately approaches stability. The stabilized time of the system can be shortened by either the increasing formation thermal conductivity or the decreasing inlet velocity of fluid entering the injection well but is not significantly influenced by the formation heat capacity. The net power depends on the total obtained heat and the outlet temperature of fluid leaving the recovery well. And increasing the inlet velocity can increase the total obtained heat but lower the fluid outlet temperature. Consequently there is an optimal inlet velocity of fluid entering the injection well to maximize the net power for a specified geothermal heat source.

1. Introduction

The current development of human civilization has been made possible by the extensive use of fossil fuels. However, fossil fuels are becoming increasingly scarce and burning fossil fuels generates carbon dioxide, which is a greenhouse gas that contributes to warming of the atmosphere. Geothermal energy is abundant and clean, i.e., it emits no greenhouse gases. Several American researchers [1] did the Los Alamos experiment in New Mexico and exploited the geothermal energy in hot dry rock to generate electricity in the 1970s. Then Japan [2] and several European countries [3] carried out the experimental study on the hot dry rock in the 1980s. However the total cost of geothermal power plants is increased significantly and the wide application is restricted by the huge cost of drilling [4]. Meanwhile there are many abandoned oil wells all round the world. These oil wells are dry holes that never struck oil but have a large amount of heat energy. Therefore the drilling costs can be saved and safety problems of abandoned oil wells will be solved through transforming those abandoned wells into geothermal wells. And it may become a new way to utilize geothermal energy.

A number of scholars began to study obtaining geothermal energy from abandoned oil wells. Kujawa et al. [5] proposed a double-pipe heat exchanger for the acquisition of geothermal energy using water as the working fluid and established a heat transfer model between the heat exchanger and the formation. The influences of different insulation materials and mass flow on the performance of double-pipe heat exchanger were analyzed. Bu et al. [6] suggested that water was utilized as the cycle working fluid for obtaining geothermal power produced from abandoned oil wells and concluded that the flow rate of fluid and the geothermal gradient were two main factors in obtaining geothermal energy.

Geothermal energy obtained from the abandoned oil wells is the medium and low quality sources. Feng et al. [7] presented the advantages of organic Rankine cycle in the use of the medium and low quality sources. Organic fluid due to its low boiling point converts into high temperature steam. Hettiarachchia et al. [8] presented a cost-effective optimum design criterion for organic Rankine cycle utilizing low-temperature geothermal heat sources. Yamamoto et al. [9] estimated the optimum operating conditions of organic Rankine cycle through a numerical simulation and an experimental apparatus. Wei et al. [10] presented the performance analysis and optimization of an organic Rankine cycle system using HFC-245fa as working fluid for waste heat recovery. The results show that choosing a proper nominal state is a good idea for improving the system output net power and efficiency according to the running environment. The effects of different working fluids on organic Rankine cycle were investigated and analyzed for improving the thermal performance [11–14]. Davis et al. [15] suggested geothermal power production from abandoned oil wells using

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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}
d_e	hydraulic diameter of injection well, m
$d\dot{Q}/dz$	rate of heat flow over d*z*, W m^{-1}
dz	length of well segment, 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_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}
Q	total obtained heat from well, W
P	actual power generated by system, W
P_{net}	net power, W
P_{pump}	electricity consumed by pump, W
Pr	Prandtl number
p_{in}	inlet pressure of fluid, MPa
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_c	condensing temperature, K
T_{ei}	formation temperature at the infinite distance from well axis, K
T_f	fluid temperature, 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_g	generator efficiency
η_m	turbine mechanical efficiency
η_{oi}	turbine relative internal efficiency
η_{pump}	pump efficiency
η_{th}	overall efficiency of system
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

isobutane as working fluid and concluded that the operation of the systems attains a maximum power that depends on the temperature of the well bottom and the injection pressure.

However, models established in these studies at present were simplified to facilitate the simulation, in some of which the formation heat transfer or the momentum transport was ignored. The focus of this article is the study on the effects of formation heat transfer and the theoretical analysis of geothermal power generation from abandoned wells using isobutane as the cycle fluid. A comprehensive model including transient formation heat transfer, fluid momentum and energy equation is presented. At the same time the factors that affect the system achieving stable state and thermal performance are investigated.

2. Geothermal power generation system

Fig. 1 shows the structure diagram of geothermal power generation system which consists of a double-pipe heat exchanger and organic Rankine cycle. Isobutane is chosen as the cycle working fluid to acquire geothermal energy and generate power. Firstly, isobutane (state 4) boosted by the pump flows into the double-pipe heat exchanger. Isobutane (state 4) is heated by geothermal energy and becomes high-temperature and high-pressure fluid (state 1) at the outlet. Then the fluid (state 1) enters the turbine and expands to work for power generation. Isobutane (state 2) whose pressure and temperature declines after working is cooled by the cooling water in the condenser and becomes subcooled liquid (state 3). The liquid (state 3) is boosted by the pump to become high-pressure subcooled liquid (state 4). The high-pressure liquid (state 4) is sent into the heat exchanger again. Thereby the entire power cycle can be completed.

Isobutane is a flammable liquid and a solvent. Leaks above ground in the piping systems or around the gas compressor can be fire hazards. Hence the piping systems are equipped with intelligent alarm detectors of gas leaks and polyester lubricants are used for preventing isobutane dissolving in lubricants.

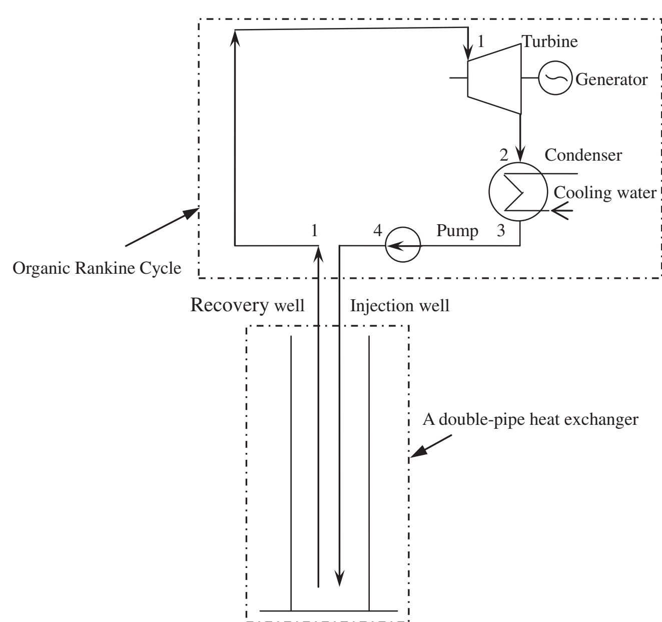

Fig. 1. Structure diagram of geothermal power generation system.