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SIMULATION OF GEOTHERMAL ENERGY PRODUCTION UTILIZING ABANDONED OIL AND GAS WELLS

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A B S T R A C T

Abandoned oil and gas wells (AOGWs) with suitable reservoir temperatures present a promising opportunity to convert subsurface heat into thermal energy or electricity for various applications. This study developed a rigorous thermodynamic model for a single-flash geothermal power plant utilizing a double-pipe direct heat exchanger (DHE), leveraging data from existing literature and modeling via Engineering Equation Solver (EES) software. The model simulates the system using R134a as the working fluid, assessing the influence of rock properties, geothermal gradient, DHE geometry, insulation thickness, mass flow rate of the working fluid, and alternative working fluids on heat extraction efficiency. This innovative approach allows for the efficient utilization of available geothermal heat resources, thereby enhancing the potential for sustainable energy generation. Key findings reveal that the power generation potential from AOGWs employing DHEs is significantly affected by the geothermal gradient within the well, the length of the heat exchanger, and the thermal conductivity of the surrounding rock. Additionally, the model projects the system's long-term performance over a 20-year period, emphasizing the importance of variable fluid characteristics inside the exchanger. Overall, the simulations underscore the necessity of carefully considering these factors to optimize energy extraction from AOGWs. The results highlight the feasibility of harnessing geothermal energy in low-flow-rate conditions, ultimately contributing to the sustainability of energy resources and offering insights for future developments in geothermal energy systems. This approach not only addresses environmental concerns associated with AOGWs but also positions them as viable assets for renewable energy generation.

Keywords: geothermal energy; abandoned hydrocarbon wells; power generation.

Date submitted: 17.09.2024 **Date accepted:** 04.12.2024

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1. Introduction

Geothermal energy, a renewable resource stored in hot rocks, can be utilized for various applications, including power generation and direct use, primarily depending on the temperature of geothermal reservoirs. Geothermal sources are generally categorized into high-temperature (>150°C), medium-temperature (80-150 °C), and low-temperature (<80 °C) sources. High-temperature geothermal resources are often utilized for electricity generation. Medium- to low-temperature resources are appropriate for direct use applications, including building heating and cooling, as well as agricultural and industrial purposes [1, 2].

The inaugural geothermal power plant (GPP) was established in Italy in 1904. Since then, advancements in geothermal power technologies have reduced the necessary resource temperature from high temperature (traditional geothermal power plants) to medium temperature (binary geothermal power plants). Recent research indicates that global geothermal power capacity exceeded 15.95 GWe in 2020. The projected growth rate for 2005 is 18.5%, which is below the approximately 25% growth rate observed over the preceding decade [3]. The decline in estimations may be attributed to a) competition from wind, solar, and natural gas power plants [4], which present lower risks, shorter payback periods, and reduced electricity production costs, b) the persistent sluggish adoption of geothermal-specific policies, laws, and regulations, and c) bureaucratic delays [5].

Recent figures indicate that approximately 20 to 30 million oil and gas wells worldwide are classified as abandoned. Retrofitting abandoned oil and gas wells (AOGWs) for the extraction of geothermal energy is seen as a lucrative strategy to prolong the overall economic lifespan of oil and gas wells [6].

Moreover, employing AOGWs for geothermal extraction has numerous advantages, including:

1. The presence of the wellbore eliminates the need for drilling activities, rendering the technology nearly 50% more cost-effective [6].

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2. The existing conditions, along with the thermal and geological properties of wells, exploration data, reservoir and fluid properties, completion data, and production history, are already established [7].
3. Casing, cement, and wellbore, along with the installation of inner piping, can also be utilized in geothermal energy extraction.
4. The selection of circulating fluid can be simply made due to favorable thermodynamic features.

The availability of geothermal energy renders it an excellent baseload source, as it is unaffected by weather conditions and can operate 98% of the time. The advantages of utilizing AOGWs will aid in eliminating substantial exploration and production cost impediments associated with geothermal energy, hence supporting the maintenance of geothermal power growth rates at 2020 levels. Geothermal fluid can be obtained by an artesian well; otherwise, a production pump or downhole heat exchangers (DHEs) are necessary. Two primary configurations of DHEs exist: open-loop and closed-loop. The open-loop configuration requires at least one production well and one re-injection well. The working fluid (geothermal fluid) is re-injected, subsequently heated by the hot formation/geothermal fluid during circulation within the reservoir, and ultimately extracted to the surface via the production well [8]. Conversely, closed-loop systems consist of a network of pipes that retain and isolate a working fluid from the heated formation or geothermal fluid. Open-loop systems frequently experience issues such as corrosion, scaling, and cavitation, contingent upon the characteristics of the geothermal fluid, whereas closed-loop systems are devoid of risks associated with geothermal fluid due to the absence of contact between the geothermal and working fluids [9].

Considering the benefits, numerous researchers focused on power generation through closed-loop DHEs, providing numerical models in geothermal wells and retrofitting AOGW. The authors examined the effects of diverse design alternatives and factors, including circulation rate, properties of the circulating fluid, wellbore geometries, and regional characteristics such as formation rock type [10]. Closed-loop DHEs generally consist of two types: U-tube and double-pipe DHEs. The design of the DHE mostly relies on the diameter, type of pipe employed, and insulation that can be incorporated to inhibit heat transfer between pipes. AOGWs can be upgraded with U-tube DHEs by inserting the tube into the decommissioned well and filling the space with grout. U-tube DHEs are identifiable by their U-shaped bent tube at the base of the parallel tubes, allowing the circulating fluid to be pumped via one tube and exit through the other. U-tube double heat exchangers are predominantly utilized in shallow wells specifically for heating and cooling systems. Gharibi et al. investigated the feasibility of employing abandoned oil wells as a geothermal energy source through the application of U-tube double heat exchangers (DHEs). The authors indicated that partial insulation is required on the exit pipe. This may be especially difficult due to the diminutive size of that sort of well [11].

Double-pipe heat exchangers are utilized for obtaining geothermal energy from AOGWs. Double-pipe heat exchangers can function in two primary flow configurations: 1) fluid is pumped downward through the outer annulus and upward through the insulated inner pipe, 2) fluid is pumped downward through the insulated inner pipe and upward through the outer annulus. The first kind is predominantly favored in double-pipe heat exchanger applications because to its superior heat transfer rate. Insulation is applied to the inner pipe to reduce heat loss to the lower temperature working fluid entering the annulus or vice versa [2, 12].

The choice of working fluid in DHEs is essential for optimizing performance in power generation systems. Consequently, the thermal characteristics of fluids significantly influence economic viability, environmental considerations, component sizing, and cycle efficiency. The influence of working fluid on the efficiency of direct heat exchangers and heat/power generation systems has been extensively researched [13]. The criteria for selecting a working fluid are grounded in thermodynamic properties, including critical temperature and pressure, density, boiling point, and latent heat, as well as environmental, safety, and health considerations such as ozone depletion potential (ODP), global warming potential (GWP), toxicity, and flammability. Water is neglected and primarily utilized as a working fluid in fossil-fueled power plants. Conversely, organic fluids that evaporate at temperatures lower than water are utilized to enhance cycle efficiencies in medium to low temperature geothermal fields [14-16].

The AOGWs has significant geothermal potential, with reservoir temperatures reaching 150-250 °C. Extracted geothermal potential can be utilized for direct uses when reservoir temperatures are low (<80 °C), whereas electricity generation is feasible when reservoir temperatures are sufficiently high (>100 °C) [17]. This study examines electricity generation from AOGWs. The choice of power cycle is determined by the reservoir temperatures. Given that the reservoir temperature range for this investigation is 120-130 °C, a single flash geothermal cycle utilizing a closed-loop DHE is used [18].

This study aims to create a thermodynamic model for a single flash geothermal power plant (GPP) with direct heat exchange (DHE) and perform a sensitivity analysis on various ground and cycle parameters, including ground conductivity, geothermal gradient, insulation thickness of DHE, type of working fluid, flow rate of the working fluid, and the future power generation performance of the plant. The objective of the model is to furnish investors with an initial assessment of technical feasibility.

2. Description of the system

The system presented in the study comprises two primary portions (A and B), as illustrated in the figure 1. The DHE is depicted on the left side of the image (Section A), where it directly facilitates the extraction of heat from the rock formation. The B section pertains to the conversion of supplied heat into electricity.

The coaxial heat exchanger is selected for its superior performance compared to other types of heat exchangers and designs, as it minimizes pressure drop. Due to its superior heat extraction capabilities, reverse flow is favored for the circulating fluid direction of the DHE. The cold fluid enters the annulus in the reverse flow. As it descends, its temperature increases and emerges from the inner tube as heated fluid. To address the issue of heat loss, the inner pipe is insulated with glass wool to prevent a reduction in temperature during the circulation process [19].

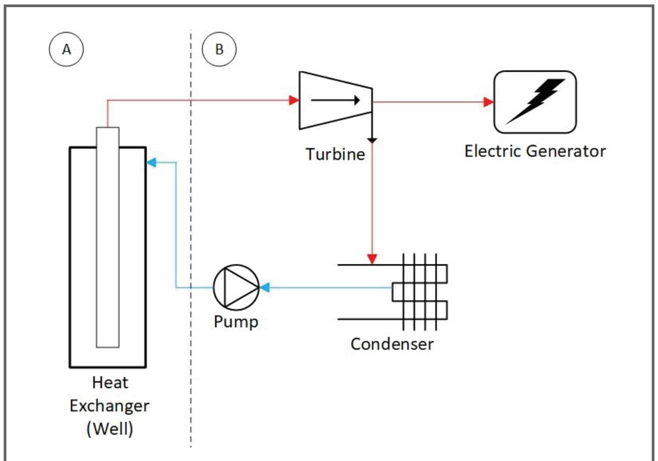

Fig. 1. Schematic representation of the examined system

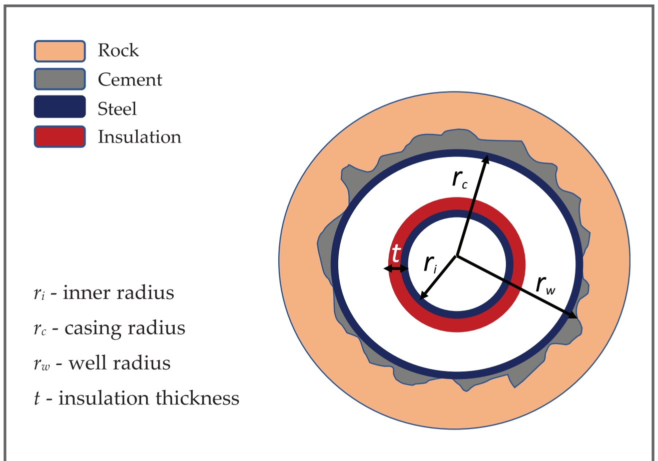

Fig. 2. The cross section of wellbore HE

Furthermore, the cross-section of the heat exchanger is depicted in figure 2. The cement is present between the rock formation and the annular pipe along the well.

The temperature gradient is considered to be 3 °C per 50 meters. The diameter of the current abandoned well is 0.1778 meters. The casing diameter (annulus diameter) is established at 0.1504 m due to the existing well diameter. The dimensions of the DHE, inner pipe diameter, pipe materials, and additional characteristics are regarded as variables to assess their impact on the heat extraction rate.

3. Methodology

Thermodynamic analysis of geothermal power generation (GPG) utilizing double heat exchangers (DHEs) for aquifer-operated geothermal wells (AOGWs) has been conducted, and a model of the system has been developed using Engineering Equation Solver (EES) software, a robust tool for addressing engineering challenges. EES provides multiple integrated libraries including thermodynamic and thermophysical parameters, making it a valuable tool for addressing thermodynamic and heat transfer challenges.

3.1. The assumptions

The major assumptions underlying the analysis are enumerated as follows:

- The system operates under steady-state conditions with a constant flow rate of the working fluid.
- The temperature profile of the rocks along the well was previously acquired during the well testing process and is regarded as linear with depth.
- DHE is assessed at 50 m intervals along the complete length, with primary parameters such as temperature, pressure, and enthalpy of the fluid examined for each interval.
- The overall depth of DHE is established at 2500 for the baseline scenario.
- The output parameters of the working fluid in each division are regarded as input parameters for the subsequent division.
- The isentropic efficiency of the turbine and generator is assumed to be 85% and 95%, respectively.
- The specifications and thermal characteristics of the Downhole Heat Exchanger (DHE) are obtained from multiple sources enumerated in table 1.

Table 1
The attributes and operational parameters of the downhole heat exchanger

Parameter	Units	Value	Reference
Diameter of the inner pipe	m	0.0779	[20]
Diameter of the annular space	m	0.1504	
Diameter of the geothermal borehole	m	0.1778	
Thermal conductivity of the pipe	W/m K	4, 231	[21]
Thermal conductivity of the insulating material (glass wool)	W/m K	0.043	
Thickness of the insulation	mm	2-12 (interval of 2)	

3.2 Calculation of Heat Transfer

Heat transfers are essential for assessing the system's heat extraction rate. In the annular segment, the working fluid is in direct contact with the steel casing wall. A cement exists between the casing and the rock formation. It is thought that heat is conducted from the rock formation to the wall and convected between the wall and the circulating fluid. The heated working fluid ascends through the inner tube from the bottom of the well. Subsequent to that phase, heat transfer transpires solely along the pipe's wall until it reaches the surface [22, 23].

The conductive heat transfer coefficient is a crucial parameter in heat transfer, ascertainable by the equation 1 [20]:

$$\frac{1}{h_{cd}} = \frac{D_w \ln\left(\frac{4\sqrt{{}_{s}t}}{D_w}\right)}{2k_{rock}} \quad (1)$$

where: h_{cd} is conductive heat transfer coefficient, D_w is the diameter of the wellbore, k_{rock} is thermal conductivity of rock, t is elapsed time, α_s is thermal diffusivity of rock.

Furthermore, thermal diffusivity can be articulated as [24]:

$$\alpha_s = \frac{k_{rock}}{{}_{rock}c_{p,rock}} \quad (2)$$

where: ρ_{rock} is the density of the rock, c_p is the specific heat of the rock.

The working fluid is pumped across the annulus due to convective force. The shape of DHEs and the characteristics of the working fluid significantly influence the values of the convective heat transfer coefficient. Convective heat transfer coefficient (h_{cv}) is determined by Eq. (3):

$$h_{cv} = \frac{Nu \cdot k}{D_h} \tag{3}$$

where h_{cv} is convective heat transfer coefficient, D_h is the hydraulic diameter, k is the thermal conductivity of working fluid

According to some properties, flow is totally laminar when the Reynolds number is less than or equal to 2300, whereas it becomes turbulent when the Reynolds number exceeds 2300 [25]. Upon ascertaining the pertinent thermodynamic parameters utilizing the water temperature within the well, and applying the Dittus-Boelter equation, turbulent flow is presumed within the pipes, leading to the Nusselt number [26]:

$$Nu = 0.023\,Re^{0.8} Pr^{0.4} \tag{4}$$

where Re, Pr is Reynolds and Prandtl numbers.

The dimensionless formulas indicating the dependencies are presented in Eq. (5):

$$Re = \frac{D_w \rho}{\mu}; \quad Pr = \frac{c_p}{k} \tag{5}$$

where ρ is the density of the fluid, μ is dynamic viscosity of the fluid, c_p is specific heat capacity of the fluid, k is thermal conductivity of the fluid.

The entire resistance of the casings can be disregarded in relation to rock thermal resistivity. Consequently, the overall heat transfer coefficient can be expressed as the summation of the individual heat transfer coefficients:

$$U_t = \left(\frac{1}{h_{cd}} + \frac{1}{h_{cv}}\right)^{-1} \tag{6}$$

where U_t is total heat transfer coefficient of heat flow in downward pipe, h_{cd} , h_{cv} are conductive and convective heat transfer coefficient The subsequent equation (7) depicts the thermal transfer in the descending conduit [20]:

$$\dot{Q}_{annular} = \pi D_w U_t \left(T_{w,z} - T_{i,z}\right) z \tag{7}$$

where $\dot{Q}_{annular}$ is heat transfer rate in downward flow, T_w is the temperature of the rock at depth z, $T_{fluid\text{-}down}$ is the temperature of working fluid in the annular pipe, Δz is the length of the pipe.

The equations for upward flow will differ from those for downward flow:

$$\dot{Q}_{inner} = D_t U_{to} \left(T_i - T_o\right) z \tag{8}$$

where $\dot{Q}_{inner}$ is heat transfer rate in upward flow T_i is the temperature of the working fluid in the inner tube, T_o is the temperature of working fluid in the annular pipe. The total heat transfer coefficient for upward flow, which has direct relations with insulation thickness can be expressed as Eq. (9):

$$U_{to} = \frac{1}{\frac{1}{h_f} + \frac{D_t}{K_t}\ln\frac{D_{t,o}}{D_t} + \frac{D_t}{h_{f,o}.D_{t,ins}} + \frac{D_t}{K_{ins}}\ln\frac{D_t}{K_{ins}}} \tag{9}$$

where U_{to} is total heat transfer coefficient of heat flow in inner pipe, D_t is internal diameter of inner pipe, $D_{t,o}$ is outer diameter of inner pipe, $D_{t,ins}$ is insulation diameter, K_{ins} and K_t are the thermal conductivity of insulated material and inner pipe, h_f and $h_{f,o}$ are the convective heat transfer coefficients for inner and outer pipe, respectively [21].

3.3. Calculation of Pressure Drop

The pressure drop in a vertical cylindrical pipe can be attributed to three components: hydrostatic pressure drop owing to gravity, frictional pressure drop, and kinetic pressure drop. The third factor can be disregarded in the computations. As the working fluid descends within the well, frictional forces manifest against the flow direction. However, that type of frictional loss owing to forces is being addressed with the use of a hydrostatic column. The hydrostatic or gravitational pressure drop is contingent upon the fluid's density, its characteristics, and the frictional pressure drop.

Neglecting the kinetic pressure drop, the pressure differential, ΔP, in a cylindrical pipe is equivalent to the aggregate of gravitational and frictional pressure losses, which may be determined using the equation (10):

$$\Delta P = \rho g L + \frac{f \rho L u^2}{2D_h} \tag{10}$$

where ρ is the density of working fluid, L is the length of DHE, f is the friction factor, u is the velocity of the working fluid, D is the diameter of the pipe [21].

The gravitational pressure loss will be eradicated in closed systems. From an alternative perspective, DHEs absorb heat from hot rock formations, resulting in varying density with increasing temperature and pressure, which consequently leads to a pressure drop owing to gravity [27].

The ultimate equation for determining pressure drop in the lower section of the DHE is expressed as in Eq. (11):

$$\Delta P = \rho g L + \frac{f \rho L u^2}{2D_h} + \frac{1}{2}\rho(\Delta u)^2 \tag{11}$$

where ΔP is pressure drop, ρ is density of the fluid, L is length of DHE, f is friction factor, D_h is hydraulic diameter, u is velocity of the working fluid.

In addition, pressure output (P_0) will be found from Eq. (12):

$$P_0 = P_i - \Delta P \tag{12}$$

where ΔP is pressure drop, P_0 is output pressure, P_i is inlet pressure.

3.4. Calculation of Power Generation

The DHE is segmented into 50-meter divisions along its complete length, and by applying the principles of heat transfer and pressure drop to each segment, the exit temperature and pressure of the working fluid from the DHE are ascertained. Consequently, the total heat transfer from the DHE is determined by the equation (13):

$$\dot{Q} = \dot{m}_f c_p \left(T_i - T_o\right) \tag{13}$$

where $\dot{Q}$ is total heat transfer rate from DHE, $\dot{m}_f$ is mass flow rate of the working fluid, c_p is specific heat capacity of the fluid, T_i is the temperature of the working fluid in the inner tube, T_o is the temperature of working fluid in the annular pipe.

The heated working fluid, originating from the DHE, is sent to the power plant for electricity generation. The power plant is located in section B of the figure 2 and functions on the Rankine cycle. The turbine, generator, condenser, and pump are the essential components of the power plant [20, 28, 29].

$$\dot{W}_{tur} = \dot{m}_f \left(h_1 - h_2\right)\eta_g \quad (14)$$

where $\dot{W}_{tur}$ is generated power, η_g is generator efficiency, h_1 is inlet enthalpy of the turbine, h_2 is out enthalpy of the turbine, $\dot{m}_f$ is mass flow rate of the working fluid.

The necessary power for the pump can be derived from the equation (15):

$$\dot{W}_{pump} = \dot{m}_f \left(h_4 - h_3\right) / \eta_{pump} \quad (15)$$

where $\dot{W}_{pump}$ pump power, η_{pump} is pump efficiency, $\dot{m}_f$ is mass flow rate of the working fluid, h_3 is inlet enthalpy, h_4 is out enthalpy.

Consequently, the net power output and thermal efficiency (cycle performance) can be articulated as Eq. (16) and (17), correspondingly:

$$\dot{W}_{net} = \dot{W}_{tur} - \dot{W}_{pump} \quad (16)$$

$$\eta_{thermal} = \dot{W}_{net} / \dot{Q} \quad (17)$$

where $\dot{W}_{pump}$ pump power, $\dot{W}_{tur}$ is generated power, $\dot{W}_{net}$ is net power, $\eta_{thermal}$ is thermal efficiency, η_{pump} is pump efficiency, $\dot{Q}$ is total heat transfer rate from DHE.

3.5. Parametric study

A parametric analysis is conducted to assess the feasibility of power generation from AOGWs utilizing DHE. To evaluate the efficacy of the Direct Heat Exchange (DHE) system for electricity production, parameters including mass flow rate, insulation thickness, DHE depth, pipe diameters, temperature gradient, and working fluid types are taken into account (table 2).

4. Results

The thermodynamic model constructed using EES software is employed to simulate the GPP-DHE system. Over 250 simulations have been conducted to examine the impact of parameters including geothermal gradient, ground characteristics, insulation thickness, well depth, mass flow rate, and kind of working fluids on system performance. For the simulations, the following parameters were selected: the working fluid is R134a, the depth of the DHE system is 2500 meters, and the temperature gradient is 3 °C per 50 meters. Additionally, the specific heat capacity of the rock is 800 J/kg·K, and the rock density is 2600 kg/m³.

4.1. The impact of soil characteristics

The characteristics of the rock, including conductivity, density, specific heat capacity, and geothermal gradient, are essential to the heat exchange process and the efficiency of power generation. The correlation between several rock parameters, including density, specific heat, and conductivity, and ground thermal resistance over time was assessed. Figure 3 and 4 show that the rock conductivity has a remarkable impact on the transfer of the heat from rock as well as the wellhead temperature in comparison with rock density and specific heat.

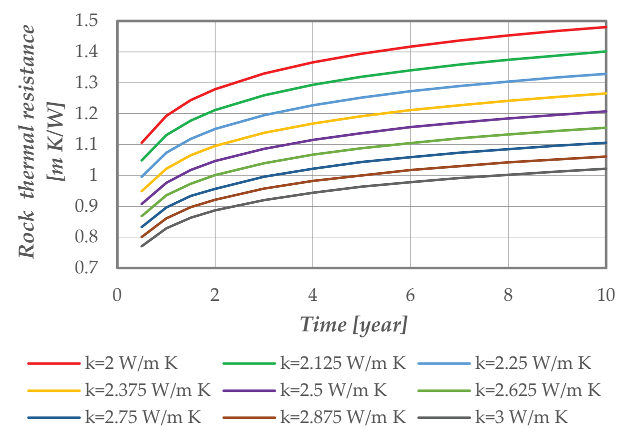

Fig. 3. Rock resistance varies over time based on the conductivity of the rock

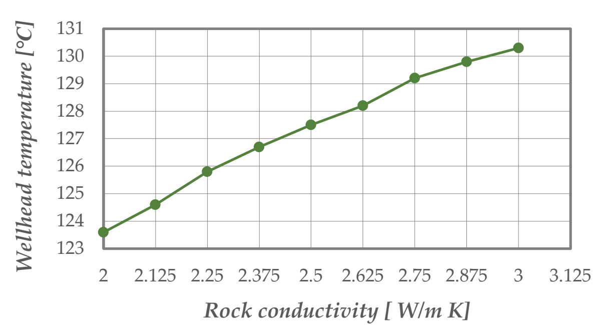

Fig. 4. Influence of rock conductivity on wellhead temperature

Table 2

Key parameters utilized in the paper [18, 20]

Parameters	Value
Geothermal temperature gradient	2-5 °C/50 m
Depth of DHE	1000-3000 m (with increment of 50 m)
Diameter of the inner tube	0.0779 m and 0.1214 m
Rock density	2080-3120 kg/m³ (with increment of 260 kg/m³)
Rock specific heat	640-920 J/kg.K (with increment of 80 J/kg.K)
Rock conductivity	2-3 W/m K (with increment of 0.125 W/m K)
Mass flow rate of the working fluid	10-90 kg/s (with increment of 10 kg/s)
Type of working fluid	R134a (main), R22, R245fa and n-butane

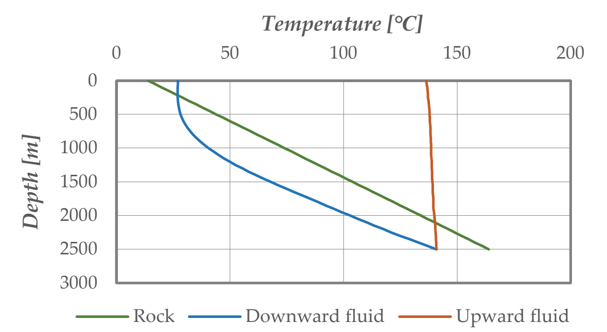

Fig. 5. The profile of temperature along the well

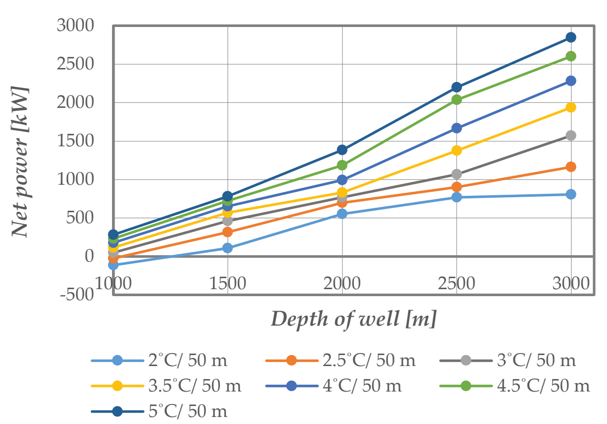

Fig. 6. Impact of the geothermal gradient and the depth of DHE on net power output

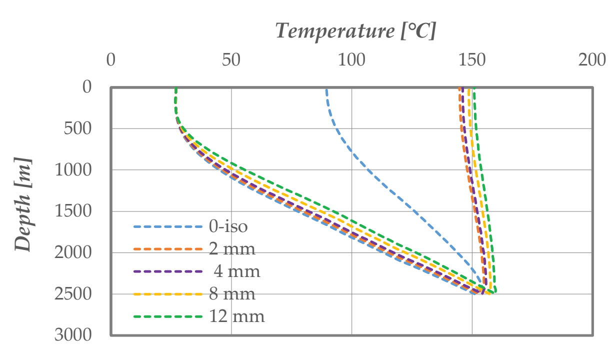

Fig. 7. Effect of the insulation thickness

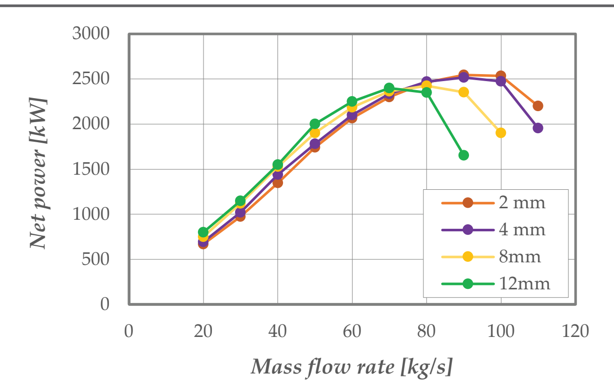

Fig. 8. Effect of insulation thickness to the mass flow rate

The thermal resistance exhibits greater fluctuations during the subsequent decade due to a reduction in rock conductivity. As indicated in table 2, the value of rock conductivity has been taken between 2 and 3 [W/m K] with increment of 0.125.

It is evident from the figure 4 that conductivity of rock can induce a substantial temperature change at the wellhead temperature.

4.2. Geothermal gradient

In most sections of the simulation, the geothermal gradient is set at 3 °C per 50 meters, with a surface temperature assumed to be 13.89 °C, as referenced in [27]. The geothermal gradient is measured at 2-5 °C every 50 meters for comparative purposes, under the assumption of linearity. Figure 5 demonstrates that within the initial 250 m, the working fluid undergoes cooling, followed by heating towards the lower section. The temperature of the working fluid decreases insignificantly from the bottom until it reaches the surface. The refrigerant is R134a, and the mass flow rate is 30 kg/s.

The impact of the geothermal gradient and depth is examined in relation to the net power generation of the facility (fig. 6). The net power generation of the DHE has been reported to rise with the gradient and depth. For example, altering the depth of DHE from 2000 to 2500 meters results in a net power boost of over 50% across nearly all temperature gradients.

Furthermore, low geothermal gradients (below 3 °C/50 m) are deemed unsuitable for the DHE, as the desired energy output is inferior to the required energy input. Consequently, the recommended gradient to be implemented exceeds 3 °C/50 m, or the depth of the DHE should surpass 2000 m.

4.3. Effect of insulation thickness and mass flow rate

In power generation with DHE, the inner pipe must be insulated to prevent heat loss from the working fluid during upward flow. Glass wool (k=0.043 W/m K) has been chosen as an insulating material. The insulation may be put at any location based on the heat loss.

The effect of the insulation on the temperature distribution across the well is illustrated in figure 7. A few millimeters of insulation can mitigate significant fluctuations in wellhead temperature. For instance, when the insulated inner pipe is employed, the wellhead temperature ranges from 145 to 151 °C, whereas it diminishes to 89 °C in the absence of insulation on the inner pipe.

Furthermore, the wellhead temperature rises with enhanced insulation thickness, as the greater insulation inhibits the transmission of heat from the inner pipe to the outer pipe. However, the wellbore radius cannot be altered due to the pre-existing well. Consequently, an increased insulation layer can diminish the diameter of the external pipe. Consequently, a reduction in the annular space will lead to an increase in the velocity of the working fluid, resulting in greater pressure loss and higher pump power consumption.

The mass flow rate of the working fluid is a critical metric in geothermal energy production utilizing DHE from AOGWs. A direct correlation exists between the mass flow rate of the working fluid and the insulation thickness of the inner pipe. Consequently, as the insulating thickness increases, the volume of the annular gap diminishes. It mostly impacts the bulk flow rate of the fluid. Figure 8 illustrates the impact of insulation thickness on mass flow rate and net power output.

The mass flow rate is a critical parameter in the system; therefore, insulation thickness that minimizes heat loss while maximizing mass flow rate should be used. Consequently, the 8 mm thickness for insulation may be chosen in accordance with the figure 8.

4.4. The selection of working fluids

R134a is a hydrofluorocarbon refrigerant commonly used as a replacement for R12 in automotive and domestic refrigeration due to its favorable thermodynamic properties and non-flammability. With a molecular weight of 102.03 g/mol and a boiling point of -26.3 °C, it is suitable for moderate cooling applications. R22, a hydrochlorofluorocarbon, has been widely used in air conditioning and refrigeration for its efficiency and material compatibility, though its use is declining. It has a molecular weight of 86.47 g/mol and a boiling point of -40.7 °C, making it ideal for low-temperature systems. R125, often found in blends like R410A, adds stability and fire safety due to its non-flammable nature. It has a molecular weight of 120.02 g/mol and a boiling point of -48.45 °C, enhancing the performance of refrigerant mixtures.

R134a, a popular refrigerant with no ozone depletion potential. R22, a moderate ozone depletion potential, whereas R125, a component in refrigerant blends, has a high GWP of 3500 but is crucial for maintaining thermodynamic stability [30].

The selection of working fluids is based on the performance of the DHE system, thermal efficiency, power generation, and environmental considerations.

Figure 9 signifies that the refrigerant fluids can be circulated at a higher flow rate compared to hydrocarbon working fluids in the DHE system. The working fluid R134a achieves the maximum net power of 2467 kW at a mass flow rate of 90 kg/s, while other fluids exhibit inferior net power outputs. It may be noticed that n-butane, a hydrocarbon fluid, exhibits superior performance compared to others at low mass flow rates.

Figure 10 depicts the trend of thermal efficiency in relation to the rising mass flow rate of various working fluids. It is evident that for all types of working fluids, thermal efficiency diminishes as mass flow rate increases. R134a and n-butane exhibit superior thermal efficiency, whereas R22 and R125 demonstrate a declining trend in thermal efficiency.

Moreover, environmental factors significantly influence the selection of working fluids alongside thermodynamic performance. Consequently, although many fluids exhibit significant performance, they are very flammable and pose environmental hazards. Therefore, they are not suitable for use as working fluids in the DHE system.

4.5. The future performance of the DHE system

Numerous simulations have been conducted shortly after the initiation of power generation. The drop in power output due to continuous generation during the twenty-year period since initial production is illustrated in figure 11. The line graph illustrates the projected trend of the bottomhole temperature. The bottomhole temperature of the working fluid has a substantial drop during the initial year, after which this metric begins to diminish marginally. The cause is the decrease in temperature at the well's wall. The trend for power reduction is nearly identical. Consequently, following a decline over the initial five years, the trajectoy of power decrease aligns with the pseudo-state condition. A decline of approximately 30% in electricity generation is anticipated during the next twenty years.

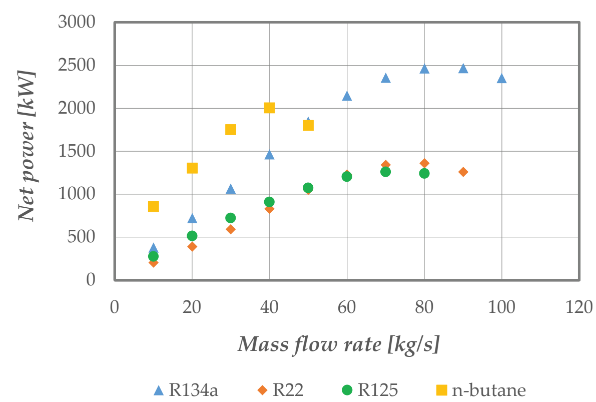

Fig. 9. The net power for various operating fluids

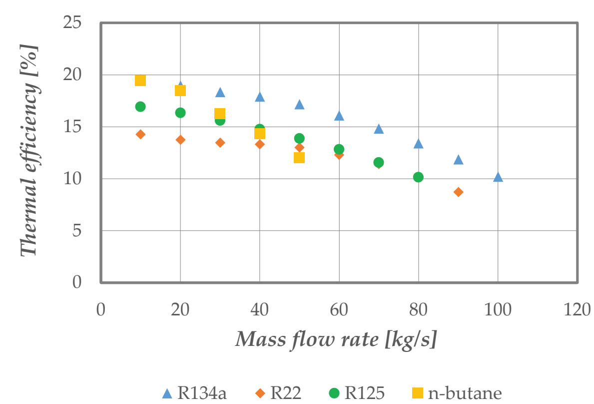

Fig. 10. The thermal efficiency depending on mass flow rate

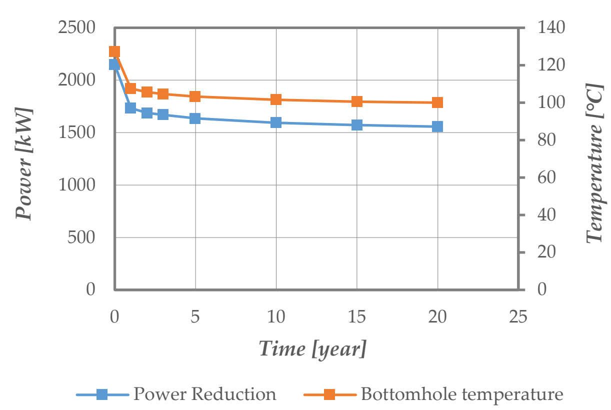

Fig. 11. Power reduction and bottomhole temperature depending on time

Conclusion

1. The extraction of geothermal energy from AOGWs through DHEs presents significant promise for future energy prospects. The thermodynamic models for a geothermal power plant utilizing a coaxial DHE system have been developed using EES software to assess the feasibility of electricity generation from AOGWs.
2. The DHE is a well completion technology that enables the utilization of heat without the extraction of geothermal fluids. Consequently, the energy required by the pump for reinjection and the associated environmental implications are significantly diminished. Furthermore, corrosion and scale issues are overlooked due to the absence of direct contact between the working fluid and the rock formation.
3. The influence of rock characteristics, insulation, mass flow rate, and types of working fluids is analyzed in a parametric research. The results indicated that rock conductivity plays a considerable influence in power generation compared to rock density and specific heat. Consequently, elevated rock conductivity correlates with increased wellhead temperature and net power output. The elevated geothermal gradient and well depth are crucial for enhancing the efficacy of the DHE system. It is advised that the inner pipe of the DHE system be insulated. Consequently, it is crucial for preventing heat loss and elevating the wellhead temperature.
4. As production time increases, power reduction and bottomhole temperature significantly decline over a period of five years, subsequently aligning with pseudo steady-state conditions.
5. Ultimately, hydrocarbon working fluids demonstrate superior performance compared to refrigerant fluids at low mass flow rates. Consequently, R134a is strongly endorsed as a working fluid in DHE systems to achieve enhanced power production. Consequently, it generates approximately 2500 kW of electricity (depth: 2500 m, ΔT: 3 °C/50, mass flow rate: 89 kg/s, Dt: 0.779 m).

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