FEASIBILITY OF ELECTRICITY GENERATION FROM ABANDONED OIL WELLS IN THE GLOBAL SOUTH

Fidelis J. Usman, Nicolas Kelly
Energy Systems Research Unit, University of Strathclyde, Glasgow, Scotland.

ABSTRACT

This paper looks at the potential of using low-temperature heat from abandoned fossil fuel sites and dedicated boreholes as a zero-carbon solution for electrical power generation. Typically, boreholes are a source of ground-source heat, however, when the heat source is far from the demand, the costs of distribution through piping and pumping can become prohibitive. Additionally, many countries in the Global South have a greater need for cooling rather than heating, especially in urban areas. The paper therefore explores the use of low-grade, ground-source heat to generate electricity via organic Rankine cycles (ORC), as electricity can be transported over long distances with minimal losses and is also the energy source for the most common refrigeration cycle, vapour compression refrigeration (VCR). The paper looks at the case study of Nigeria, a country with a predominant cooling demand in buildings and a significant number of abandoned oil and gas wells, which could be exploited for energy conversion. An initial critical review of low-temperature geothermal heat-to-electricity work is presented. The paper then describes an integrated model, which uses CFD to compute heat recovery from the oil well along with a custom MATLAB model to assess thermal resource depletion and ORC efficiency. The model can be used to assess the feasibility and potential for power generation for communities from abandoned oil wells, this form of electricity generation has an efficiency that can be comparable to or better than PV (>15), and unlike PV, the generated electricity is dispatchable.

This research contributes to the broader goal of diversifying Nigeria’s energy sources and promoting environmentally friendly alternatives in urban energy provision.

Keywords: ORC, electricity, geothermal, abandoned oil wells, numerical analysis.

INTRODUCTION

According to Nairametrics (2022) as of the year 2020, Nigeria had more than 7,000 oil wells scattered around the Niger-delta region, and more than half of which were either suspended or abandoned. There have been several studies (theoretical) done in the past (Cheng et al (2016), Chong et al (2021), Jiang et al. (2016), Wang et al (2016), Macenic and Kurevija (2018)) in a few physical tests carried out (Al-khawaja et al (2021), Sun et al (2018), Xin et al (2012)), to show that abandoned hydrocarbon wells located in areas with high geothermal gradient can be used as low- temperature heat sources for purposes like electricity generation, agricultural applications and space heating.in most of these cases the heat was used for space heating in countries like China and Croatia (Wang et al (2016) and Macenic and Kurevija (2018))and in a few cases for electricity(e.g. Syarifudin et al., 2016)

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Typically, the location of the abandoned oil well is remote from settlements, and this will mean that distribution of heat due to distant urban areas is infeasible.

Further countries in the global south like Nigeria have a need for space cooling in contrast to countries like the United Kingdom, that require heating in winter and much of the transition seasons (Churchill et al(2023)) .

the average annual temperature in Nigeria ranges from 25-32°C [1]. Retrofitting selected abandoned oil wells and their thermal resources for electricity generation can offset increasing demand for space cooling, needed to achieve thermal comfort in hot climates.

REVIEW

Studies conducted on low-temperature geothermal heat-to-electricity with focus on abandoned oil and gas wells, show the technical feasibility of such projects and how they can be adapted to fit the resources in the environment. Syarifudin et al. (2016) ran a simulation to depict operation of retrofitted oilwells to geothermal resources in the Arun region in Indonesia, the results showed that it was technically possible to convert the oil-wells into geothermal resources for either direct use or for electricity generation. Macenic and Kurevija (2018) also simulated the extraction of heat from deep abandoned oil-wells converted to geothermal resources using a coaxial heat exchange. Kurnia et al., (2021) conducted a numerical evaluation the effects of heat extraction from a shallow depth-high geothermal gradient abandoned oilwells in Malaysia for direct use. The results of these simulations showed that even though it was not economically viable to run this project more abandoned oil wells could be added to the system to upgrade the system. Kujawa et al. (2006) [31], Bu et al. (2012) simulated the heat extraction process of a retrofitted oil and gas wells with results showing that it was economically feasible to convert oilwells to geothermal resources in comparison to drilling new geothermal wells. These models use heat exchangers to extract heat from the rock surroundings.

Reinhardt et al (2012) conducted a test for the conversion of deep and high temperature oilfield to produce electricity using a binary cycle in Rocky Mountain Oilfields Testing Centre (RMOTC) showing very promising results. Wang et al (2018) reported that the oil fields in Huabei, Daqing, Zhongyuan and Liaohe in China, were used to test the conversion of these fields to geothermal resources, the heat was used for direct use.

Heat Recovery Systems

There are 2 types of heat exchangers used in extraction of heat from abandoned oil and gas wells 1) Double pipe or coaxial pipe heat exchangers and 2) U-tube heat exchangers (Nian and Cheng (2018)). Figure 1 & 2 show an illustration of a U-tube heat exchanger and a coaxial pipe heat exchanger. The coaxial pipe heat exchanger is more efficient than the U-tube heat exchanger (Nian and Cheng (2018)), hence the use of the coaxial pipe heat exchanger is analysed in this paper. The coaxial pipe heat exchanger in the well is a closed loop. For power generation from a low enthalpy resource, another closed loop which has a working fluid with low boiling point is added to form a second cycle. This setup forms the binary cycle.

The binary cycles are classified according to their working fluids. The organic Rakine cycle (ORC) uses an organic fluid as working fluid while the Goswami and Kalina cycle use ammonia as working fluid.

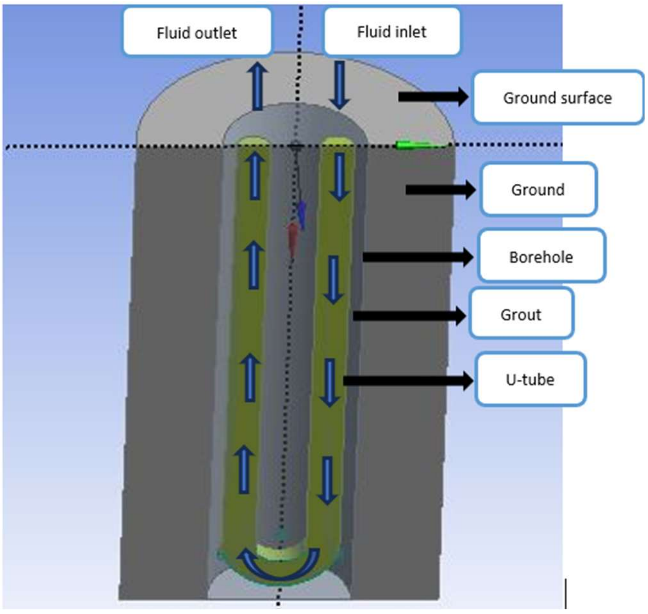

Figure 1. U-tube heat exchanger

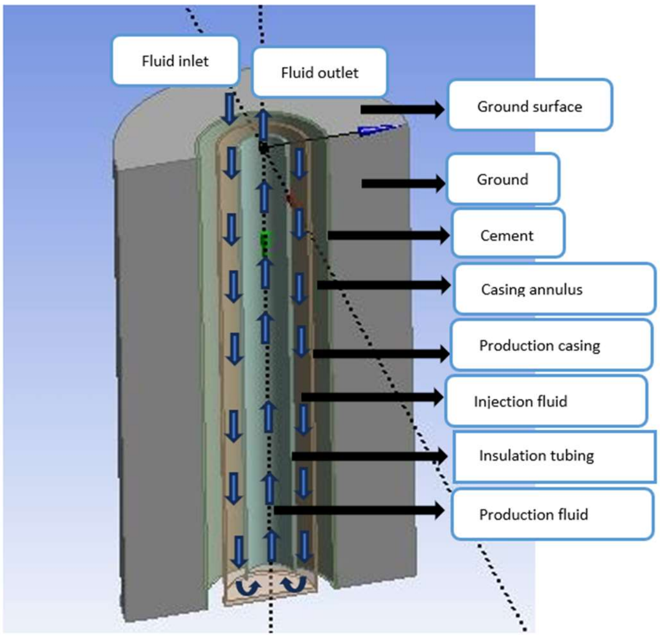

Figure 2. Coaxial pipe heat exchanger

The ORC was used in this paper as it is the most popularly commonly used binary cycle (Nian and Cheng (2018)). Butane was chosen as the working fluid of the ORC because it is compatible with the temperatures available from abandoned oil wells in Nigeria.

Contribution

An integrated model of a heat-to-electricity system has been developed for the case of an abandoned oil well in Nigeria; this comprises a CFD model of the oil well heat exchanger, a MATLAB finite volume model to assess heat depletion in the surrounding rock and an ORC model to determine conversion efficiency. Additionally, a techno-economic study of this system has been undertaken for the case of oil wells in the Niger-delta area of Nigeria.

AIMS AND OBJECTIVES

The aim of this research is to assess the overall feasibility of converting heat from abandoned oil wells to electricity for use in the Global South. This will require

1) the development of an integrated model,

2) simulation of the system performance over multi-year timescale, and

3) assessment of the technical performance.

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METHOD

To assess feasibility of heat-to-electricity from abandoned oil -wells an integrated model has been created. The components of this model are as follows: ANSYS FLUENT CFD has been used to model the ground heat exchanger and to compute the heat extraction from the surrounding rock.

1. MATLAB has been used to develop a thermal model of the rock the surrounding the oil well and simulate thermal depletion and hence to estimate the viable technical and economic life of the heat-to-power system.
2. CoolProp an add-on for MATLAB R2023a was used to model the Organic Rankine Cycle and estimate its thermal efficiency, the tool was also used to the select the appropriate working fluid and the optimal setup of the conversion cycle.

MODELLING

The borehole system modelled in this paper is based on a borehole-heat-to-power system empirical model described by Lin Z. et al (2021). The borehole modelled has the characteristics shown in Table 1.

During the drilling of oil-well, there are several layers of cement that is applied to protect the walls of the well from collapse and shrinkage, this forms a cylindrical cement wall when cured. To retrofit an abandoned oil well a conductor pipe with a closed bottom is inserted into the borehole. An annulus is created between the cylindrical cement walls and the conductor pipe. Lin Z. et al (2021) reported that by filling the annulus with water higher temperature yields were obtained. An open-ended insulated pipe is place in the middle of the production pipe, forming a coaxial pipe heat exchange arrangement. The insulated pipe does not reach the bottom of the production pipe, water is injected into the production pipe and returns to the surface through the insulated pipe.

This heat in the water is passed on to the working fluid in the evaporator of the ORC (Butane), via a heat exchanger, which causes it to super-heat and increase in pressure. The steam from the working fluid enters the chambers of the turbine with high pressure and speed to turn the blades of the turbine. The turbine is connected to a generator for electricity. The steam is cooled at the re-generator by working fluid flowing at a lower temperature. From there it moves to the condenser where it is converted liquid to be pumped through the re-generator to the evaporator to repeat the process.

CFD Borehole Model

The CFD model is a 2D representation of a vertical, coaxial pipe heat exchanger. The pipe is 3020m deep. Because of the length the geometry was scales down to a ratio of (10:1) due to the limitations of computational space. The elements in the mesh amounted to (510,000) and This assumes that the system has radial symmetry around the vertical axis. The borehole heat exchanger (shown in Figure 3) has 5 concentric layers of material. The innermost layer (A) is the pipe which returns hot water to the surface, this is insulated to reduce heat loss. The pipe is surrounded by water pumped down from the surface (B), which picks up heat from the outer surface of the heat exchanger, which is a steel sleeve (C). The sleeve is adjacent to a layer of waterlogged space (D) which is collects heat from the cement grout casing (E), which thermally couples the sleeve to the surrounding rock (F).

Table 1 shows the input parameters of the wellbore, and the working fluid used in the CFD model.

Table 1. Initial model input parameters

Samples (unit)	**Parameters**	**Values**
C_f(J/(kg·°C))	Specific heat of working fluid	4200
C_a(J/(kg· °C))	Specific heat of casing annulus fluid	4200
m (°C/m)	Geothermal gradient	
$\dot{m}$(Kg/s)	mass flow rate	1.157
r_{ii}(m)	Inside radius of the insulation tubing	0.031
r_{io} (m)	Outside radius of the insulation tubing	0.04445
r_{pi} (m)	Inside radius of the production casing	0.06215
r_{po} (m)	Outside radius of the production casing	0.06985
r_{ci} (m)	Inside radius of the intermediate casing	0.11222
r_{co} (m)	Outside radius of the intermediate casing	0.12225
r_h (m)	Radius of cement-formation interface	0.14225
ts (°C)	Temperature at surface	25
$T_{in\,j}$ (°C)	Temperature for working liquid at wellhead	30
Z (m)	Depth of well	3020
λ_e (W/(m·K))	Thermal conductivity of the formation	1.8
λ_{cem} (W/(m·K))	Thermal conductivity of the cement	0.933
λ_{ins} (W/(m·K))	Thermal conductivity of insulation in tubing	0.04
$\lambda_{cem\text{-}a}$ (W/(m·K))	Thermal conductivity of the cement in casing annulus	0.35
ρ_1 (kg/m^3)	Density of working fluid	1000

The heat is transferred from the rock formation to the cement casing via conduction. The working fluid flows down the steel-lined injection pipe picking up heat via convection. The fluid is then transported back to the surface via the innermost insulated pipe.

Figure 3 shows the layout of the coaxial pipe heat exchanger, the surrounding rock formation, and the movement of the working fluid. The model has been validated with the results from Lin Z. et al (2021). The results showed that the temperatures obtained from the well-bore in the CFD model accurately followed the results from the empirical model Lin Z. et al (2021), as shown in Figure 2. This shows that the model built can reliably predict the operation of a ground-coupled coaxial heat exchanger.

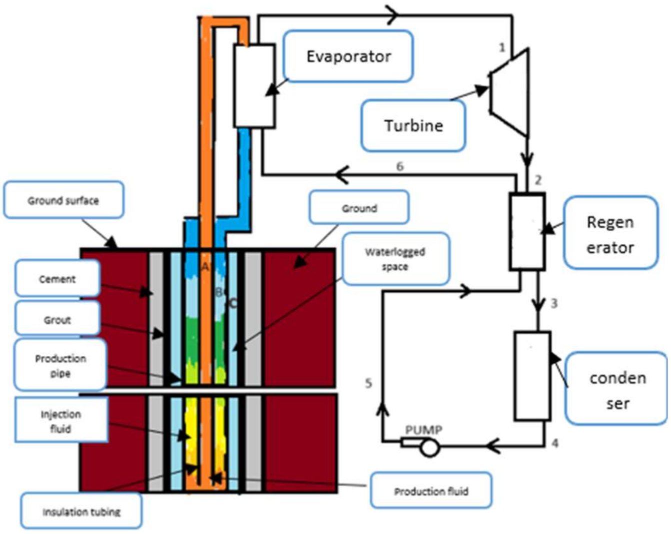

Fig 3. Schematic representation of a power generation from an abandoned oil and gas borehole

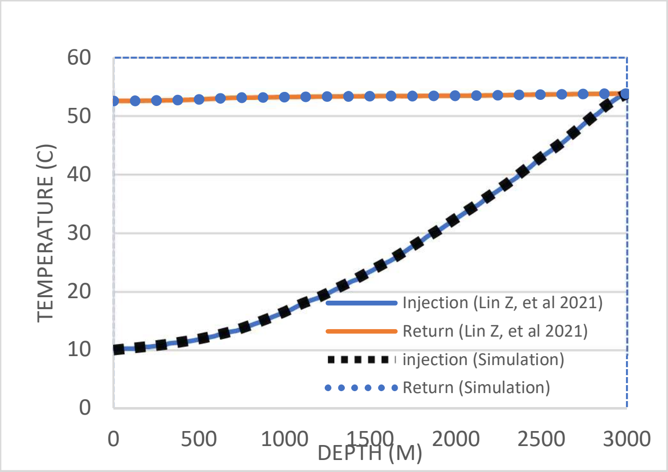

Fig. 2. Model verification: a comparison of working fluid temperatures of Lin Z. (2021) and built model.

Model Adaptation to Nigerian Conditions

Data was collected from 13 oil and gas wells in Nigeria, the data showed the well depths, the bottom hole Temperatures and these were used to calculate the temperature gradient of the surrounding rock formation. This data has been used to adapt the base model to Nigerian conditions.

Table 2. Borehole parameters from Nigeria

WELL NAME	Test Depth (TVD)(m)	Temp (deg C)	Geothermal Gradient (C/m)
UTA 14PH	3297.82	120.6611	0.036588
UTA 14 ST	2383.978	97.45	0.040877
UTA 16PH	3175.208	118.1778	0.037219
UTA 16 ST	3169.597	118.2944	0.037322
UTA 18 GI	2289.645	90.46667	0.039511
IBOTIO 3	2477.533	94.54444	0.038161
AKAI 2	2021.248	79.87222	0.039516
UTA 32ST	2573.46	105.3889	0.040952
UTA 27	3154.589	118.7556	0.037645
UTA 32PH	3203.603	117.3	0.036615
UTA 23	3201.214	119.0778	0.037198
UTA 21ST	2946.806	113.8889	0.038648
UTA-22	3093.683	116.5889	0.037686
UTA 20	3208.916	120.6222	0.03759

Heat Depletion Modelling

A mathematical model has been developed on MATLAB to simulate the transient heat depletion of the surrounding rock and reduction in output temperatures over time. The model uses the outlet temperature of 80.64°C from the CFD model.

The governing equation for the transient heat transfer model was a two-dimensional asymmetric temperature field expressed as:

$$\frac{\rho c}{k}\frac{\delta T}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta T}{\delta r}\right) \qquad (1)$$

where:

ρ is the density of rock formation
c is the specific heat of the formation

k is the conductivity of the formation

r is the arbitrary radius of the formation be considered

t is the time variable

It can be shown that

$$T(r,t) = T_0 - \frac{Q}{4\pi k}\int_x^{\infty}\frac{e^{-s}}{s}ds \qquad (2)$$

Where,

$$x = -\frac{\rho c}{k}\frac{r^2}{4t^2} = s \qquad (3)$$

Equation 2 allows dynamic the temperature field around the borehole to be solved, allowing the depletion of the thermal resource over time to be assessed.

ORC model

The ORC model was also built on MATLAB, an add on (CoolProp) was used to identify the appropriate working fluid for optimal efficiency and to calculate the efficiency of the system depending on the input variables gotten from the CFD model.

SIMULATIONS

A multi-stage simulation process was adopted. Firstly, the CFD model was used to improve the heat recovery from the borehole, by varying pipe diameters and flow rates.

Secondly, the depletion model was run to assess the degradation in performance of the borehole over 30 years.

Finally, the ORC model was run to assess the overall efficiency of the system.

The parameters in table 1 were used as initial input parameters to develop a CFD model. The diameter of pipe and flow-rates were varied in order to improve the heat recovery.

The diameter of the insulation pipe was reduced and then increased by intervals of 0.005m to observe the change in the coefficient of performance of the developed model. The mass flow rate was also varied by 0.01Kg/s steps to find the optimum flow rate to achieve the best coefficient of performance.

The outlet temperature from UTA23 from Table 2 was the highest (80.64°C) and it was used to calculate the coefficient of performance.

The coefficient of performance (COP) of the borehole was computed to determine the best operating conditions. The COP of the system is the ratio of the heat delivered by the heat exchanger to the work input by the pump.

$$\text{CoP} = \frac{Q_H}{W_{in}} \tag{6}$$

where:

Q_H is the heat delivered by the heat exchanger

W_{in} is the work input to the system by the pump

The results of the simulations were fed to a MATLAB model developed with the Coolprop which was used to select the appropriate working fluid for the ORC and calculate the coefficient of performance for the system. The solution from the ORC model was fed into the MATLAB depletion model, to estimate the heat degradation of the surrounding rock formation over time.

RESULTS AND DISCUSSIONS

The results indicated that the optimal borehole coefficient of performance of 3.42 could be obtained when the mass flow rate was at 1.157 Kg/s, the inner radius of the insulation pipe was set at 0.0305m and the outer radius of the insulation pipe was at 0.04395m. This is shown in Figure 3.

This was an improvement from the 3.40 recorded from the parameters used by Lin Z et al (2021).

The surface roughness of the surface of the insulation pipe and the surface of the steel pipe were also varied as shown in Figure 4. The results showed that the coefficient of performance decreased dramatically as the surface roughness on the surfaces increased thereby indicating that smoother surfaced materials are needed to maximise the coefficient of performance.

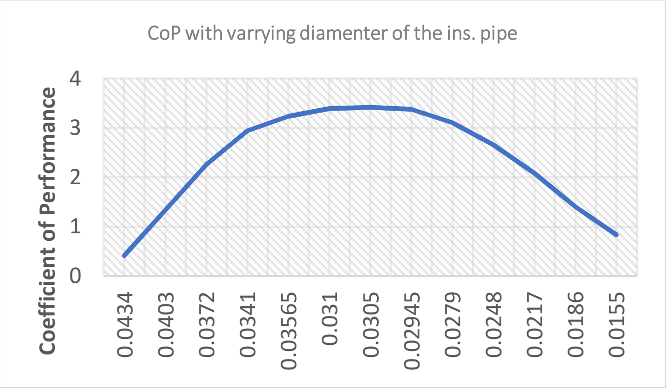

Fig 3. COP of the borehole and with variation of the inner radius of the insulation pipe.

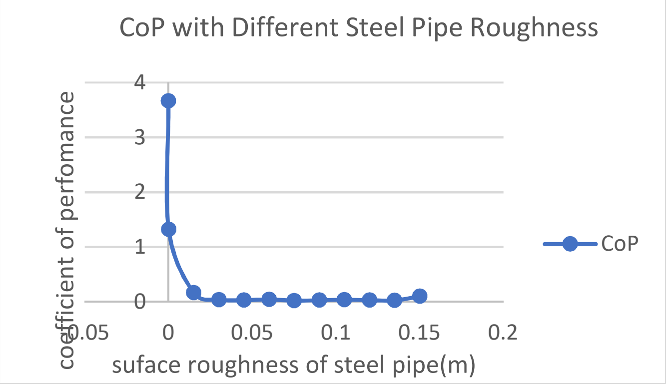

Fig.4. COP of the borehole with different steel pipe roughness

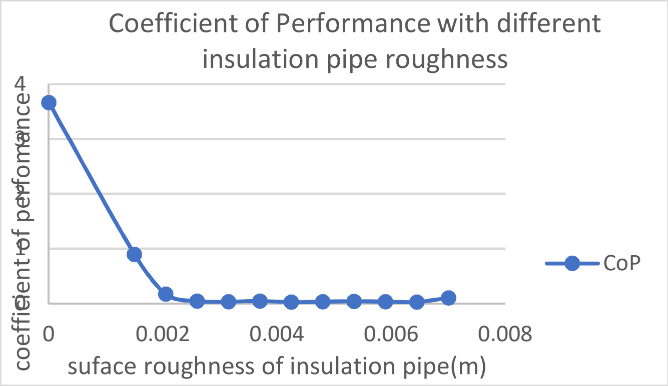

Fig. 5. Coefficient of Performance with different insulation pipe roughness

The outlet temperature from the CFD model was input into the MATLAB COOLPROP ORC model. The efficiency of the cycle was found to be 15.3%, with butane as working fluid.

Fig. 6 shows the impact of heat depletion of the borehole surrounds over a 30-year period, as computed by the MATLAB model; this showed a drop of 5°C in outlet temperature over the period.

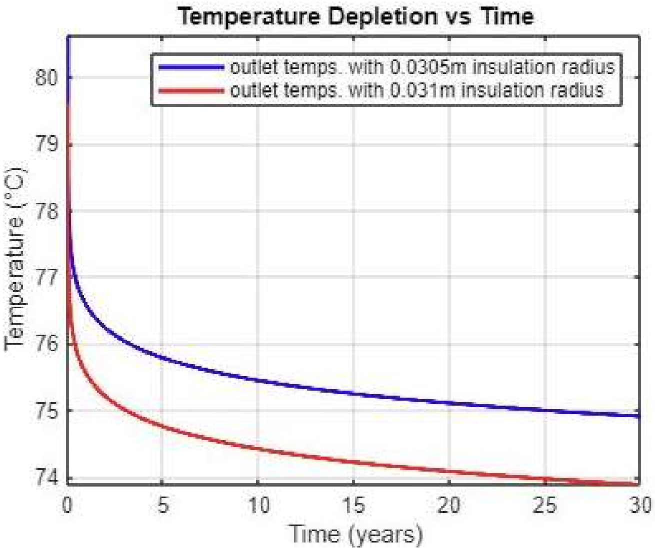

Fig. 6. Temperature depletion of outlet temperature over a 30-year period for 0.0305m and 0.031m insulation radius.

CONCLUSIONS

This paper investigates the feasibility of generating electricity from abandoned oil and gas wells in the global south by conducting a technoeconomic analysis of a multi-tool modelling system.

- The results showed that a flow rate of 1.157kg/s gave the optimal outlet temperatures. A decrease from this value caused the outlet temperature to decrease because of heat losses due to prolonged dwelling periods and an increase to the value also caused a decrease in outlet temperature because the fluid moved too quickly to pick up enough heat.
- It was also established that 0.0305m was the optimal radius for extracting the highest temperature values which increase the coefficient of performance from 3.40% in Lin Z (2021) to 3.42%.
- The effect of surface roughness was considered in this work, and it was established that the smoother the surface of the steel used as the production pipe, or the polystyrene used as the insulation pipe, the higher the CoP. This should be compared with the cost of such materials to investigate feasibility.
- The ORC model computed an efficiency of 15.27% which shows an improvement in comparison to R. Loni et al.(2021) which was 13.5%.
- The heat depletion of 5℃ after 30 years, indicating that the borehole could still produce useful heat for long periods of time.

There is need for further study into the economics associated with the smoothness of the material for optimal results.

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