Geothermal Power from Dry Wells

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ABSTRACT

A numerical simulation for the determination of geothermal power production from abandoned oil wells by injecting and retrieving a secondary fluid was performed. The analysis takes into consideration local geothermal gradients and typical well depths and pipe diameters. Isobutane is chosen as the secondary fluid, which is injected in the well at moderate pressures and allowed to heat up and produce vapor. The computational model that was developed takes into account mass, energy, and momentum conservation equations for the well flow, and the simulation helps determine the state of the fluid from injection to retrieval. It is observed that the operation of such systems attains a maximum power that depends on the temperature of the well bottom and the injection pressure. In general, 1 MW of electric power may be produced from wells that are typical in the South Texas region.

Keywords: geothermal power, double-pipe heat exchanger, oil well, energy, isobutane.

1 INTRODUCTION

The current economic environment and impending climate change from the combustion of hydrocarbons makes the use of alternative energy sources, including geothermal, imperative for the near future. Geothermal resources that are utilized today are essentially the high-temperature resources, where wells of moderate depth (1000-2000 m) intrude into aquifers and produce either steam or a mixture of steam and water. Such resources are utilized with steam turbines (e.g. Geysers) or in single- and dual-flashing plants (e.g. Warakei and Imperial Valey). Since most of the high temperature aqueous resources have been utilized, the next expansion of geothermal power plants will necessarily be with lower temperature resources where water may come to the surface as liquid at temperatures in the range of 120-150 ^{o}C. Binary geothermal systems, which utilize a secondary fluid such as a refrigerant or a hydrocarbon, are typically used for the development and exploitation of such resources.

Several recent studies have evaluated the performance of different organic substances used as working fluids in Rankine and the Clausius-Rankine cycles [1-3]. In all such cases, geothermal water was used to exchange heat with working fluids in the cycle. Other similar studies were performed based on the exergy and energy analysis, and new plant designs to improve the performance of geothermal power plants [4-9]. For low temperature resources, binary-flashing units have been recommended to provide more power than conventional geothermal units [9]. Recently Kujawa et al. [10] studied the utilization of geological wells, from which geothermal fluid was extracted, and they performed calculations on the heat flow and power produced. Kujawa et al. proposed a double-pipe heat exchanger that would inject water deeply into the geothermal formation, and would extract heat from the well.

A glance at the geothermal potential of the United States and of the entire planet {reference maps, 11, 12}, proves that there are many areas where the geothermal gradient is relatively steep, but there are no aquifers nearby, from which hot water may be drawn. If these geothermal resources are to be utilized, one must inject and retrieve a fluid at a higher temperature in order to extract heat and utilize the energy of the geothermal resource. Several such sites with excellent geothermal potential exist in the southern part of Texas, where the geothermal gradient is relatively high. In addition, several deep oil wells exist in the same areas that are currently abandoned. These are oil wells that were struck dry or are now dry, because the oil reservoir has been depleted.

This study focuses on the total power that may be extracted from such geothermal wells. We are using an existing well and propose to refit it in order to produce a double-pipe heat exchanger. Instead of using water as in [10], we propose to use an organic fluid, such as isobutane, which has thermodynamic properties better suited for the extraction of heat from geothermal resources. Isobutane boils at lower temperatures than water, and hence, the well would produce isobutane vapor that may be easily used in a small turbine with a condenser. In addition, we performed a simple optimization study on the effect of fluid injection pressure, and determined that there is always an optimum value for the produced power. This optimum depends chiefly on the temperature of the well, the injection pressure, and the flow rate of the isobutane.

2 GOVERNING EQUATIONS

Data for the gas and oil wells in Texas are available from the *Rail Road Commission of Texas* [11]. Based on an extensive review of such data, we have chosen an existing well with a depth of 3 km, bottom-hole temperature of 140 ^{o}C, and a 0.20 m diameter (8 inches). A double-pipe heat exchanger may be easily made by retrofitting this well with an internal pipe of smaller diameter and with a small amount of insulation, as shown in Fig. 1. The bottom of the well may be sealed off by sealants to allow the isobutane to rise on the internal part of the pipe. Isobutane may be injected at the outer part of the double pipe as a compressed liquid coming from the condenser at a temperature of 40-45 ^oC and with pressure in the range of 5-20 bar. It heats up from the heat extracted from the surrounding rocks and goes to the bottom of the well, where its temperature reaches a maximum. There, the flow is reversed; the fluid enters the core of the pipe and ascends to the wellhead. The conservation equations for the model are continuity, momentum, and energy equation.

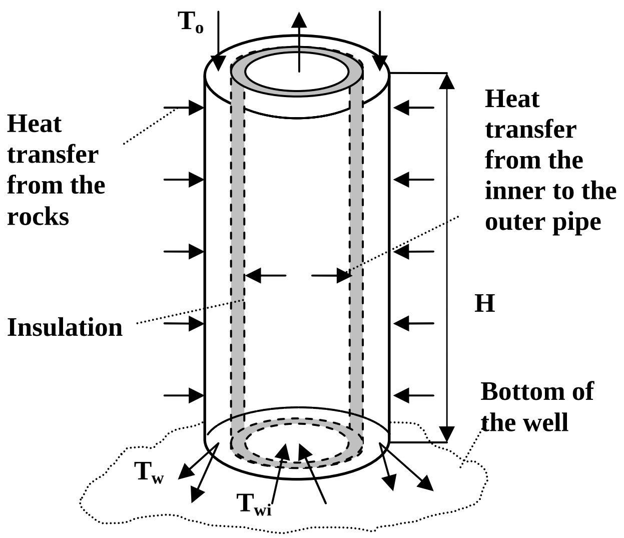

Figure 1: Schematic representation of the heat transfer in the well.

2.1 Continuity equation

The continuity equation is as follows:

$$\dot{m} = \rho VA = const \tag{1}$$

where ρ is the density of the fluid, V is the velocity, and A is the area of the fluid conduit. For the downward part of the flow the area is:

$$A = \pi(R^2 - (r+t)^2) \tag{2}$$

and for the upward flow:

$$A = \pi r^2 \tag{3}$$

2.2 Momentum equation

The momentum equation is given in terms of two states of the fluid at heights z_1 and z_2, and is being used for the calculation of the static pressure of isobutane as follows:

$$\frac{P_1}{\rho_1 g} + \frac{V_1}{2g} + z_1 = \frac{P_2}{\rho_2 g} + \frac{V_2}{2g} + z_2 + h_l \tag{4}$$

where P is the static pressure, z is the height, and g is the gravitational acceleration.

2.3 Energy equation

The energy equation is essentially the First Law of Thermodynamics for an open system. The rate of external work in the pipeline is always zero, and the heat that enters results in the change of the enthalpy, which includes the kinetic and potential energy. The rate of heat transfer from the rock to the isobutane in the outer pipe is:

$$\dot{Q} = hA(T_w(z) - T_1) \tag{5}$$

The temperature of the rocks T_w at any height, z, may be approximated by a linear interpolation of the geothermal gradient, which is obtained from the known temperatures of the surface and the bottom of the well. The inner pipe has an insulation of thickness, t. Therefore, the heat transfer in the inner section 3-4 is:

$$\dot{Q}_{34} = AU(T_3 - T_{out}) \tag{6}$$

$$\dot{Q}_{34} = \dot{m}(h_3 - h_4) = \dot{m}c_p(T_3 - T_4) \tag{7}$$

In addition to the governing equations, we obtained the transport properties of isobutane, such as viscosity and thermal conductivity; and thermodynamic properties, such as density, enthalpy, and entropy. Appropriate functions with temperature and pressure as independent variables were fitted to these tables in order to obtain expressions that were used in the numerical subroutines. Throughout the computations we assume that the dimensions of the well are constant. Also, that the temperature of the fluid injected to the well is also constant at 310 K, and that it is not affected by any other conditions. The bottom-hole temperature and the injection pressure and flow rate were parameterized, and their effect on the total power produced is evaluated in the computations.

3 RESULTS

In the downward direction, the results obtained from the simulations indicate that the liquid isobutane is further pressurized by the weight of the column and reaches supercritical pressures at the bottom of the well. As the direction of the flow is reversed, the fluid moves upwards, and the static pressure is reduced. However, because of the heat addition and the rise of temperature, the density of the fluid in the upward direction is lower. Even though

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frictional pressure losses are always present, the depressurization of the ascending fluid occurs at lower rates than the pressurization in the descending part. During ascend, isobutane passes from the state of supercritical vapor to superheated vapor. It was observed in most simulations that heating up of the fluid in the geothermal well resulted in the production of superheated vapor without boiling and a two-phase regime. The Fig. 2 depicts the thermodynamic enthalpy-pressure diagram of the heating process. The rise of the static enthalpy at the upper stages of the well is due to the fact that the enthalpy of isobutane increases significantly when the pressure is reduced. However, since entropy is also increased significantly, this increase of the enthalpy is accompanied by an exergy decrease.

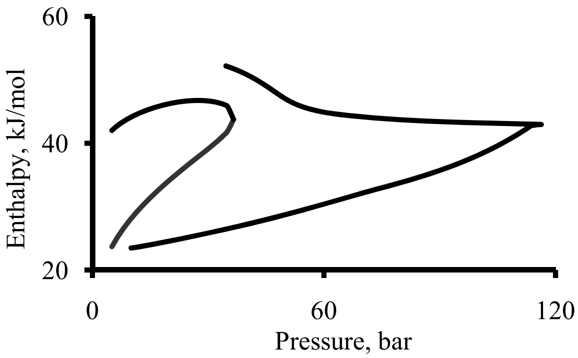

Figure 2: Thermodynamic diagram of enthalpy versus pressure for isobutane.

In order to obtain more realistic values for the potential of such a well to produce power, we have assumed in the computations that the turbine efficiency is 85%, and the pump efficiency is 80%.

Net power obtained from this well for the thickness of insulation t=0.5 and t=0.75 inches is shown in Figs. 3 and 4 respectively. The three curves in these figures are for three different bottom-hole temperatures, namely 415 K, 430 K, and 450 K. The injection pressure is the variable in the two figures, and the injection velocity is constant at V = 1 m/s. It is observed that there is a flat maximum in all three cases, where the maximum power may be obtained. The maximum power is obtained when the injection pressure is approximately 30-40 bar. It must be pointed out that the steep drop at the lower injection pressures in the curve, corresponding to 450 K (Fig. 4), is due to a significant reduction of wellhead pressure in the fluid. This implies that at injection pressures below 15 bar, there is insufficient pressure to operate the double-pipe heat exchanger.

The outer diameter D=8 inch and the thickness of insulation t=0.5 inch in the well are constant, but the injection velocity of the well is one of the parameters that may be optimized in such a study. For three inner radiuses: 1.5, 2.0, and 2.5 inches and velocity in the range of 0.1 m/s < V < 2.5 m/s, with the injection pressure at P=40 bar and bottom well temperature at T=450 K; the produced power as a function of velocity was calculated and shown in the Fig. 5. At lower velocities, frictional losses are significantly lower. The mass flow rate in the well is low, and hence, the produced power would be lower. At very high velocities, friction losses become significant and a great deal of the exergy of the fluid is destroyed to friction. It is observed that the net power of the well exhibits a sharp maximum at about 1.2 MW when the injection velocity is approximately 2.2 m/s, and the inner radius is 2.5 inches. The other curves also exhibit sharp maxima at different velocities and slightly lower rates of power production. This leads us to conclude that the exact control of the injection velocity, or equivalently, the injection mass flow rate is very important for the power production from such wells.

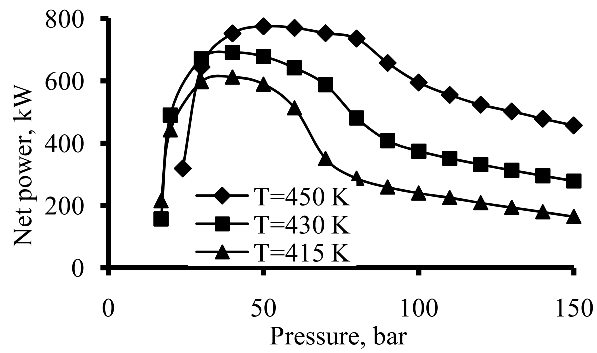

Figure 3: Net power for different temperatures and injection pressure with thickness of insulation t=0.5 in.

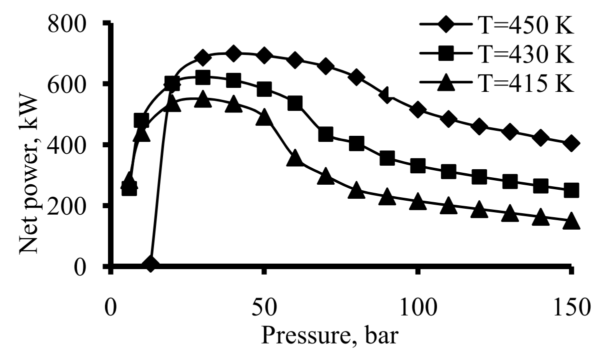

Figure 4: Net power for different temperatures and injection pressure with thickness of insulation t=0.75 in.

Finally, we conducted a parametric study with different thickness, which varied in between the range of 0.05 in < t < 1.8 inch. The injection pressure, velocity are 80 bar and 1 m/s respectively, the well-bottom temperature is 415 K, 430 K and 450 K. The outer and inner pipe diameters were kept constant as 8 and 4 inches respectively. From Fig. 6 is observed that maximum power is received for the thickness of insulation taken as 0.3-0.4 in for all three cases. This is the consequence of the fact that the fluid exits the well at almost the same state from that point. However, the power produced is significantly higher in that case, because the double-pipe carries a higher mass flow rate of isobutane.

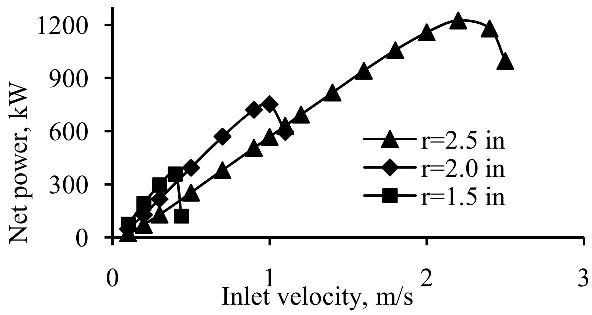

Figure 5: Net power change with velocity for three different inner pipe radii.

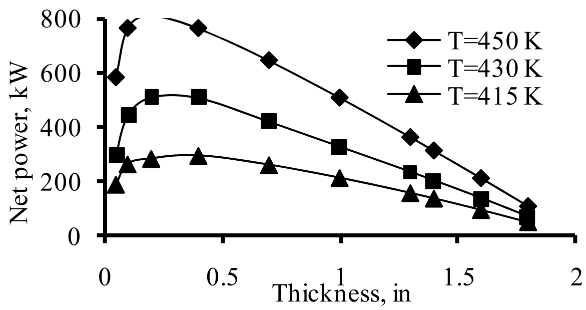

Figure 6: Net power for different temperatures as a function of the thickness of insulation.

4 CONCLUSIONS

The results of the computational study showed that abandoned oil wells have the potential to produce a significant amount of power when they are modified to become double-pipe heat exchangers and when a secondary fluid with desired thermodynamic properties, such as isobutane, is injected at the outer rim. The calculations show that the net power produced from such a well may exceed 0.7 MW for a bottom-hole temperature of 450 K and an injection pressure of 40 bar. This amount of power is not intermittent as with other renewable energy sources, and it may be available for peak demand as well as basic demand. The power produced varies and depends significantly on the down-hole temperature, the injection pressure, the injection velocity, and the geometric characteristics of the pipe (inner and outer radii and insulation thickness). For the 450 K bottom-hole temperature with 3000 m depth well examined in this study, which is typical of South Texas oil wells, it is observed that an injection pressure of 40 bar is sufficient and almost optimum for the operation of the system. Half-inch (1.27 cm) insulation maintains the fluid temperature to an almost constant in its ascent. When the injection velocity and inner pipe radius are optimized, this system would produce approximately 1.2 MW of power.

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