

Geothermal energy production utilizing abandoned oil and gas wells

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ABSTRACT

The objective of this study is to demonstrate the feasibility of acquiring geothermal energy from existing abandoned oil and gas wells. The equations describing the heat exchange between fluid and rocks are developed, and parametric studies are conducted in order to specify the optimum values of the main parameters. Computational results indicate that the geothermal energy produced from abandoned wells depends largely on the flow rate of fluid and the geothermal gradient. The temperature of extracted liquid is 129.88 °C, and it drops to 127.92 °C after ten years of operation. It is observed that both hot water and electricity can be acquired from the abandoned wells. Results also indicate that the distance of two wells should not be less than 40 m in order to avoid interaction between them. Furthermore, the financial reward of electricity is 36833.26 US \$/year for a retrofitted well.

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1. Introduction

Geothermal energy, as natural steam and hot water, has been exploited for decades to generate electricity, and both in space heating and industrial processes. Over the past 20–25 years, worldwide electricity production based on geothermal sources has increased significantly, the installed generating capacity has grown from 1300 MWe in 1975 to almost 10,715 MWe in 2010 [1–3]. These geothermal power projects convert the energy contained in hot rock into electricity by using water in place to absorb heat from the rock and transport it to the earth's surface, where it is converted to electrical energy through turbine-generators [3]. In systems of this kind, there are some problems that are not easy to be solved, which include the injection of waste water, high cost of geothermal well drilling, corrosion and scaling problem [4]. The cost of drilling can run as high as 50% of the total cost of a geothermal project. Geothermal energy will have broad market if these problems can be solved successfully [5].

The number of oil and gas wells drilled by Petroleum China are more than 200,000, but many oil/gas wells in China are abandoned now [6]. If these abandoned wells could be used for producing geothermal energy, it will not only reduce the cost of drilling wells,

but also acquire more renewable energy. At the same time, the problems of re-injection, corrosion and scaling can be solved because the circulating system of fluid is closed and the working fluid doesn't touch directly with rocks due to the single well is used for geothermal production. Recently, some researchers have paid much attention to the utilization of abandoned wells. Kujawa et al. [7] investigated the utilization of existing deep geological wells for acquisitions of geothermal energy, and they concluded that the flow rates and insulation had important effects on heat exchange. Davis and Michaelides [8] studied geothermal power production from abandoned oil wells, their analysis taken into consideration local geothermal gradients and well depths. However, the temperature of the rocks was considered invariable with time in this paper, which indicated the power production calculated in this article was higher than the true value. The experiments of extracting geothermal water from oil wells for power generation were carried out in Huabei oil region in China [9], and the experimental results showed that the mass flow rate of hot water was 1932 t/d with temperature of 116 °C. However, few studies considered the heat exchange between rocks and fluid comprehensively. Therefore, it is of great importance to find a good way to estimate the heat exchange between rocks and fluid and geothermal energy production from abandoned wells.

The main purpose of this study is to demonstrate the feasibility of acquiring geothermal energy from abandoned oil and gas wells. We first develop a mathematical model for describing heat exchange between fluid and rocks and solve it by numerical method, and then analyze the impact of the geothermal gradient and the flow rate of working fluid on the heat attainment and the

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power generation from abandoned wells. Lastly, we briefly discuss the flow resistance and the pump power.

2. Physical models

The existing abandoned oil and gas wells can easily be retro-fitted as geothermal wells by sealing the bottom of the well and by covering insulation, as shown in Fig. 1. The circulating fluid is injected through the ring-shaped channel and flows downward along the channel being gradually heated by surrounding rocks. The flow is reversed at the bottom of the well, and then the fluid ascends through the inside channel and flows out to the earth's surface [10]. The abandoned oil and gas wells geothermal systems are different from the conventional geothermal systems. In abandoned oil and gas wells geothermal systems, the circulating fluid doesn't touch directly with rocks, just like a double-pipe heat exchanger, thus just heat transfer occurs without mass transfer. While in the conventional geothermal systems the fluid is extracted from the porous rock or soil. Meanwhile, in order to maintain the high temperature of extracted fluid, the fluid flow rate for abandoned oil and gas wells geothermal systems is less than that of conventional geothermal systems due to smaller heat exchange areas between well walls and rocks. The geothermal gradient is generally more than 25 °C/km [7–9], so, we chose an abandoned well, with a depth of 4 km and geothermal gradient of 25 °C/km and 45 °C/km respectively, as the object of study. The inner diameter of the extraction well is 0.1 m. The diameter of injection well on the

top part is 0.34/0.3 m with the length of 2500 m, while on the bottom the diameter is 0.33/0.3 m with the length of 1500 m.

3. Mathematical models

The mathematical model includes the energy conservation equations and the flow resistance equation. Neglecting the variation of the tube wall temperature of injection well and extraction well, heat exchange takes place between fluid and rocks and between injected fluid and extracted fluid simultaneously [11–14].

3.1. Energy equation in extraction well

The temperature of extracted fluid is higher than that of injected fluid, so heat transfer occurs from extracted fluid to injected fluid, the energy equation in extraction well may be expressed as follows [11,13]:

$$\frac{\partial T_r}{\partial t} + \frac{\partial(VT_r)}{\partial z} = -S_{rR} \quad (1)$$

where

$$S_{rR} = \frac{k_l[T_r - T_R]}{\rho A_r C_p} \quad (2)$$

$$k_l = \frac{\pi}{\frac{1}{2h_{r1}r_1} + \frac{1}{2\lambda_S \ln \frac{r_2}{r_1}} + \frac{1}{2h_{r2}r_2}} \quad (3)$$

3.2. Energy equation in injection well

Injected fluid is heated by surrounding rocks and extracted fluid, so the energy equation in injection well may be given by the following equation:

$$\frac{\partial T_R}{\partial t} + \frac{\partial(VT_R)}{\partial z} = S_{rR} + S_{RW} \quad (4)$$

where

$$S_{RW} = \frac{h_W 2\pi R (T_{wall} - T_R)}{\rho A_R C_p} \quad (5)$$

3.3. Energy equation of the rocks

Energy equation of the rocks is written in following general form [12]:

$$\rho_W C_W \frac{\partial T_W}{\partial t} = \frac{\partial}{\partial z} \left(K_W \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r K_W \frac{\partial T_W}{\partial r} \right), \quad R \leq r \leq r_\infty \quad (6)$$

3.4. Pressure loss

Pressure loss, namely the flow resistance along the wells, is presented below [13]:

$$\frac{\Delta P}{\Delta z} = \lambda \frac{\rho V^2}{2d_e} \quad (7)$$

For extraction well: $d_e = 2r_1$, for injection well: $d_e = 2(R - r_2)$.

For laminar flow: $\lambda = 64/Re$, for turbulent flow: $\lambda = 0.11((\Delta/d_e) + (68/Re))^{0.25}$.

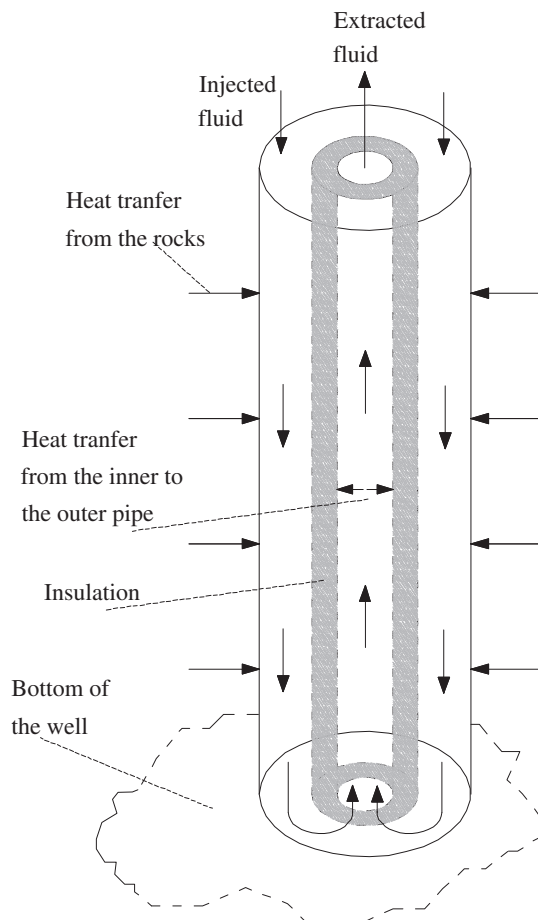


Fig. 1. Schematic representation of heat exchange in the single well.

Table 1
Parameters used in calculation.

Symbol	Value	Unit
r_1	0.05	m
K_W	2.1	W/m ² °C
λ_s	0.027	W/m ² °C
ρ_W	2730	kg/m ³
C_W	1098	J/kg/°C
Δ	0.26	

3.5. Heat transfer coefficient

The convective heat transfer coefficient, h_{r_2} and h_W , for extraction well is determined by:

$$h = 0.023 \lambda \frac{Re^{0.8} Pr^{0.4}}{d_e} \quad (8)$$

And the convective heat transfer coefficient for injection well is calculated as follows:

$$h_{r_1} = 0.023 \lambda \frac{Re^{0.8} Pr^{0.3}}{2r_1} \quad (9)$$

Re number, Pr number, the length and diameter for injection and extraction well can meet the demand of the Dittus–Boelter formula [15], so, Eqs. (8) and (9) are suitable for calculating the convective heat transfer coefficient.

3.6. Initial conditions

Inlet flow rate $V_{in} = \text{const}$, inlet fluid temperature $T_{in} = 30$ °C, the temperature at the ground surface $T_{biao} = 15$ °C. Injection and extraction wells are full of fluid at initial time, and the fluid temperature is equal to inlet fluid temperature.

The initial temperature of the rocks is given by:

$$T_{W,0} = T_{biao} + \frac{T_g}{1000} Z \quad (10)$$

3.7. Boundary conditions

The heat exchange between fluid and rocks is given according to third boundary condition:

$$h_W(T_{wall} - T_R) = K_W \frac{\partial T_W}{\partial r} \Big|_{r=R} \quad (11)$$

Eq. (11) is used for calculating the boundary temperature of rocks near the fluid. It is assumed that the temperature of rocks is constant and not influenced by the fluid when r is larger than 200 m.

3.8. Numerical algorithm

Eqs. (1), (4) and (6) are discretized by finite volume method with the implicit scheme [16], and then solved by algorithm of TDMA (Tri-diagonal matrix algorithm) [17]. The software used is MATLAB. The accuracy of the calculation results is not grid dependent if $\Delta r < 3$ m and $\Delta Z < 15$ m, so, the time step value $\Delta t = 1800$ s, the spatial discretization step value $\Delta r = 2$ m and $\Delta Z = 10$ m are selected in this article.

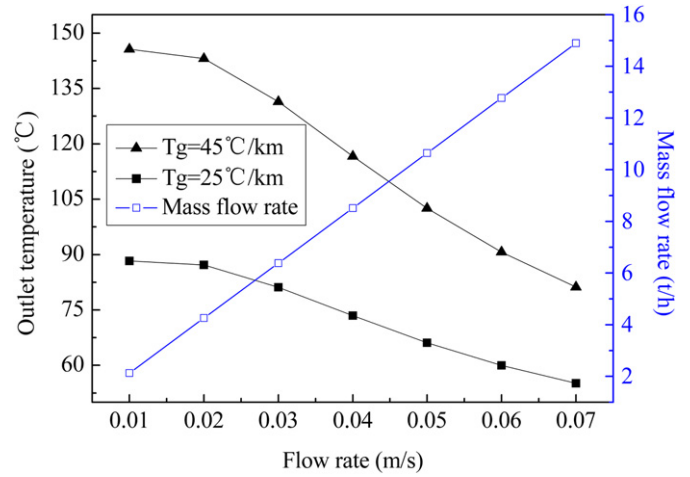


Fig. 2. Outlet temperature change with flow rate after 2 months operation.

4. Results and discussion

The parameters used in calculation are presented in Table 1. The depth of the abandoned well is 4 km, and the thickness of the insulation material is 0.01 m. The geothermal gradient T_g is 25 °C/km and 45 °C/km, respectively. In addition, the flow rate of injected fluid varies between the range of $0.01 \text{ m/s} < V_{in} < 0.06 \text{ m/s}$.

The gained heat Q and net output power P_{net} can be calculated according to the following equation:

$$Q = m(H_2 - H_1) \quad (12)$$

$$P_{net} = mC_p(T_{out} - T_{in})(h_1'' - h_2)(1 - X)\eta_Z/(2r_w) \quad (13)$$

The type of power generation is flash-steam, with principle and computational formula presented in Refs. [18,19]. The flash-steam means that water begins to boil in the flash vessel when the pressure is less than its saturated vapor pressure. The inlet temperature of injection well is equal to 30 °C, and the waste water, which is not evaporated yet in the flash vessel, is used for direct heating or cooling. The double-flash system is used if the outlet temperature of extracted fluid is greater than 120 °C.

Fig. 2 illustrates the variation of T_{out} as a function of the flow rate after 2 months of operation, it can be seen in Fig. 2 that T_{out} depends largely on V_{in} , and it decreases when V_{in} increases. The reason for this is that the heat loss from rocks to fluid can rapidly be compensated by heat conduction of rocks at a lower V_{in} , resulting in a higher T_{out} . However, the heat loss cannot rapidly be compensated at a higher V_{in} , which leads to a lower T_{out} .

The variation of Q , P_{net} and T_{was} with V_{in} is shown in Figs. 3 and 4, respectively. T_{was} is the temperature of waste water which is not evaporated yet in the flash vessel. From Fig. 3, T_{was} decreases with the increasing V_{in} for $T_g = 25$ °C/km. However, for $T_g = 45$ °C/km, T_{was} decreases firstly, and then it reaches the maximum value when $V_{in} = 0.04 \text{ m/s}$, this is due to the fact that the single flash is used for generating electricity at $V_{in} = 0.04 \text{ m/s}$ and $T_g = 45$ °C/km because T_{out} is less than 120 °C, while the double flash is used at $V_{in} = 0.03 \text{ m/s}$ due to T_{out} is larger than 120 °C, as shown in Fig. 2. Although the double flash has a relatively low T_{was} , it has the maximum net power, as shown in Figs. 3 and 4. It can be observed in Fig. 4 Q and P_{net} increase with the increase of T_g . There is an optimal V_{in} which makes maximum P_{net} for different T_g , as can be seen in Fig. 4. The maximum P_{net} can be obtained in such cases when V_{in} is approximately 0.03 m/s for $T_g = 25$ °C/km and 45 °C/km, respectively. However, the maximum Q can be acquired at

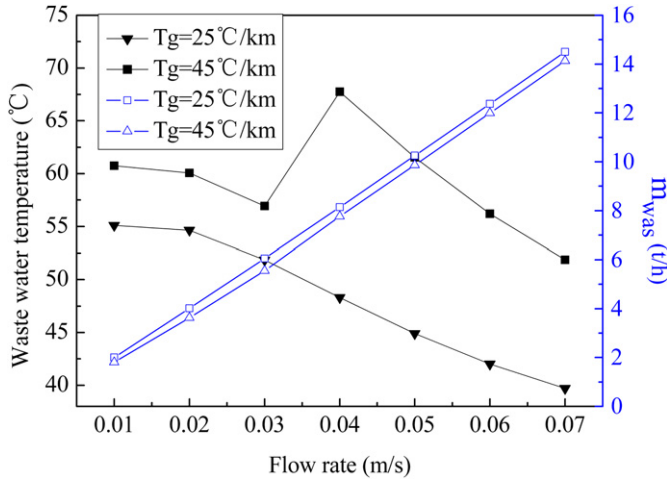


Fig. 3. Waste water temperature for different flow rate after 2 months operation.

$V_{in} = 0.05$ m/s. For $T_g = 25$ °C/km and 45 °C/km, the maximum P_{net} is 11.95 kW_e and 53.70 kW_e respectively, and the maximum Q is equal to 454.38 kW_{th} and 947.65 kW_{th} respectively. For a fixed T_g , the change tendency of T_{was} , m_{was} and P_{net} with V_{in} are different. Taking $T_g = 45$ °C/km for example, T_{was} is 56.92 °C and 61.53 °C, m_{was} is 5.55 t/h and 9.86 t/h and P_{net} is 53.70 kW_e and 37.30 kW_e for $V_{in} = 0.03$ m/s and 0.05 m/s respectively. The waste water can be used for direct heating or cooling. The purposes of either attaining heat or attaining electricity or both should be made sure before utilizing the abandoned oil and gas wells due to different purposes have different optimal flow rates. So, it can be concluded that V_{in} , or equivalently, m is very important for the electricity generation and heat attain from abandoned wells, as shown in Figs. 2 and 4.

Fig. 5 describes the variation of fluid temperature for injection and extraction well with geothermal gradients as a function of well depth at $V_{in} = 0.03$ m/s. As illustrated in Fig. 5, the fluid temperature depends largely on T_g , and increasing T_g will also cause the fluid temperature to increase. The fluid temperature rises because heated by surrounding rocks when fluid moves downwards. The highest temperature is reached at the bottom of well, and then fluid moves upwards. T_{out} is 81.15 °C and 131.39 °C for $T_g = 25$ °C/km and 45 °C/km, respectively. Due to heat transfer from extraction well to injection well through insulation material, T_{out} , as compared to the bottom temperature, drops by 8.54 °C and 16.2 °C for $T_g = 25$ °C/km and 45 °C/km, respectively, as can be seen from Fig. 5. This implies

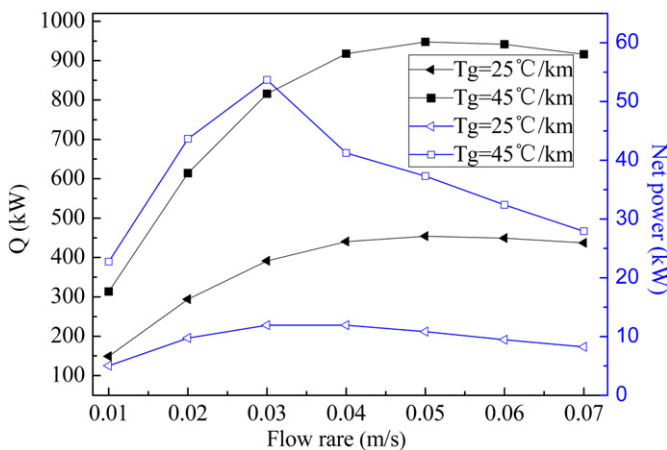


Fig. 4. Attained heat and net power for different flow rate after 2 months operation.

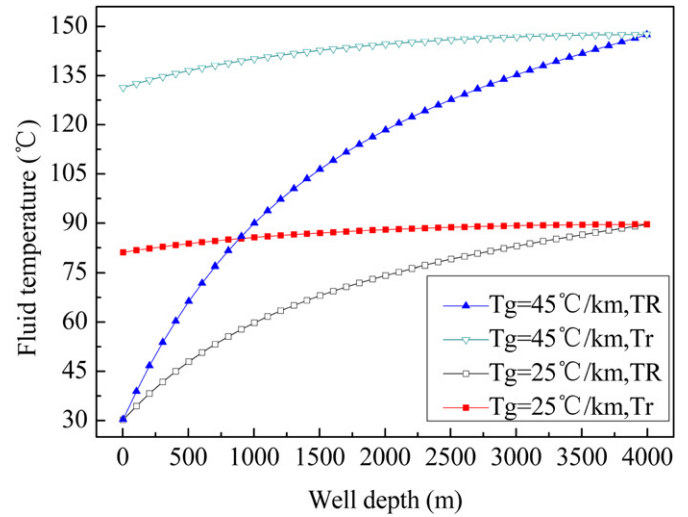


Fig. 5. Temperature change in injection and extraction well for different depth after 2 months operation, for $v = 0.03$ m/s.

that the thickness or the performance of insulation material is not sufficient to effectively preserve T_{out} . So, the performance of insulation material should be improved if condition permit.

Table 2 answers the question whether Q , P_{net} and T_{out} will vary with time or not. T_{out} is 127.92 °C after ten years of operation, corresponding to $T_g = 45$ °C/km and $V_{in} = 0.03$ m/s, compared with after 1 year of operation drops by 1.96 °C. The difference of T_{out} between after 1 year of operation and after 10 years is very small, and it would become smaller if considering maintenance during the run or discontinuous run. In addition, the difference of P_{net} , Q , T_{was} and m_{was} between after one year and after ten years of operation is also very small, as can be seen from the data in Table 2. So, this leads us to conclude that P_{net} , Q , T_{was} and T_{out} will almost invariable with time, the geothermal energy production system can work steadily for long term.

Fig. 6 shows the change of T_W as a function of depth, radius and time for $V_{in} = 0.03$ m/s and $T_g = 45$ °C/km. It can be observed in Fig. 6 that T_W close to fluid varies greater than that of far away fluid, and it doesn't vary approximately with time and radius when the radial distance $r > 20$ m. So, for the practicing engineer, the distance of two wells proposed should not be less than 40 m in order to avoid their interrelationships. The effective heat exchange section of the abandoned well with depth of 4000 m is from 2500 m to 4000 m according to computational results. T_W is almost equal to T_R between the depth of 2400 m and 2500 m. Due to heat transfer from extracted fluid to injected fluid through insulation material and much higher T_{in} , T_R is higher than T_W when the depth is less than 2400 m, as a result, the heat transfers from fluid to rocks. From the point of view of feasibility, whether the abandoned wells can be

Table 2
Parameter variation for different times, with $v = 0.03$ m/s.

Time (year)	T_{out} (°C)	P_{net} (kW)	Q (kW)	T_{was} (°C)	m_{was} (t/h)
1	129.88	52.26	802.14	56.51	5.562
2	129.28	51.69	796.94	56.35	5.567
3	128.93	51.36	793.93	56.25	5.570
4	128.69	51.13	791.81	56.19	5.572
5	128.50	50.96	790.18	56.14	5.574
6	128.35	50.81	788.85	56.09	5.575
7	128.22	50.69	787.73	56.06	5.576
8	128.11	50.59	786.77	56.06	5.577
9	128.01	50.50	785.92	56.00	5.578
10	127.92	50.42	785.17	55.98	5.579

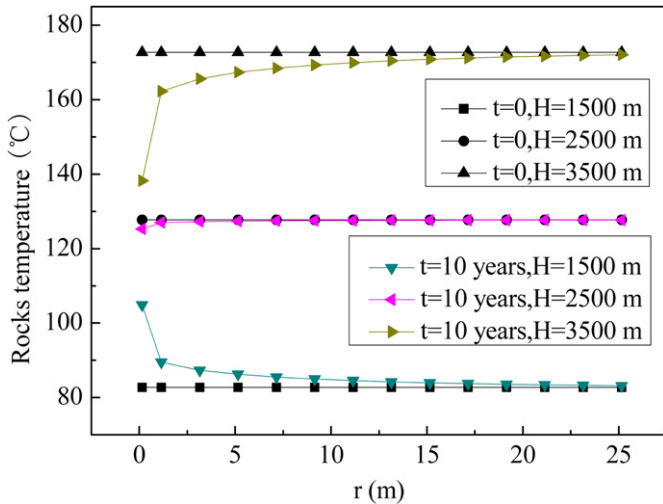


Fig. 6. Temperature variation of surrounding rock with time and position.

used as geothermal wells or not lies on the wells depth, geothermal gradient, the performance of insulation materials and the temperature of injected fluid. The abandoned well cannot be used as geothermal well if its depth is less than 2400 m with $V_{in} = 0.03$ m/s, $T_g = 45$ °C/km and $T_{in} = 30$ °C. So, it should be considered before the utilization of abandoned wells.

Fig. 7 shows the influence of V_{in} on the pressure loss and the pump power for $T_g = 45$ °C/km. Both the pressure loss and the pump power increase with V_{in} , as illustrated in Fig. 7. Energy needs to be consumed in order to overcome the frictional resistance in injection well and extraction well. Taking $V_{in} = 0.03$ m/s for example, the pressure loss and the pump power are 1.44 bar and 0.73 kW respectively. Under like conditions, P_{net} and Q are 53.70 kW_e and 815.76 kW_{th} respectively. The pump power accounts for 1.36 percent of P_{net} . In addition, to make sure that the boiling behavior doesn't happen in the abandoned well, the outlet pressure should be greater than the saturated vapor pressure of outlet fluid, which can be calculated by T_{out} . The inlet pressure can correspondingly be determined according to the outlet pressure and the pressure loss.

Considering geothermal energy production from economic standpoints, P_{net} is 53.70 kW_e for $V_{in} = 0.03$ m/s, $T_g = 45$ °C/km and

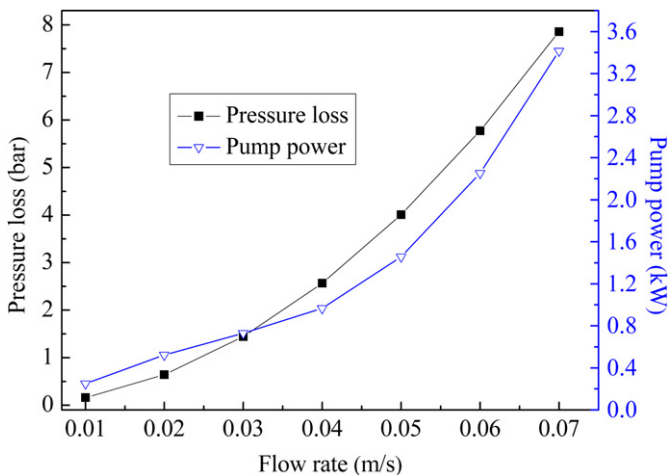


Fig. 7. Pressure loss between inlet and outlet of well and pump power for different flow rate.

$H = 4000$ m, and the financial reward of electricity is 36833.26 US \$/year for a single well, which is calculated according to the current electricity price of 0.0783 US \$/kW h. Furthermore, the waste water with $T_{was} = 56.92$ °C and $m_{was} = 5.55$ t/h can be used for direct heating and cooling. The installed capacity could be enlarged and geothermal power plants could be set up if multi-wells are connected together.

5. Validation of mathematical model

Whether the mathematical model can describe the geothermal energy acquirement from abandoned oil wells or not, it needs to be validated with experimental data or the others calculated results. The computational results from the above mathematical model in this article were validated with the others calculated results, which were acquired from the Ref. [7].

In Ref. [7], the well depth is 3950 m, and the diameter of injection and extraction wells are 222 mm and 50.7 mm respectively. When the injection flow rate, injection temperature and bottom temperature are 2 m³/h, 25 °C and 105.78 °C, respectively, the extraction temperature and heat attained are 86.63 °C and 139.69 kW_{th} respectively. In our research, the well depth is 4000 m, and the diameter of injection and extraction wells are 300 mm and 100 mm respectively. The extraction temperature and heat attained are 88.25 °C and 148.88 kW, respectively, for this geothermal system with bottom temperature of 115 °C, injection temperature of 30 °C and injection flow rate of 2.13 m³/h. So, it can be concluded that the results from this article, as compared with the calculated results from Ref. [7], are reasonable.

6. Conclusions

To demonstrate the feasibility of acquiring geothermal energy from existing abandoned oil and gas wells, a mathematical model describing the heat transfer from rocks to fluid is developed, and solved by numerical method. And then the geothermal energy production from abandoned well is calculated by the mathematical model. The computational results indicate that the geothermal energy production from abandoned wells depends largely on the fluid flow rate and the geothermal gradient. The net power output for a single well is 53.70 kW_e for a geothermal gradient of 45 °C/km, and the outlet temperature is 129.88 °C and doesn't vary approximately with time, which indicates that the geothermal production system can work steadily for long term. The optimal flow rate, at which the maximum net power can be attained, is 0.03 m/s, while the maximum Q can be acquired at a flow rate of 0.05 m/s. So, it can be concluded that the flow velocity of fluid, or equivalently, the mass flow rate is very important for the geothermal energy production from abandoned wells. The computational results also indicate that the distance of two wells proposed should not be less than 40 m in order to avoid their interrelationships. Although the pressure loss and the pump power increase with the increase of flow rate, the pump power is still small as compared to the net power, and the percentage is only 1.36%. The economic returns of electricity is 36833.26 US \$/year for a retrofitted well with $T_g = 45$ °C/km, and it will be better if $T_g > 45$ °C/km. Besides electricity, the waste water with temperature of 56.92 °C and mass flow rate of 5.55 t/h can be used for direct heating and cooling. Furthermore, it costs lower to modify abandoned wells to become geothermal wells than drilling new wells. The overall calculation results indicate that it is feasible to modify abandoned oil and gas wells to become geothermal wells for geothermal energy production.

This paper just focuses on the theoretical research on geothermal energy production from abandoned oil and gas wells,

but it must be noted that there will be several practical considerations, including the construction of double pipe and the cover of heat insulation material.

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List of symbols with units

A_r	flow area of extraction well, m^2 ; $A_r = \pi r_1^2$
A_R	flow area of injection well, m^2 ; $A_R = \pi(R^2 - r_2^2)$
b	thickness of insulation material, m
C_p	specific heat of fluid, J/(kg °C)
C_W	rock specific heat, J/(kg °C)
d_e	hydraulic diameter, m
H	depth below surface, m
H_1	enthalpy of injected fluid, kJ/kg
H_2	enthalpy of extracted fluid, kJ/kg
h_1''	inlet enthalpy of turbine, kJ/kg
h_2	outlet enthalpy of turbine, kJ/kg
h_{r_1}	heat exchange coefficient of internal wall of extraction well, $W/(m^2 °C)$
h_{r_2}	heat exchange coefficient of external wall of extraction well, $W/(m^2 °C)$
h_W	heat exchange coefficient of external wall of injection well, $W/(m^2 °C)$
k_l	heat conductivity coefficient for unit length, $W/(m °C)$
K_W	rock thermal conductivity, $W/(m °C)$
m	mass flow rate of fluid, kg/s
m_{was}	mass flow rate of waste water, t/h
P_{net}	net output power, kW
Q	heat obtained from rocks, kW
r	radial distance from the central axis, m
r_1	inner radius of extraction well, m
r_2	external radius of extraction well, m; $r_2 = r_1 + b$
r_w	latent heat of vaporization, kJ/kg
R	radius of injection well, m
S_{rR}	heat exchange rate between injection and extraction well, °C/s
S_{RW}	heat exchange rate between fluid and rocks, °C/s
T_{biao}	the temperature at the ground surface, °C
T_g	geothermal gradient, °C/km
T_{in}	inlet temperature of fluid at wellhead, °C
T_{out}	outlet temperature of fluid at wellhead, °C
T_r	fluid temperature of extraction well, °C
T_R	fluid temperature of injection well, °C

T_W	rock temperature, °C
T_{wall}	rock temperature at the wall, °C
T_{was}	waste water temperature, °C
V	flow rate, m/s
V_{in}	inlet flow rate of the injected fluid, m/s
z	the vertical distance from earth surface, m
λ_S	thermal conductivity of insulation material, $W/(m °C)$
ρ_W	rock density, kg/m^3
λ	friction factor
Δ	absolute roughness
ΔP	flow resistance, Pa
X	the proportion of electricity used by electric power plant, %
η_Z	unit efficiency, %

References

- [1] Earth Policy Institute. Data for world geothermal power generation nearing eruption, <http://www.earthpolicy.org/Updates/2008/Update74data.htm#table1>; 2008.
- [2] Bertani R. Geothermal power generation in the World 2005–2010 update report. In: Proceedings World Geothermal Congress 2010, Bali, Indonesia, April 25–30, 2010.
- [3] Gallup DL. Production engineering in geothermal technology: a review. *Geothermics* 2009;38:326–34.
- [4] Stáhl G, Pátzay G, Weiser L, Kálmán E. Study of calcite scaling and corrosion processes in geothermal systems. *Geothermics* 2000;29:105–19.
- [5] Barbier E. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews* 2002;6:3–65.
- [6] Lei Q, Wang H, Wei W. Potential analysis on exploration of geothermal resources in oil and gas fields. *Natural Gas Industry* 2008;28:127–9.
- [7] Kujawa T, Nowak W, Stachel AA. Utilization of existing deep geological wells for acquisitions of geothermal energy. *Energy* 2006;31:650–64.
- [8] Davis AP, Michaelides EE. Geothermal power production from abandoned oil wells. *Energy* 2009;34:866–72.
- [9] Wei YZ, Wang FQ, Ren BY. Drainage and production by using geothermal in Huabei oil region. *Oil Drilling & Production Technology* 2009;31:93–5.
- [10] Davis AP. Geothermal power production from abandoned oil wells. Ph.D. thesis. University of Texas at San Antonio, USA; 2009.
- [11] Alfonso GG, Gilberto EP, Isaías HR. Study on the flow production characteristics of deep geothermal wells. *Geothermics* 2002;31:141–67.
- [12] Bu XB, Tan YF, Li BX. Heat and mass transfer and creep in underground oil storage with cavern. *Journal of Xi'an Jiao Tong University* 2009;43:104–8.
- [13] Kim EJ, Roux JJ, Rusaouen G, Kuznik F. Numerical modeling of geothermal vertical heat exchangers for the short time analysis using the state model size reduction technique. *Applied Thermal Engineering* 2010;30:706–14.
- [14] Rémi R, John RT. A theoretical model for the prediction of the critical heat flux in heated microchannels. *International Journal of Heat and Mass Transfer* 2008;51:1216–25.
- [15] Zhang XM, Ren ZP, Mei FM. Heat transfer. 4th ed. Beijing: China Construction Industry Press; 2001.
- [16] Li RX. Basis of finite volume method. 2nd ed. Beijing: National Defense Industry Press; 2008.
- [17] Tao WQ. Numerical heat transfer. 2nd ed. Xi'an: Xi'an Jiao Tong University Press; 2001.
- [18] Wu ZJ. New energy and renewable energy utilization. 1st ed. Beijing: Mechanical Industry Press; 2006.
- [19] Yan LG, Gu GB, He DX. Electricity generation using renewable energy. 1st ed. Beijing: China Electric Power Press; 2009.