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Extraction of geothermal energy resources associated with abandoned oil and gas wells: benefits and limits

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Abstract

Abandoned oil and gas wells (AOGWs) in mature oilfields with adequate bottomhole temperature are associated with geothermal energy resources which can be used for various utilizations. In recent years, the majority of researches has been focused on the extraction of geothermal energy from AOGWs using downhole heat exchangers (DHEs), a closed-loop type of system potentially applied to harness geothermal energy from deep wells.

In this study, we investigated selected AOGWs with the aim to evaluate the feasibility of power generation by using a DHEs. A thermodynamic model is developed by using Engineering Equation Solver (EES) software. In addition, the impacts of rock properties, geothermal gradient, geometry of downhole heat exchanger, insulation thickness, mass flow rate of working fluid, selection of working fluid on the rate of the heat extraction are investigated in the parametric study proposed. Moreover, the future performance of the system depending on rock properties is also analysed.

The fluid of R134a has been selected as a working fluid regarding the simulations done by EES. The simulation's results indicated the importance to take changing fluid properties along exchanger into account. Additionally, the results lead to conclude that the generation of power from AOGWs by using DHEs is strongly dependent on the geothermal gradient through the well, the length of the heat exchanger and rock conductivity.

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Importance of geothermal energy resources at a world scale

Geothermal energy represents one of the renewable energy-type of resources, exploitable both for generating electricity and direct use applications while producing very low levels of GHG emissions. Depending on the temperature of the geothermal reservoir, it is used in a broadly defined heating sector, agriculture, industry. There is very high temperature in certain depths of the underground which is extracted by stream and water to surface and converted to any types of energy. As a consequence, in geothermal energy production, a sustainable type of energy can be obtained without burning fossil fuels such as oil, gas and coal [1], [2].

There are several types of geothermal sources of it. For example:

1) Deposits of geothermal dry steam which some parts of all geothermal power plants use heat from that source,
2) Deposits of wet steam which are a mixture of hot water and steam (very common),
3) Geothermal water deposits (hot water or steam and water) are the largest geothermal reservoirs formed by filling underground cavities with water from precipitation heated by dry hot rocks (at a depth of 2 km or more) [3].

From a geothermal point of view, the most important parameter is the temperature which has an increase with depth, thus it is determining by the geothermal gradient. Geothermal gradients can vary from over 80 °C per kilometer in hot basins (e.g., Bombay basin) to less than 20 °C per kilometer in cold basins (e.g., in parts of the Gulf of Mexico). The global average for temperature values in oil and gas-bearing basins is about 30 °C per kilometer. According to their enthalpy values, they can be found different uses of geothermal energy resources:

1) High enthalpy energy (temperature higher than 100°C) for production of electricity through high-temperature steam

2) Medium enthalpy energy directly used for district heating or used (temperature lower than 100°C)

3) Low enthalpy energy (temperature lower than 50°C) for the air conditioning of buildings (heating and cooling).

Depending on the temperature of the reservoir, there are many direct use applications such as agricultural purposes, cooking, space heating, greenhouse and covered ground heating, snow melting, raceway heating, bathing and swimming [4]. All applications regarding different temperatures are illustrated in Fig.1 which is called Lindal diagram.

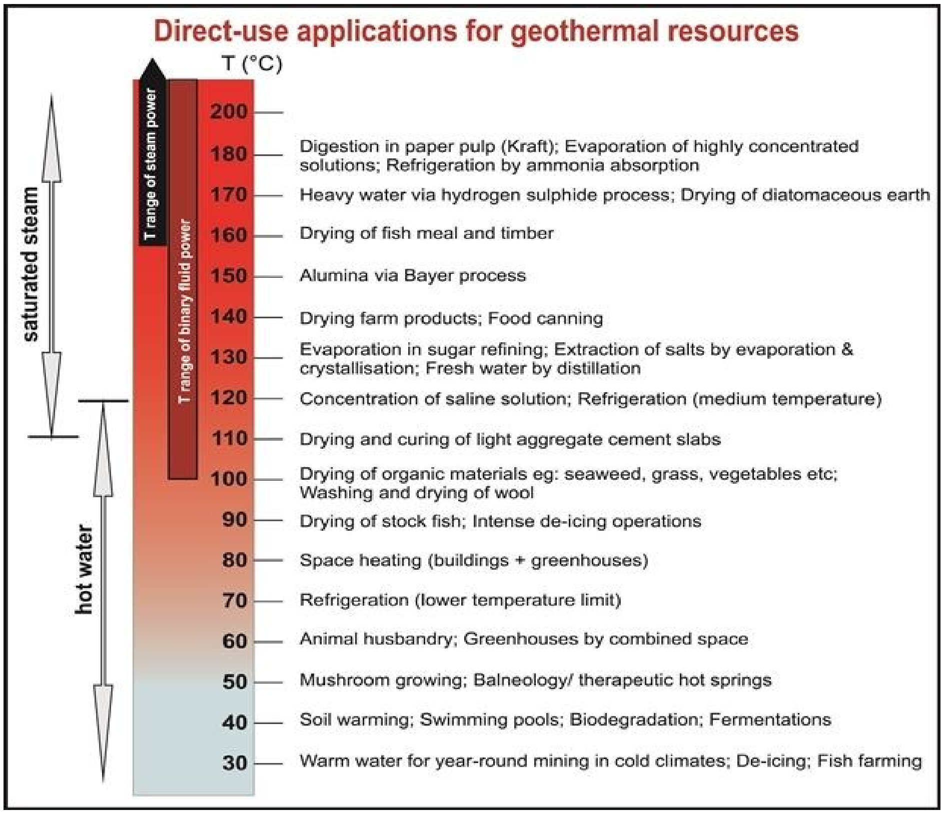


Fig.1 The Lindal diagram shows that a range of applications for different temperature geothermal resources [5].

1.1.1 Geothermal energy production and its benefits

The first geothermal power generator was created on 4 July 1904 in Italy. After that, the process was developing decade by decade. According to recent statistics, worldwide geothermal power capacity was approximately 10 GW, in 2019 that data was accounted for about 14 GW [6]. There are several works in USA, Canada and China, which illustrate the effective utilization of geothermal energy from hydrocarbon fields. The first pilot project was performed in an oil field Fort Liard, located in the north-west of Canada. Geothermal system is capable of generating 2900 MWh of electricity every year. Another successful project is in China, Huabei oil field. The capacity of the power plant is 400 kW [7].

Geothermal energy is currently considered as one of the most advantageous sources of energy. Although, having some negative sides, geothermal energy has many beneficial aspects in comparison with other types of energy sources. One of the most important advantages is that the energy process is environmentally friendly. Secondly, this type of energy source is constant and not dependent compared with other renewable sources (wind, solar, biomass). Another benefit is that it does not need regular maintenance, so the life of the equipment is used for geothermal energy extraction process is very high [8].

Geothermal technology has been developed year by year and it has been extensively studied, simultaneously, its supporting technologies have been investigated and improved to mitigate global warming, decrease air pollution and meet the demand for global energy. Recent data illustrates that more than 20 countries are using geothermal energy to generate 74 TWh/year electricity [9].The capacity of geothermal power production has risen up approximately by 27% (3.7 GW) with the high proportion recorded in USA, Turkey, Indonesia between 2015 and 2020 [10].

1.2 Geothermal energy resources in sedimentary basins

Geothermal energy development has a future as a part of an energy supply at a global scale. In order to increase geothermal energy production conditions, it is required to comprehensively know porous and permeable reservoir rocks in sedimentary basins, where those packages of rocks have sufficient temperature, thickness, porosity, and permeability. A significant amount of geothermal energy resources is hosted in sedimentary basins as geological contexts. At the same time, sedimentary basins are directly related to hydrocarbon wells associated with geothermal resources in deeper parts.

Heat transfer is a process, where the internal energy of one body decreases and the internal energy of another one increases. Heat transfer in geothermal systems is carried out in the form of heat conduction, convection, radiation and phase transitions. The process of heat transfer consists in transferring heat from one environment to another through the wall that separates them. So, the hot sink transfers its heat to the surface of the wall, which, due to thermal conductivity, gives off heat to the cold heat carrier. The thermal conductivity of rocks has direct influence on the conductive heat transfer process. Convective heat transfer is a process of heat transfer between heated parts of a liquid or a liquid and solids [11].

As a consequence, the efficiency of the geothermal reservoir system is dependent greatly on the fracture aperture thickness and the production or extraction rate from a reservoir depends directly on the permeability of the fractured media of the reservoir. The permeability in turn is dependent on the square of the fracture aperture thickness [12].

1.3 Description of oil and gas wells from a technical point of view

Oil and gas wells are drilled with a series of casings which are metal tubes. They are cemented and their main purpose is to provide strength to the well and create a barrier between the well and fluids. Each casing is built into the previous one and the diameter is decreasing with the increasing number of the casings. There are some types of casings: conductor pipe, surface casing, intermediate casing, and production casing (Fig.2).

Conductor pipe is the first casing and its diameter (about 30”) is larger than other types. The main function of this casing is to prevent erosion of the unconsolidated shallow formations [13].

The second one is the surface casing which has a diameter of 20”. It is mainly built to tackle the problem of hydrocarbon contamination in underground freshwater and salt water.

After the surface casing has been set, a new one is installed which is called intermediate casing having a 13 3/8” diameter. The number of intermediate casings can be 1 or more (9 5/8”), it depends on the depths of the considered well. Their function is to isolate formations that can create potential hole problems (circulation losses, abnormal pressures, instability, etc.).

When the total planned depth is reached and in case the well results to be productive, the last casing string is run in a hole with the purpose to allow the production of the well; this casing string is called production casing (7”).

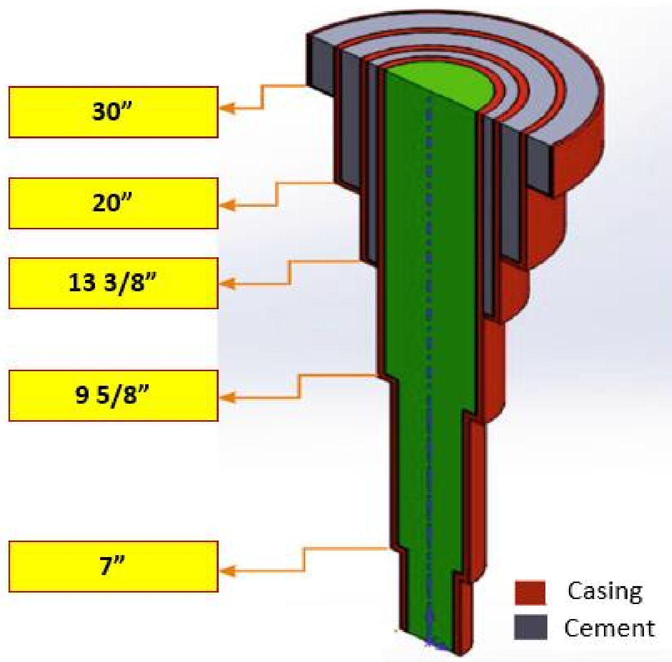


Fig.2 Description of hydrocarbon wells [14].

1.4 When and why hydrocarbon wells are abandoned?

The abandonment of an oil well is the final part of well’s life that starts with drilling, production and abandonment (Fig.3). According to the production of oil wells, there 3 steps of recovery: primary (natural flow), secondary (waterflooding and pressure maintenance) and tertiary (gas injection, thermal and other methods). After the last stage, thus when the last methods are not efficient, the oil well can be considered abandoned. Producing a low amount of oil and gas is not only one reason for closing wells, there are also other causes for that [15].

- Changes in a well design;
- Failure or lack of equipment which plays a crucial role;
- Destruction of a production column;
- Occurrence of flows mixture;
- Unprofitable operation due to low flow rates;
- Gas manifestation;
- Seasonal difficulties;

- Other reasons, including force majeure

Retrofitting from oil and gas wells has few influences on the environment to produce geothermal energy. Most of the time, that type of wells is abandoned because of having high water-cut that makes a way for the uneconomical production [16]. There are 2 types of hydrocarbon wells potentially suitable to supply geothermal energy for electricity production:

(1) a production oil or gas well that has a water cut

(2) a geo-pressured brine well that has dissolved gas

The application of water flooding and decreasing pressure in the reservoirs are the most significant reasons for water influx in oil and gas production wells [17].

There are some barriers using drilling (casing, blowout preventer, wellhead, drilling fluid) and production stage (casing cement, tubing, packer, safety valve, Christmas tree) that are imperative during the transformation of the well into the geothermal well to extract the energy (Fig.2).

In general, without depending on onshore or offshore applications, well abandonment has 3 main phases: reservoir abandonment, intermediate abandonment, and removal of wellhead and conductor [18].

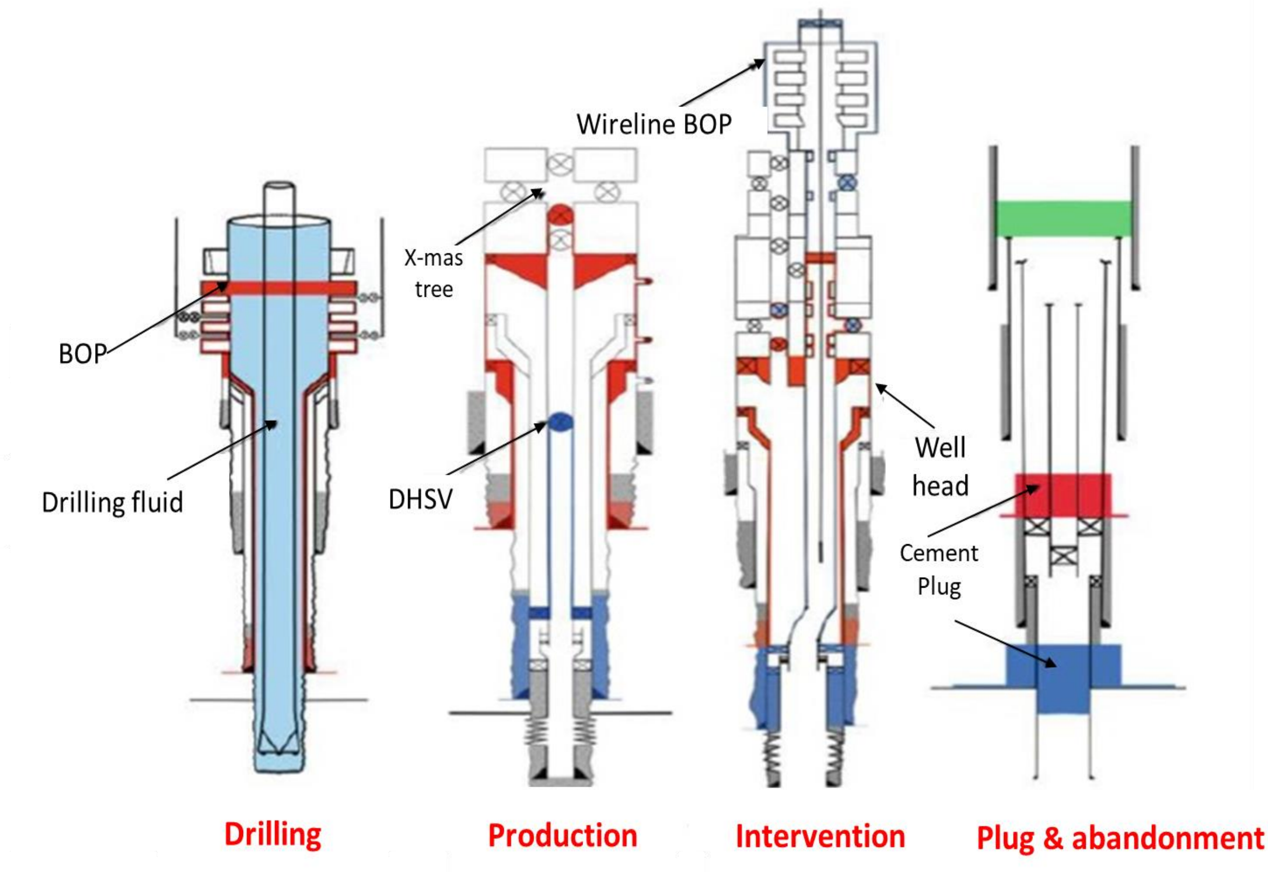


Fig.3 Life cycle of petroleum wells [19].

1.5 Advantages of using abandoned hydrocarbon wells for geothermal energy production

It is fact that many petroleum wells have been produced more than half of a century, as a result, the majority of them have reached or approximately reached their final productive period. There are nearly 20-30 million hydrocarbon wells indicated as abandoned in the world and they can make a way for environmental pollution issues including contaminant dangers, exposure pathway-routes and biological receptors [20]. Thousands of hydrocarbons wells in the world need to be abandoned onshore or offshore. Additionally, due to the current pandemic circumstances, several wells are expected to pass to their abandonment stage because of having low demand [21].

Using abandoned petroleum wells for geothermal extraction is a good idea because of having the fact that hydrocarbon wells are generally located deeper which is enough to reach a high-temperature area. Geothermal power has the ability to decline dependence on non-renewable energy sources such as coal, oil, natural gas and nuclear energy. Generally, due to its advantages and accessibility, geothermal energy extraction from abandoned hydrocarbon wells should be taken into consideration as an alternative energy source. Those are below:

1. Due to having the wellbore of the well, that method does not require any drilling activities which makes it almost 50% cost-effective. In comparison with the development of geothermal reservoirs, having the construction of wellbore and downhole will play a crucial role in avoiding the explosion risk and decline cost of the completion and drilling significantly as well as payback period. In addition, existing of the surface facilities such as service roads, pipes will eliminate the initial investment.
2. Current conditions are already known and also thermal and geological properties of wells, exploration data, reservoir and fluids properties, completion data and production history are available which provide important convenience for evaluating geothermal energy from abandoned oil and gas wells [22].
3. Corrosion, scaling problems, groundwater recession can be removed because of no extracting groundwater.
4. The casing, cement and wellbore with equipping inner piper can be used also in geothermal energy extraction.
5. Due to existing desirable thermodynamic properties, selection of circulating fluid can be chosen easily [23].
6. Geothermal energy's reliability makes it a good baseload source because it is not affected by weather and can remain available to operate 98% of the time.
7. Geothermal extraction with a closed-loop system releases no dissolved gas into the atmosphere that may be in the groundwater or soil, whereas there are a few emissions of dissolved gas from open-loop systems which can be considered always lower than gas releasing from fossil fuel sources
8. Finally, significant geothermal energy and power can be produced continuously [24].

There are have low temperatures varying from 40 $^{\circ}$C to 120 $^{\circ}$C in oil and gas reservoirs. However, according to the geothermal gradient and well depth, the bottom hole temperature can be higher than

150 °C in abandoned oil wells. Thus, depleted petroleum reservoirs have a remarkable potential of the geothermal energy used for direct applications or electricity generation [25].

1.6 Closed and open-loop systems

Geothermal systems can be constructed as open-loop or closed-loop. The open-loop system needs one production and at least one injection well. Thus, in that process, working fluid is injected into the injection well, it gains sufficient heat from the hot formation during circulation in the reservoir, then it is brought to the surface through production well and delivered to use. The amount of circulated fluid is crucially dependent on permeability of the rocks which can have impacts on thermal breakthrough action. Moreover, that type of system has often some problems such as corrosion, scaling and cavitation [26].

Utilization of an open-loop system is applicable only when the geothermal fluid is not extremely corrosive and with the intention to scaling. Thus, closed-loop systems are much more convenient.

The implementation of advanced geothermal energy extracted technologies consist of closed-loop system in which the circulating fluid is isolated from the hottest formation, thus it is not directly in contact with the formation rock which can tackle the corrosion problem, the losses of working fluid and scale formation. The velocity of fluid circulation, pipe dimensions and other parameters are optimized to acquire maximum amount of extracted energy which depends on thermal conductivity of the rock sediments [27].

However, in that kind of system, heat conduction through rocks is the main heat transfer mechanism, it reduces the performance of the system due to poor thermal conductivity of rocks. In other words, making an increase on the thermal conductivity of rocks or decreasing its thermal resistance is an effective method to improve the performance of the system [28]. The considerable drawback is the low efficiency in heat extraction related to the conventional geothermal plants. The lower mass flow rate which circulates in the heat exchanger and the heat is transferred mainly by conduction cause a lower final temperature, as a result, less heat output [29].

1.7 Geothermal power plants

There are different technologies for using geothermal energy depending on the well bottom temperature and pressure of the reservoir:

1) Dry steam technology

In a high-temperature reservoir (which is more than 240 ° C), this technology can be used. The working process of that system is that the superheated steam is transported from the geothermal reservoir through the well to a steam turbine which converts thermal steam energy into mechanical energy which is further converted into electrical energy. That technology is related to the exhaust steam turbine (the vapor is discharged to air) and Condensing steam plant (vapor is discharged to condensing). The second one is the most used because of having higher pressure drop through turbine.

But, the utilization of dry steam system is very limited due to requiring extremely high-temperature reservoir which is strongly rare [30].

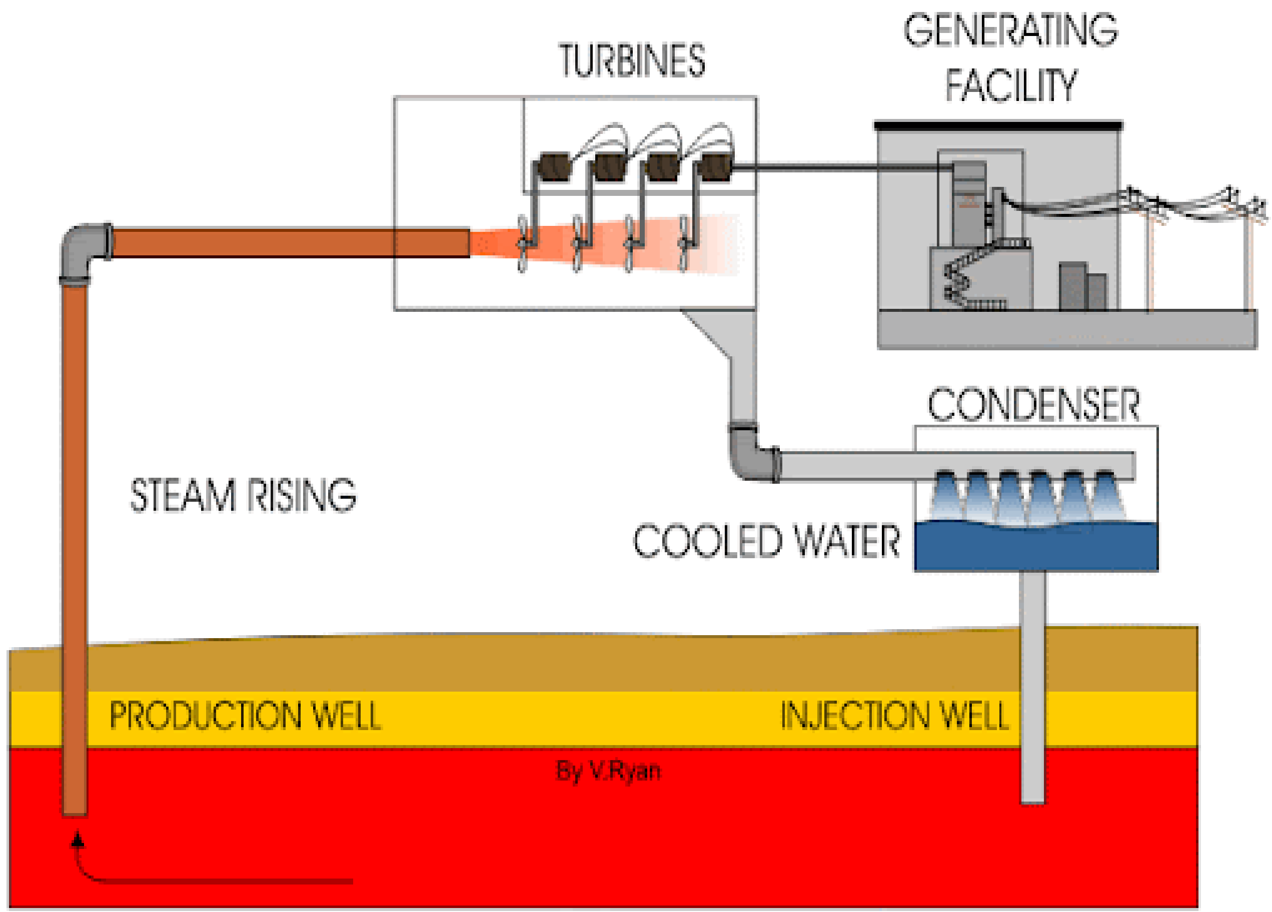


Fig.4 Dry steam power plants [31].

2) Flash steam technology

The technology used in reservoirs in which the temperature is higher than 180 ° C. During the working of that system, the steam comes out within production well and the hot water is separated from it, then is sent to geothermal plant (pressure is reduced dramatically) to the turbine to generate electricity. After that, the steam is cooled and reinjected into the reservoir again through an injection well to stabilize reservoir pressure [32].

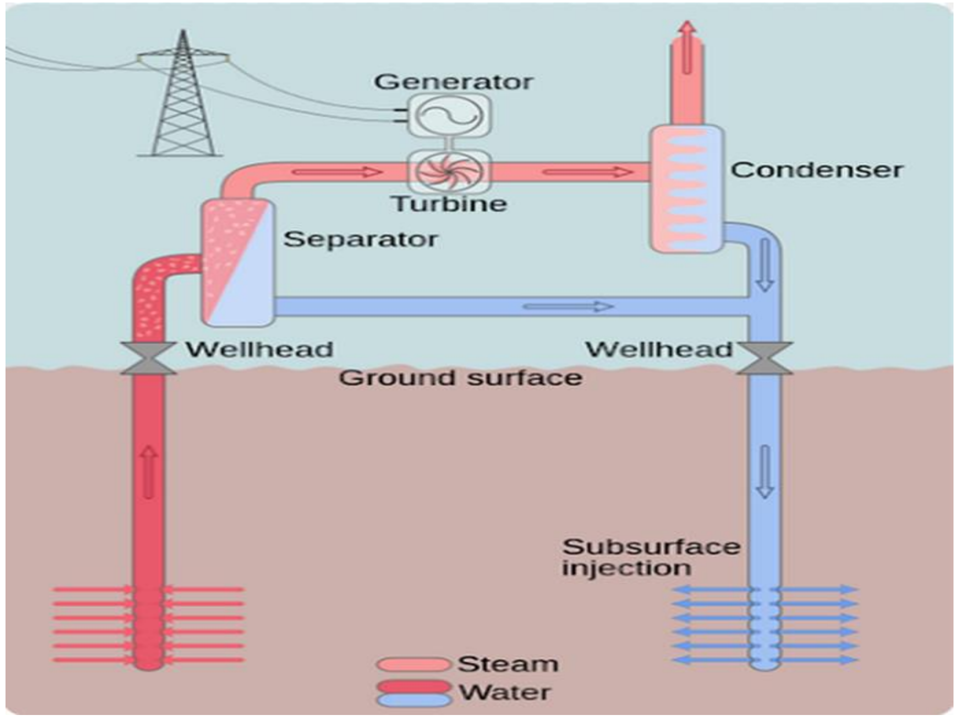


Fig.5 The description of the flash steam plants [33].

3) Binary cycle technology

The technology used in lower temperature reservoirs (80℃ to 180 ℃). In the system, the working fluid which has higher vapor pressure and lower boiling temperature is vaporized by the geothermal source and drives the turbine. The geothermal water is circulated within a heat exchanger to pass the heat to a secondary working fluid which is operated within the conventional Rankine Cycle. After running the turning, the secondary working fluid is condensed to liquid as illustrated in Fig.6.

High-temperature condition is limited due to ensure the thermal stability of system whereas low-temperature condition cannot be applicable from economically insufficient points of views [34].

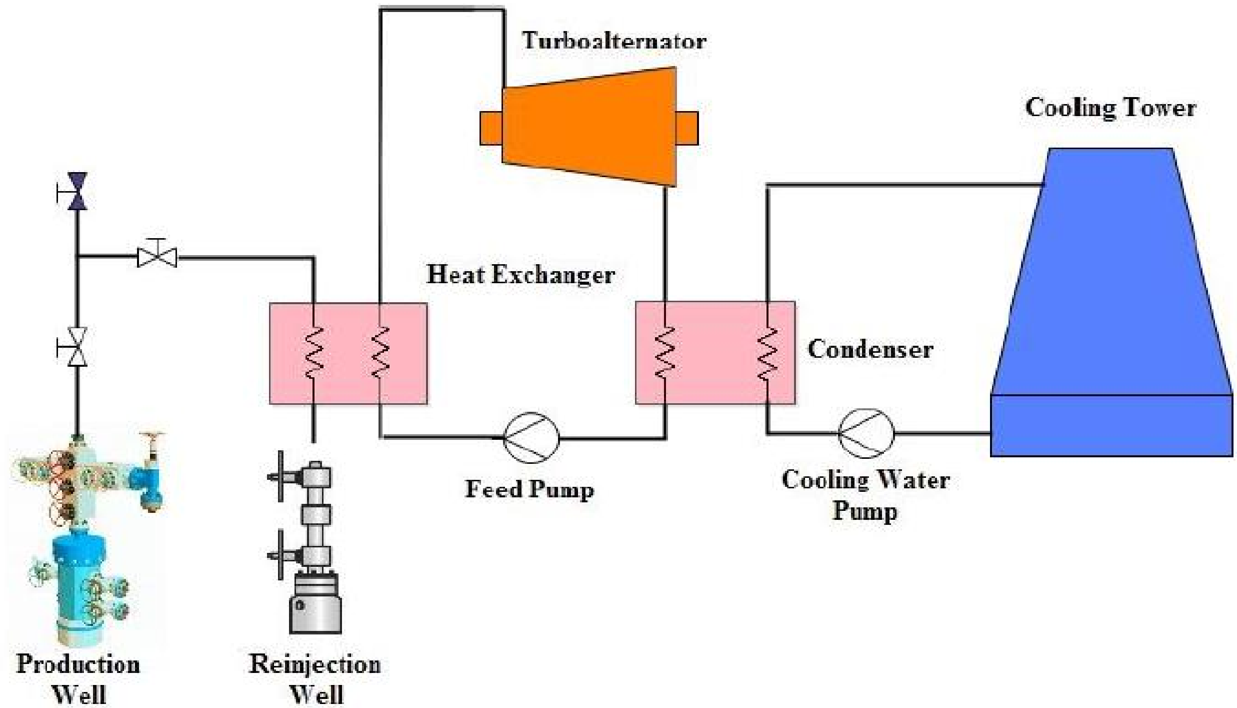


Fig.6 Binary cycle geothermal plant [34].

The remarkable beneficial side of Binary cycle system is the decreased possibility of pollution and there is no leakage to the environment, thus the liquid which comes from the well does not have any opportunity to meet the atmosphere because of the existing closed system. Moreover, the liquid which comes from the well can be injected into well again in order to keep liquid availability and enhance the life of the project. The drawback of that system is the low efficiency of heat output in comparison with other systems.

In some configurations, geothermal systems can be constructed with other energy sources together such as solar energy and biomass. It can make extracted geothermal energy maximized. In addition, that type of plant can be utilized for the generation of electricity or heating and cooling.

1.8 Heat exchangers

In general, HEs have three main types: Coaxial, U-pipe BHEs and double U-pipe BHE (Fig.7). Mainly, variation of design depends on diameters, type of pipe utilized, insulation which can be added in order to prevent passing heat from one pipe to another [23].
AOGWs can be retrofitted with U-tube heat exchangers by lowering the tube into the abandoned well and filling the void with grout. U-tube borehole heat exchanger (BHE) can be recognized when there is U shape bended tube at the bottom of the parallel tubes, so the circulating fluid is pumped through one tube and it will come out from the other. As a result, during the travelling period of working fluid through the pipe, it will gain the heat from surrounded rocks to have the satisfaction of energy production [24].

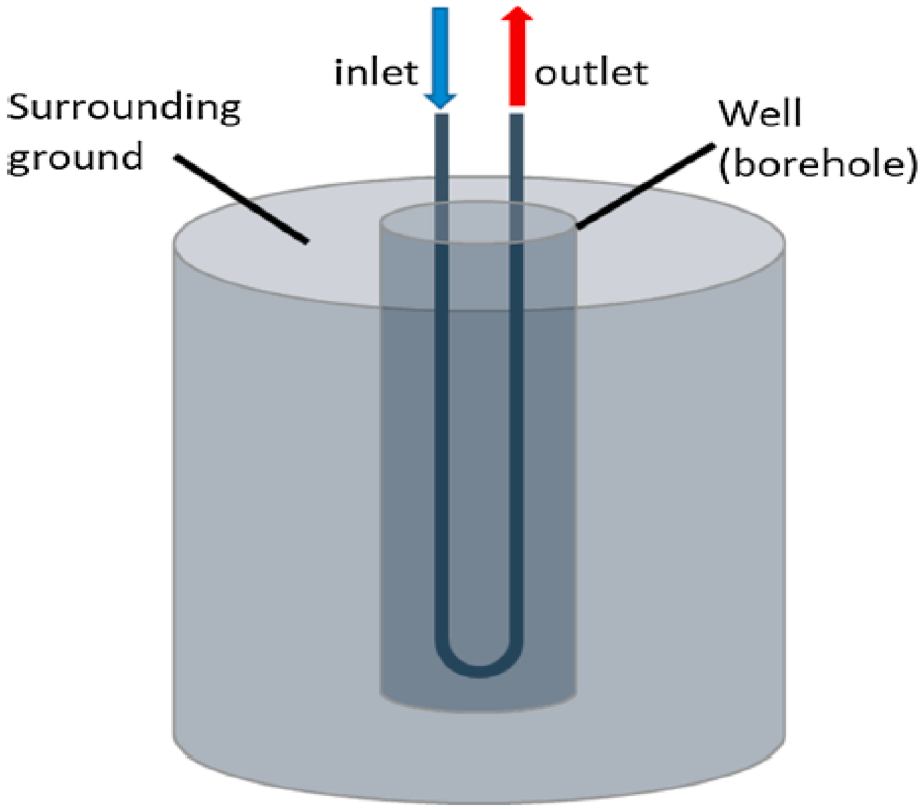


Fig.7 Scheme of Vertical U-tube heat exchanger [35].

For extracting geothermal energy from abandoned oil and gas wells, a coaxial wellbore heat exchanger is used. In heat exchanger, circulating fluid (generally water) is injected into the outer pipe, then it is heated by surrounding formation during its descent. The casing is usually a barrier for infected fluid to touch formation. When arriving bottom of the well, the flow of fluid will be kept and it will rise up along inner pipe, then the heat will be transformed to other type of energy on the surface [23].

There are two flow paths of coaxial DHEs (Fig.8). Path A is that the fluid which carries the heat flows downward in inner pipe and then upward through annular area and Path B is reversed. For heat production, thermal performance of DHE in Path B is better than that in Path A [36].

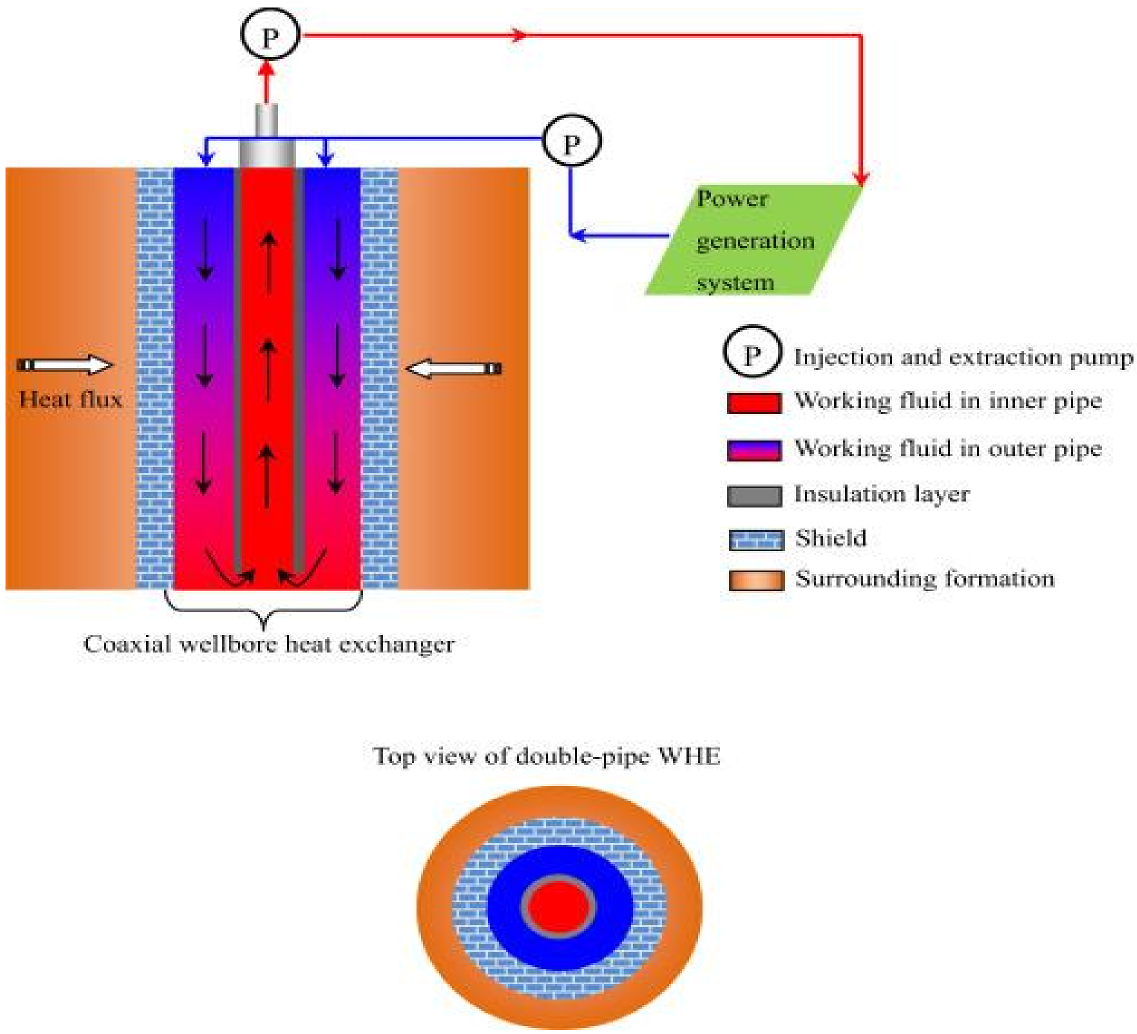


Fig.8 Schematic diagram of geothermal power generation using AOGW [23].

In practice, when extraction of heat from shallow wells for heating or cooling is needed, the u-tube DHEs are the most common method to utilize. However, coaxial DHEs are the best option for deep wells and it exceeds u-tube types due to heat exchange efficiency, saving pump power, less utilizing of grout. Moreover, in comparison with u-tube DHEs, there is a larger surface area in coaxial DHEs to make heat transfer. Also, if the injection rate of working fluid is the same for both types of heat exchangers, there will be low fluid velocity in coaxial geometry, thus less hydraulic pressure will be needed. Additionally, constructing a coaxial DHE is a better choice than a U-tube, because of having the outer pipe, saving time and the part of the budget. Finally, a coaxial geometry heat exchanger has benefits in decreasing the thermal resistance between the working fluid and the wellbore [37].

The purpose of the thesis work is to evaluate the utilizing AOGWs to harness geothermal energy. The parameters which have remarkable impacts on the heat extraction are focused on and the parametric study is implemented to investigate the desirable conditions.

Chapter 2

Literature Review

2.1 History of geothermal energy production from AOGWs

The potentiality of transforming AOGWs into geothermal wells has been studied throughout the world. The research done by Macenic et al., 2018 has been concentrated on geothermal energy extraction from abandoned deep oil and gas wells in Croatia [38]. Moreover, the potential utilization of AOGWs to produce geothermal energy in Turkey has been evaluated by Kaplanoglu et al. in 2019. The main result described how it is possible to reuse AOGWs in southeastern part of Turkey [25]. Apart from the above mentioned studies, other researches have been done in Poland [39], Pakistan [40], Qatar [41], India [42].

If we have a look at the background of that topic, we can observe that some of the researches have concentrated on open-loop system designs. Many countries in the world have allocated some part of the budget and work into the modernization of geothermal energy production with the application of open-loop systems, such as: United States, Israel, Albania, New Zealand have several advanced and comprehensive kinds of research on open-loop geothermal energy extraction from AOGWs with illustrating the effects of many technical parameters [43].

On the other hand, the majority of researches that have been carried out during the last decades is focused on geothermal energy production from AOGWs with a closed-loop design system. U-tube and coaxial DHEs are two types of closed-loop technologies described. There are a few papers concerning the extraction of geothermal energy from AOGWs with applying U-tube DHEs and they have been focused on characteristics of heat transfer and thermal resistance model for U-tube [23], [24]. Considering the coaxial DHE, a few articles are available in the bibliography describing its technology [44].

2.2 Open-loop system (direct use)

The primary research about open-loop system was done by Reistad and Culver in 1978, thus they illustrated that the promoter pipe (perforation) was added into the well after casing to allow working fluid circulation. As a result, they observed that using promoter pipe in the well could achieve more heat output than a solid-cased well [45]. Besides, other studies introduced that using that pipe leads to develop thermal efficiency [4].

Moreover, diameters, extraction of heat, flow rate are dependent on the geometry of heat exchangers. Dominguez, 2010 has found that the inner pipe diameter has an impact on the generation of heat. The consequences of his study indicated that the last temperature of circulating fluid (considering water) on the surface is high as increasing the diameter of inner tube. Thus, the heat exchange can have an almost 6-8% increase with changing inner diameter [46].

For open-loop applications, the locations of the wells should be close to potential users. During distribution, transportation of the hot fluid from the geothermal wells to the customers may be a challenging task due to heat losses from the pipelines. Regarding Ovando and other's study which is related to heat loses along with the network of geothermal field in Cerro Preito geothermal area, an approximate amount of the heat loses in pipeline network is about 73 MW (58 MW in high-pressure network whereas 15 MW in the lower one.). It is mentioned about half of the heat losses was in the pipeline because of the insulation of the pipe, nearly 48% and 26% for higher and lower pressure network, respectively [47].

2.3 Closed-loop system (indirect use)

Closed-loop systems can allow working not only with low-temperature wells but also it can address extremely high-temperature resources which increases power generation. Many researches have been done regarding ensuring the flow in permeable formations and produce deeper and very hot layers. In their study Andrew Van et al., 2020 concluded that closed-loop geothermal systems can access to vast heat in deeper, hotter rocks and permeable layer geothermal resources [48].

Another study done by Lafta and Hashim in 2012 is about the variation in the amount of power production in geothermal plants depending on seasons. In detail, they investigated that the highest proportion of energy production is obtained in December and January whereas the lower portion is at June and July. They concluded that geothermal energy production using a closed-loop system is dependent on depths and months during a year [49].

According to the research of Nalla (2004), the impacts of different design parameters (such as circulation rate, circulating fluid properties, wellbore geometries and regional properties including formation rock type) on DHEs performance, that decide circumstances for optimal thermal energy production and determine the potential DHE model for power generation have been investigated. The research demonstrated that the residence time of fluid, contact area for heat changing and the thermal properties of rock formation play a more significant role in geothermal energy extraction [50].

From another point of view, the process of pumping has an important role in the extraction of geothermal energy as it provides the circulation of working fluids and also pressurize it. However, pump consumes some part of the energy which affects to power output. K. Morita considered that aspect in 2005 and, according to her study, the diameter of the well and inner tube turns to be more important for minimizing consumption of energy by pump. The study also considered that the gravity in heat exchanger is possible to alternate the function of pump on flowing circulating fluid [51].

Regarding the comparison between open-loop and closed-loop system, we can refer to M. Kanoglu`s work (2008). He noted that power generation is the best option for geothermal resources where have high temperatures since electricity is enough expensive than heat energy. On the other hand, the efficiency of conversion in a geothermal plant is nearly 0.1 which means for producing 1 unit of electricity, 10 units of geothermal energy should be extracted. Finally, he concluded that profits of geothermal production can have an increase of 25% with using a direct method instead of producing and selling electricity [52].

2.4 U-tube DHE

U-tube DHE can be placed inside AOGW before filling it with materials with suitable thermal properties. Practically, U-tube DHE is more common for shallow wells, specifically for heating and cooling systems. Lyu et al. in 2017 developed a numerical model for a U-tube DHE, in which coupled circulating fluid with geothermal fluid inside wellbore, to study the impacts of key parameters on the rate of heat extraction [53].

According to several researches, coaxial DHEs surpass the U-tube DHEs because of having low pressure drop without being dependent on the rate [54].

Due to the different thermal performance of the DHEs, many researches paid more attention to heat transfer analysis and modelling of thermal resistivity which is related to the resistance of each tube

and rocks. When U-tube DHEs are used for retrofitting abandoned hydrocarbon wells, the wellbore should be reconstructed because of having cement, tubing and casing in petroleum [55].
Gharibi et al. in 2018 studied the possibility of utilizing an abandoned oil well as a geothermal energy resource by using U-tube DHEs. They mentioned that partial insulation is needed on the outlet pipe. This may be particularly challenging regarding the small size of that type of the well [20].

2.5 Double Pipe (coaxial) Heat Exchangers

Figure 9 represents a hydrocarbon well which is equipped with coaxial DHE. There are two options, firstly the injection fluid is pumped through the inner pipe and come back to surface along the outer tubes (forward flow). Secondly, circulating fluid is injected into outer pipes and goes up along the inner (reverse flow). The most used is the second one shown in the chart.

When the fluid is flowing through the pipe, its temperature increases due to heating by the surrounded formation. Then, extracted circulating fluid to power generation system in which it is cooled and pumped again into the outer pipe to recirculate.

Pan in 1985 paid attention in comparing U-pipe, forward coaxial and reverse coaxial DHEs. The result obtained showes that the reverse model is more effective than others due to having larger heat extraction [56].

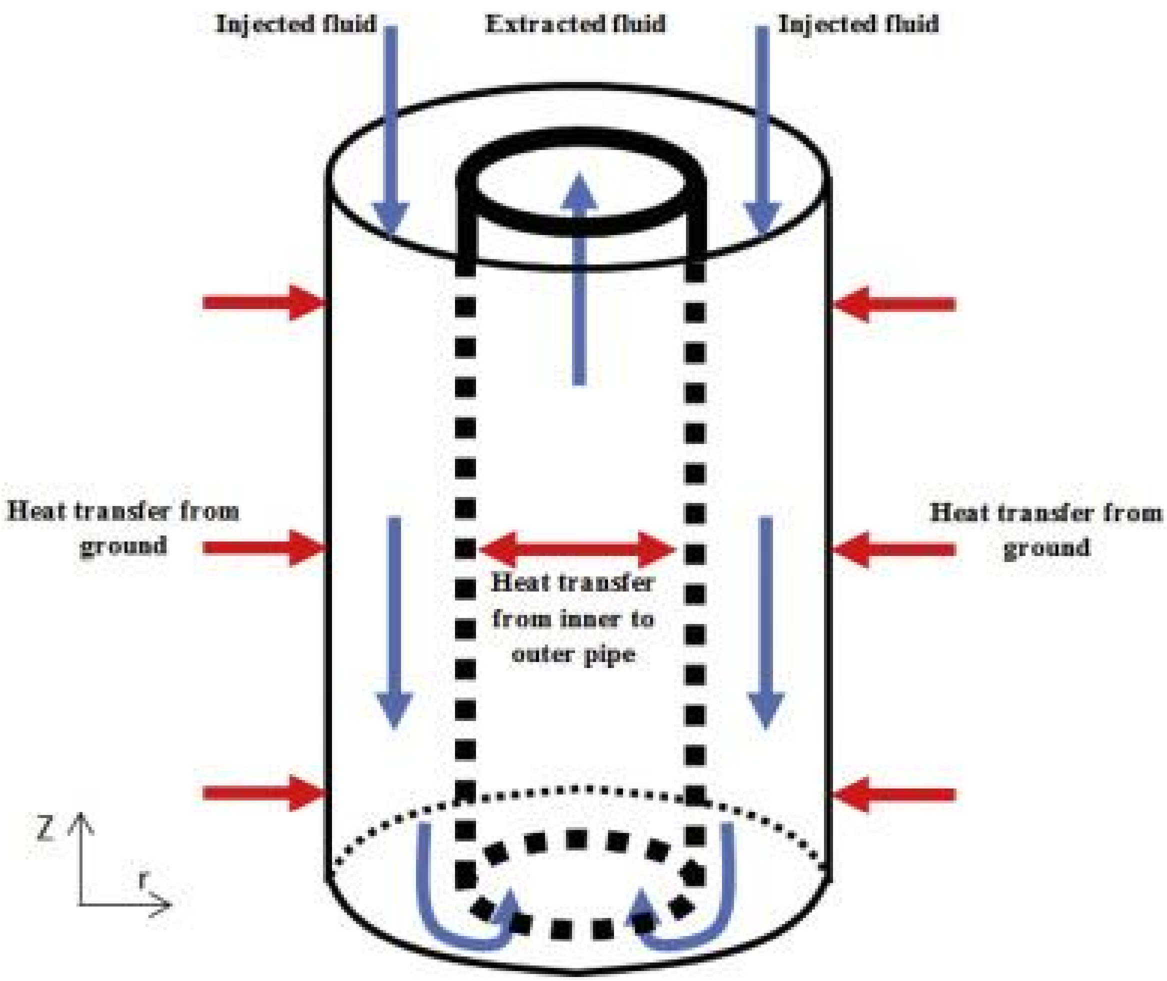


Fig.9 Scheme of a double pipe heat exchanger which can be applied to a hydrocarbon well [24].

In order to acquire achievement of the coaxial system design partly depends on choosing the working fluid which the heat is carried by. Generally, using the non- aqueous fluid such as isobutane, ammonia can have more high efficiency than water where there is no very high-temperature because those fluids have lower boiling temperature in comparison with water. So, it is easy that the non – aqueous fluids change to vapor at a lower temperature. Regarding to drawbacks of using non-aqueous fluid in circulation, leaking the fluid into formation or other is possible and it can make a way to environmental damage. As a consequence, using those fluids requires sufficient insulation and also large volume of non-aqueous fluids to heat exchanger, depending on depths and diameters [44].

Additionally, production of geothermal energy from AOGWs is substantially dependent on geothermal gradient and the flow rate of fluid through the coaxial DHE. Thus, the researchers observed that there was nearly a decrease 2 °C in the temperature of the extracted fluid within 10 years [57].

There are several researches on heat transfer development in DHEs. Cheng et al. (2019) used the protrusion on the annulus side of coaxial DHE and achieved more heat transfer rate at the expense of more pressure drop [58]. In another study, Iry et al. (2020) illustrates implementation of baffle to the annulus side of the DHE to increase its performance and mentioned that a higher heat acquisition can be adopted at a higher pumping power requirement [59].

2.6 Other researches

Caulk et al. (2017) focused on the prospect of extracting geothermal energy from abandoned oil wells by using open-loop and closed-loop systems in California in which there is nearly 40-73 °C /km of geothermal gradient. They highlighted that some part of them can be drilled extra few hundred meters to achieve enough heat output for heating applications [60]. Other researchers studied that for shallow wells, extra drilling is necessary and the wells which have depths below 3 km are not appropriate for geothermal energy extraction [61]. [37] illustrated that the temperature at 5 km depth can exceed the temperature at 2 km with more than 30 °C .

On the other hand, there are several parameters that have impact on harnessing geothermal energy from AOGWs. In the respect of pump power, Holmberg et al. (2016) created a numerical model to study the performance of DHEs and carried out parametric study related to pressure drop and circulation pumping [36]. Wight and Bennett (2015) studied the acquisition of electricity from AOGWs and evaluated pump horsepower required to circulate the working fluid [62]. Noorollahi et al. (2015) studied about extraction of geothermal energy from AOGWs as low-temperature resources and concluded that well casing geometry and the size of injection and extraction pipes play a crucial role in the acquiring of heat output [14].

2.7 The insulation

The insulation is implemented to decrease the heat transfer between outer and inner pipes during the circulation of the working fluid. The deep wells which have high temperatures require more insulation, even near the surface to minimize heat lost especially near the ground [23], [24].

Kujawa et al. created a computational model in 2006 to study the utilization of deep geological wells for acquiring geothermal energy and investigated the effect of insulation tube length [63].

Moreover, the other investigation is addressed to know the effect of insulation by doing some measurement and simulation. The insulation cover was applied to the inner pipe and the consequence showed that placing insulation on the pipe has a crucial impact on the heat extraction rate, thus when the pipe is insulated the final (exit) temperature is higher than other circumstances in which there is no any insulation on the inner tube. So, it was obtained that applying insulation has great performance [64].

Additionally, another researcher mentioned in his study that for maximizing the heat out from AOGWs using downhole heat exchangers, it is recommended to use an inner tube made from material which has the lowest thermal conductivity coefficient. Vacuum insulated pipe, as one of the options of insulated inner tube, can crucially improve heat uptake and raise the efficiency of energy use.

2.8 Selection of working fluids

The selection of fluid in the circulation process is very crucial to achieve high performance in power generation systems. Thus, thermal properties of the fluids have an important role in economic feasibility, environmental aspects, sizing components and efficiency of cycle. That topic and the effects of circulating fluid on the efficiency of the systems have been studied by many researchers. Liu, Chien and Wang (2004) analysed the effects of working fluids, studying its impact on thermal effectiveness and the total heat output. It was also investigated that having hydrogen bonds between molecules of working fluids leads to wet fluids condition which is not appropriate for organic Rankine cycle (ORC) systems. Additionally, they noted that thermal effectiveness for different working fluids is influenced negligibly by the critical temperature and the maximum amount of the total heat production efficiency declines when working fluid that has lower critical temperature used [65].

In another study, Koglbauer et al. (2007) evaluated more than 30 types of circulating fluid (alkanes, ethers and so on) for ORC. They mentioned that for the condition in which water is working fluid, the fluid with a lower critical point is acceptable [66]. Moreover, Chen et al. (2010) analyzed 35 fluids and systems performance to know selection criteria. The properties such as thermal stability, density, environmental perspective, latent heat and critical points have been focused on. The conclusion is that working fluids having high latent heat and density can make a way to achieve high heat recovery and fluids with low critical pressure and temperature would have priority for ORC [67]. Related to that topic, the comparison between pure and mixture working fluids has been reviewed. The study says that the working fluid which is mixture of several fluids can have good temperature that is appropriate for increasing the total efficiency [68].

Due to having lower boiling temperature, organic working fluids are used broadly in geothermal sites in which have low temperatures for power recovery with ORC. Selection of working fluids indeed depends on aspects of well (depth) and geothermal resources of AOGWs. Cheng et al., 2014 gave the review about nearly 7 sorts of organic working fluids (R600, R600a, R134a, Propylene, R290, R245fa, R143a) for use in geothermal heat extraction and evaluated which was the optimal fluid for net output rate regarding the depth and geothermal gradient. It was found that the characteristics of R290 were very similar to propylene and except R600 and R600a, the others had accordingly low evaporation latent heat. As a consequence, they noted that all of the fluids had low power generations profit when the depth of the well is below 3 km and so abandoned petroleum wells are inappropriate to be produced for geothermal energy which exists less than that depth. Thus, regarding Table 1 which is reported below, geothermal energy extraction with using AOGWs is suitable for depths above 4 km and from the study, it was obvious that R134a and R245fa were more favorable for power generation using AOGWs [61].

Table 1. Optimal working fluids for power production using AOGW [61]

Well depth [km]	Geothermal gradient [K/m]	Optimal fluids and net power output
4	0.04	R134a [53kW], R143a [51W]
4	0.05	R134a [81kW], R143a [74W]
5	0.04	R134a [108kW], R143a [101W]
5	0.05	R134a [154kW], R245fa [152W]
6	0.04	R134a [189kW], R245fa [174W]
6	0.05	R245fa [266kW], R134a [257W]

Similar to the study above reported, Mokhtari et al. 2016 evaluated R22, R134, R123, R245fa. As a conclusion, they mentioned that R123 is the most appropriate working fluid for geothermal ORC because of having higher power generation and thermal efficiency [69]. In another research, the potential utilization of CO_2 as a working fluid is indicated in geothermal energy production from AOGWs due to its benefits such as decreasing the requirement of pump power, high mobility in comparison with water and so on [70].

2.9 Other different applications

One of the different approaches to produce geothermal energy with applying to AOGWs is using the two wells method. According to the investigation of Mehmood et al. (2019), the dual wells system can be addressed to AOGWs to get heat extraction. Thus, in that method, at least one injection well and also one production well should be utilized. There are two flow ways so the working fluid goes through injection well into the geothermal reservoir and comes out to the surface along the other well with carrying the heat from the hot formations. Using that approach, the energy can be harvested with high efficiency which is different from the traditional closed-loop systems. They presented that, the average final temperature has a fluctuation with changing the distance between production and injection wells. Thus, as shown in Fig.10, over the 50 years, as decreasing the distance between a pair of wells, the average outlet temperature increased dramatically. However, it was found that if the distance was higher 350 m, the final temperature at the surface remained stable during that period. They concluded that when the distance between two wells is sufficiently high, the residence time will be high and it will make a way to acceptable energy transfer between hotter rocks and the fluids whereas it has the working fluid lost. Moreover, on the other side, they illustrated that the outlet temperature can be affected by the injection pressure. Therefore, when that pressure is enough lower (nearly 20 MPa), the declining rate of final temperature was not rapid (approximately 25 ˚C at the end of 50 years period). In contrast, if the injection pressure was above 35 MPa, there was a decrease of 55 ˚C in outlet temperature at the last year of the period [71].

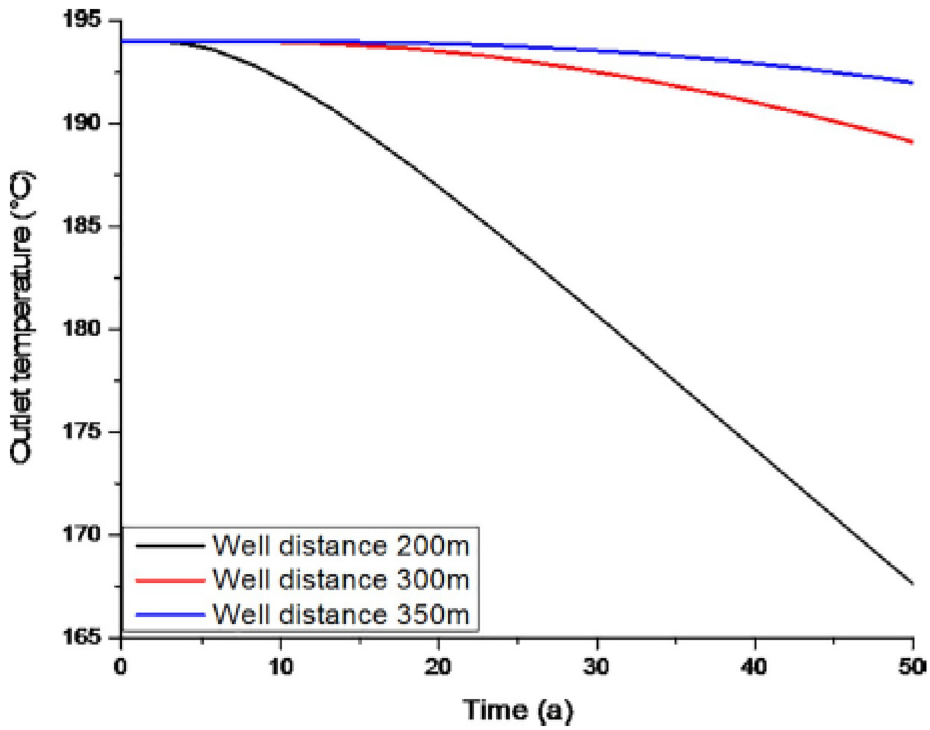


Fig.10 The average outlet temperature with various distances (m) between the production and injection wells [71].

In another research, the geothermal energy production from abandoned oil wells with utilizing in situ combustion has been represented. It was studied that a larger amount of geothermal energy can be harvested by applying that method to abandoned and also productive wells without having direct contact with working fluid and affecting petroleum production. That approach explains that the air is injected into oil reservoir to oxidize the heavy oil for heating up. The burning of oil leads to be much heat in the reservoir and it could make a way to produce a high proportion of the energy (Fig.11).

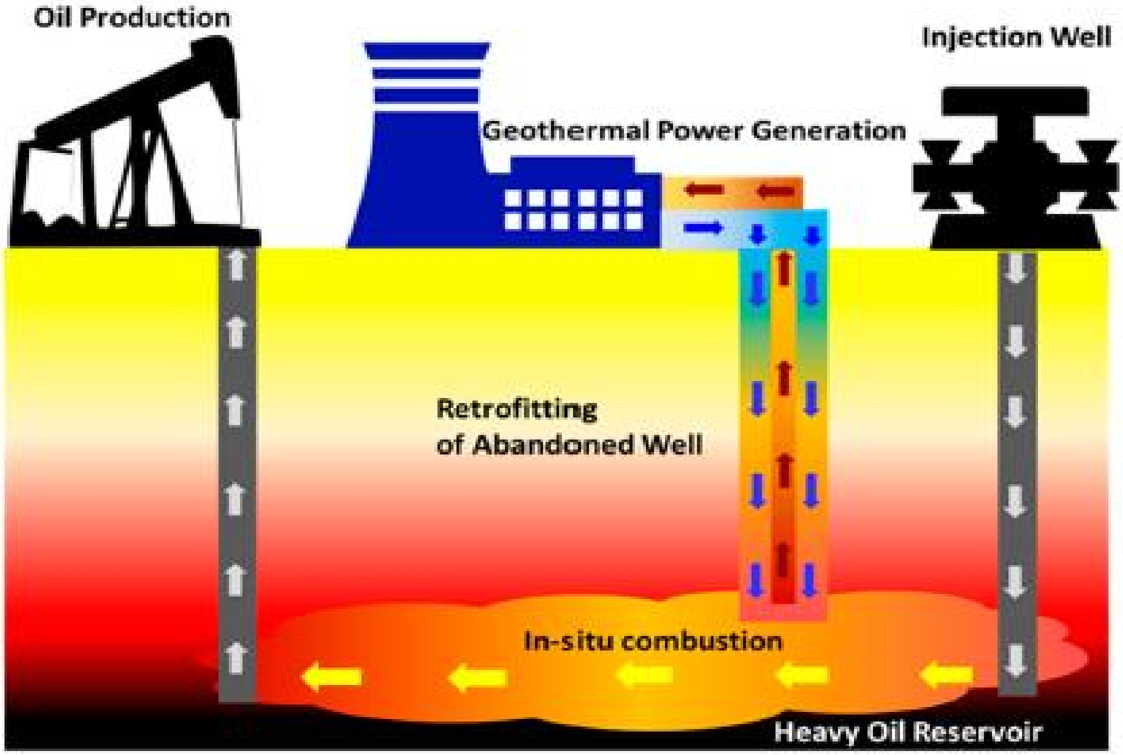


Fig.11 The scheme of utilizing in situ combustion system for abandoned wells [72].

Based on the conclusion of that study, subjecting in situ combustions to abandoned wells was highly beneficial, especially from an economic side. Thus, appearing much amount of heat helps to make short the payback period. The computational results showed that the outlet temperature raised up significantly after doing in situ combustions [72].

According to using in situ combustion method, Cinar (2013) took another approach to apply that. Thusly, he used wet in situ combustions whereas it was not sufficient because wet combustion extinguished the flame process. Consequently, it led to less heated formation fluid and he pointed that it might also conclude with high depletion of formation fluid.

2.10 Economic and environmental aspects

From an economical side, geothermal energy production from AOGWs is also very critical. That aspect should be considered in configuration of heat exchangers in order to acquire viability regarding economical parameters. Barbacki mentioned that the acquisition of 2 MW heat by utilizing AOWs in Poland can need approximately 1 million USD investment [73]. Moreover, Nian and Cheng (2018) indicated the annual cost of geothermal heating from AOGWs be 1.72 USD per 1 m^2 which is crucially lower in comparison with the conventional geothermal system that costs 3.4 USD per 1 m^2 [74]. In addition, Eliasson (2005) performed research about that in DHEs for power generation. He has mentioned that DHEs are feasible when the price of electricity surpasses approximately 0.1 Eur/kWh [75]. Moreover, in her study, Karla (2012) has said that selection of the type of the material in DHEs and also the component of sizing is more crucial from an economical point of view [76].

On the other hand, the environmental aspects should also be taken into account during geothermal energy production from AOGW. Even for the transformed geothermal wells that have been plugged

carefully, leaking does occur but is forecasted to appear in the future. Leaking liquid or gas from AOGWs can make a way to remarkable damage to human health and the environment. AOGWs can be a path line for CH_4 and other gases to release into the atmosphere [77]. Additionally, that types of wells are often indicated as the potential sources of groundwater contaminations. Several studies have done gas and liquid leakages from AOGWs [78].
Kang et al. (2016) made measurements of CH_4 emissions from AOGWs and found a considerable amount of methane gas escaped which is not paid attention to in the current emission inventory. They estimated that this emission will occur during the coming years [79]. In another survey, it is noted that old AOGWs have more risk of leakage than the new AOGWs. Moreover, there are different aspects affecting leakage from abandoned wells such as geological circumstances, the life of the well, existing of shallow gas [80]. Riddick et al. (2019) studied that the emission from an active well is extremely higher as compared to the plugged or unplugged abandoned well [81].
One of the problems with geothermal extraction from AOGWs is the gas escaped from the well. This issue is more common for direct use systems such as flash and dry steam systems. These gasses can include H_2S, CO_2, CH_4, H_2 and boron. Yilmaz and Kaptan (2017) mentioned the increase of the percentage of boron gas which can lead to toxicity in the soil of the Aydın region where there is a geothermal power plant [82]. In addition, Manzella et a.l (2018) estimated the effect of geothermal improvement on the atmosphere, soil and water in Italy. They also reported the impacts of a geothermal plant on places with high antique and historical value. According to a report of seismicity, in South Korea, the largest earthquake was connected to the operation of a geothermal plant [1].

Table 2. Summary of literature review

Author	Year	Direct or indirect use (power generation)	Working fluid type	Explanation	Main consequences
Culver and Reistad	1978	PG	Water	Vertical heat exchanger	The well with promoter pipe can give more heat output than solid-cased well
Lund et al.	2005	Direct use	water	Theoretical	Using perforated well improves thermal efficiency
Dominguez	2011	Direct use	water	Vertical DHE	The final temperature of working fluid is increase as enhancing of inner pipe diameter and resistance.
Lafta and Hashim	2012	PG	Water	Theoretical	Geothermal energy production with closed-loop system depends on depths and months of year.

Shook et al.	2004	PG		Study on energy production	Energy generation is dependent on residence time of fluid, contact area, thermal characterization.
Morita et al.	2005	PG	Water	Vertical DHE	Decreasing the energy consumption of the pump due to circulation of fluid is significant.
Eliasson et al.	2005	PG		Economic analysis	DHE is applicable when the price of electricity is above nearly 0.1Eur/kWh
Karla et al.	2012	PG		Economic analysis	Material selection in DHE designing is very crucial.
Kanoglu and Bolatturk	2008	Direct use and PG	water	Efficiency analysis	PG is the best option where temperature is extremely high whereas in other cases, 25 % efficiency can be obtained using direct method
Pahud and Matthey	2001			U-tube and coaxial	Coaxial is more common than U-tube due to low pressure drop.
Pan et al.	1982	Direct use	water	Vertical DHE	A reverse flow of DHE has better performance in comparison with forward flow.
Templeton	2013	PG	Water	Vertical DHE,thesis	The wells with high temperature needs more insulation because of diminishing the amount of heat lost.
Guillaume	2011	Direct use	Water	Vertical DHE	Applying insulation to inner pipe has significantly positive impact on heat extraction.

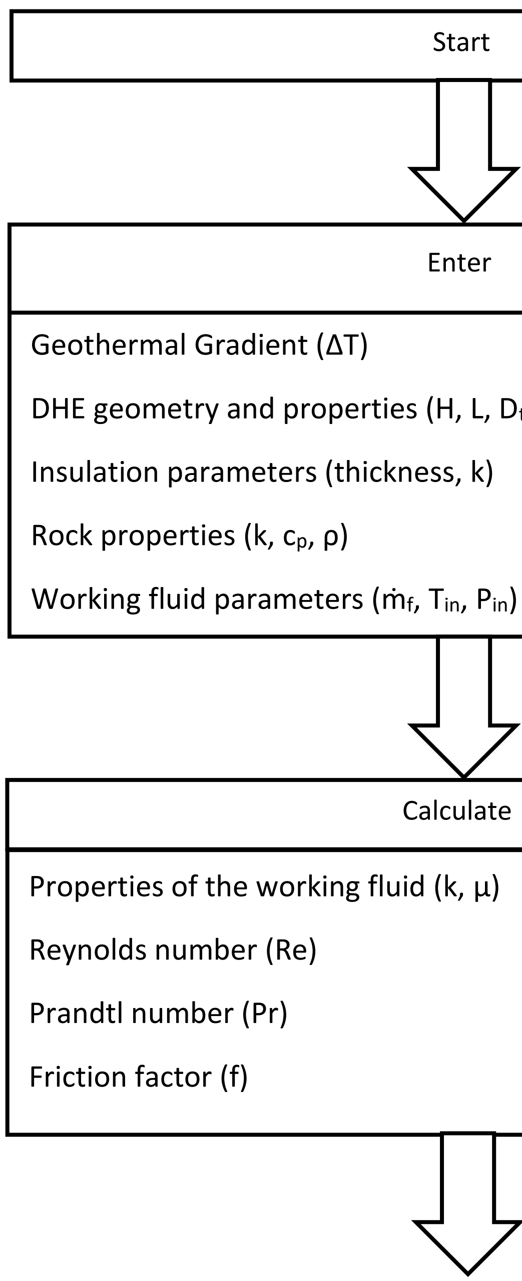
Bu et al.	2012			Theory	The temperature of extracted fluid is decreasing decade by decade.
Chen	2010	PG	35 different fluids	Vertical DHE	The higher heat extraction can obtain with using working fluid which has high latent heat and density.
Bao et al.	2010	PG	Several fluids	Vertical DHE	The mixture of fluids can have appropriate temperature to get good efficiency.
Cheng	2014	PG	R600, R600a, R134a, Propylene, R290, R245fa, R143a	Working fluids selection	R134a and R245fa are more suitable to generate power using abandoned hydrocarbon wells.

Chapter 3

Methodology

3.1 The workflow of the calculation in Engineering Equation Solver (EES)

All codes developed are written in EES software which is a highly sophisticated software tool and has plenty of thermodynamic properties database with high accuracy that is applicable for many substances. The main parameters (temperature, pressure, enthalpy and others) of the fluid are evaluated in EES along the depth of the DHE with increment of 50 m. The output parameters of the working fluid in every section are input parameters for the next one. The flowchart of applications in EES is indicated below:



Nusselt number (Nu)

Convective heat transfer coefficient (h)

Total heat transfer coefficient (K_t)

Heat flow (Q)

$\Downarrow$

Calculate

T_{out}

P_{out}

$\Downarrow$

Calculate

$P_{in\text{-}condenser}$

$P_{out\text{-}pump}$

η pump

$\Downarrow$

Calculate

$\dot{W}_{turbine}$

$\dot{W}_{pump}$

$\Downarrow$

Finish

$\dot{W}_{net}$

$\eta_{thermal}$

3.2 Description of the heat exchanger

A coaxial heat exchanger (see Fig.12) is chosen for the proposed work as it turned out to have higher performance than other kinds of heat exchangers and configurations by declining pressure drop to a minimum value [83]. Moreover, it can easily be observed from the description below that the type of circulating fluid direction is a reverse flow which has several positive sides than other types of flow such as a higher heat extraction [56]. In that type of flow direction, the cold fluid enters the annulus, goes to the bottom and comes out through the inner pipe as a heated one. For tackling the problem of heat loss, the inner pipe is insulated to avoid having a decrease in temperature during the circulation process and an increase in the amount of extraction of the heat.

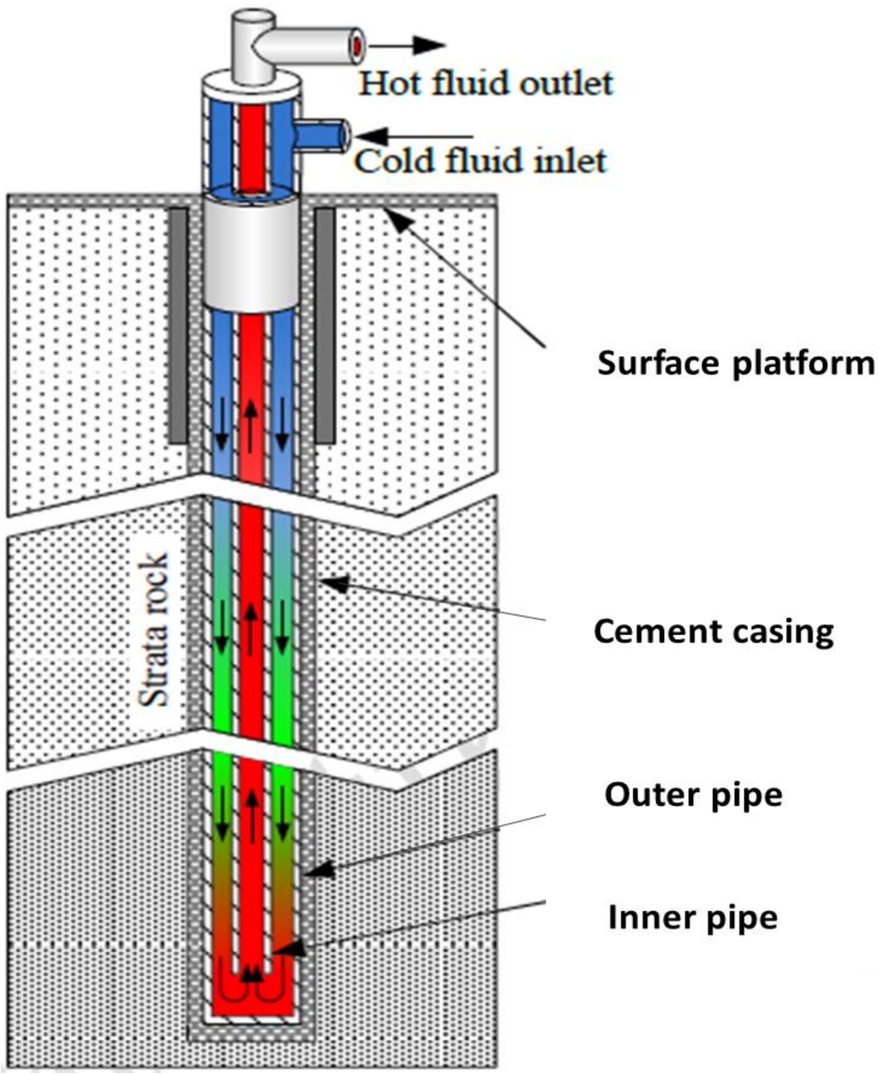


Fig.12 The scheme of double-pipe downhole heat exchanger.

Cross-section of the heat exchanger is illustrated in Fig.13: it can be easily seen that along the well, there is the cement between the rock formation and the annular pipe. The inner pipe is insulated to tackle the problem of heat loss during upward flow.

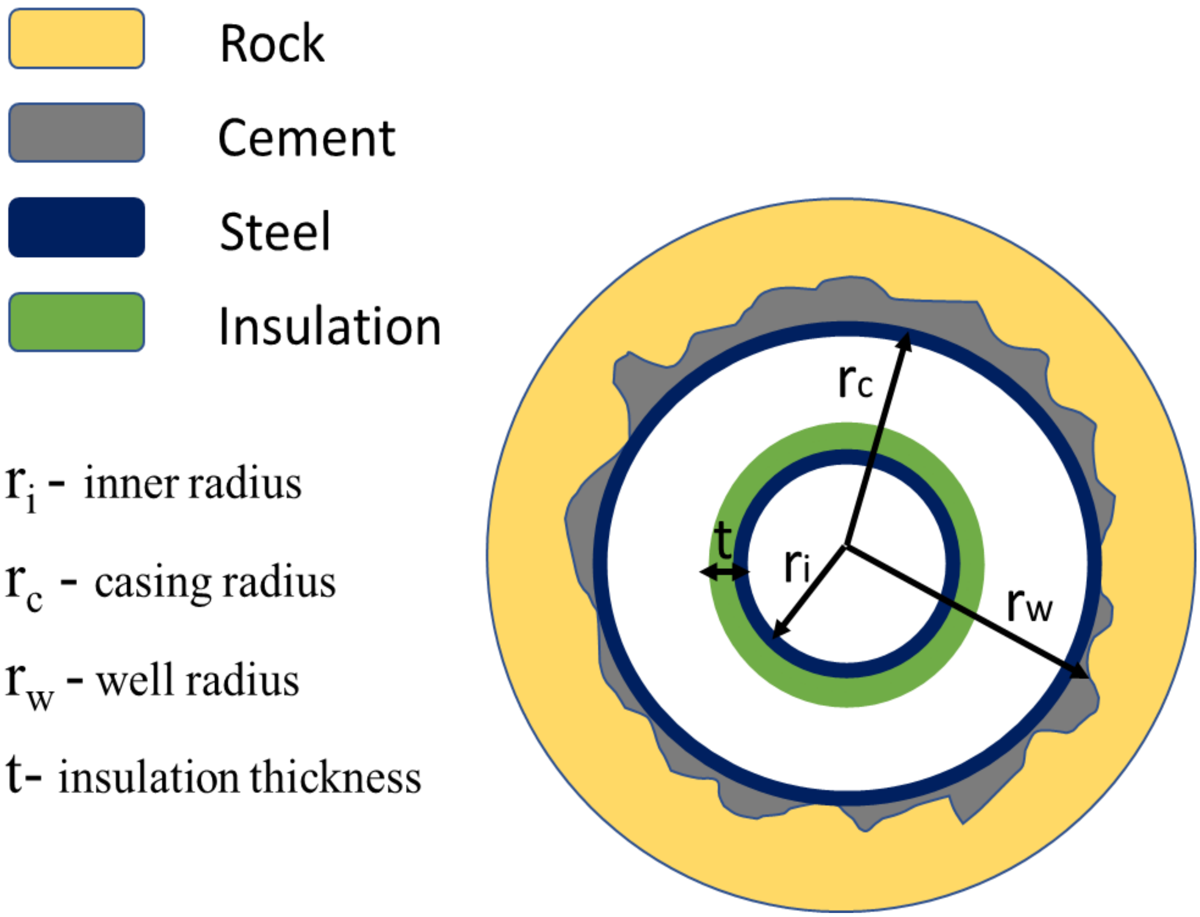


Fig.13.The cross section of wellbore heat exchanger (Add reference).

3.3 Critical insulation radius

It is known that adding more insulation can diminish heat transfer phenomena. A thicker insulated layer means a low rate of heat transfer. Regarding cylindrical pipe, adding insulation is a different matter. Thus, make an increase in insulation thicker in that type of pipes can improve the conduction resistance of the insulation layer while it declines the connection resistance of the surface because of expansion of the outer surface area for convection. For characterizing the critical insulation layer, the critical insulation radius is used and it can be determined by using equation 3.1.

$$r_{cr}=\frac{k}{h} \tag{3.1}$$

In that equation above:
k is the thermal conductivity of the insulation layer [W/m K]
h is the convective heat transfer coefficient [W/m²K]

The critical radius is strongly dependent on both parameters which are indicated in the formula.

The dependency between heat transfer rate and outer radius of insulation is shown in Fig.14. When the Q (heat transfer rat)e reaches maximum values, the value of r_2 can be defined from the zero slop.

The maximum value of heat transfer rate from a cylindrical pipe can be observed when r_2 is equal to r_{cr}. Additionally, the heat transfer rate tends to rise up with adding insulation while $r_2<r_{cr}$ is true. As a consequence, insulation pipe can increase the rate of heat transfer instead of having a decrease on it when $r_2>r_{cr}$ [84].

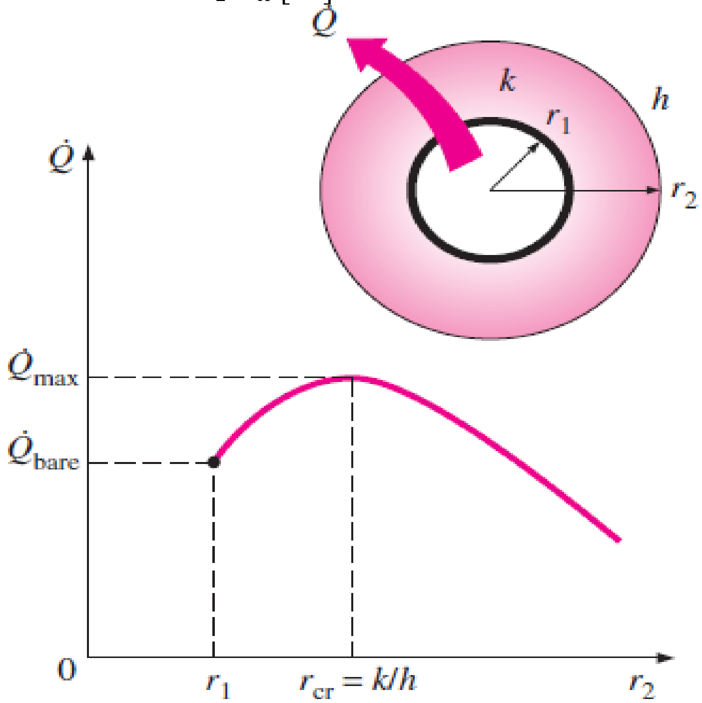


Fig.14 Variation of heat transfer rate with r_2, outer radius of insulation when $r_1<r_{cr}$ [84].

3.4 Thermodynamic Analysis

The thermodynamic description of the geothermal power generation (GPG) with DHE is related to logarithmic mean temperature difference (LMTD). From the overall thermal resistance point of view, there are a couple of components to be described:

a) Inner pipe and annulus
b) Rock formation (hot geothermal source)

The assumption is that the temperature profile of rocks along the well was already obtained during the well testing process.

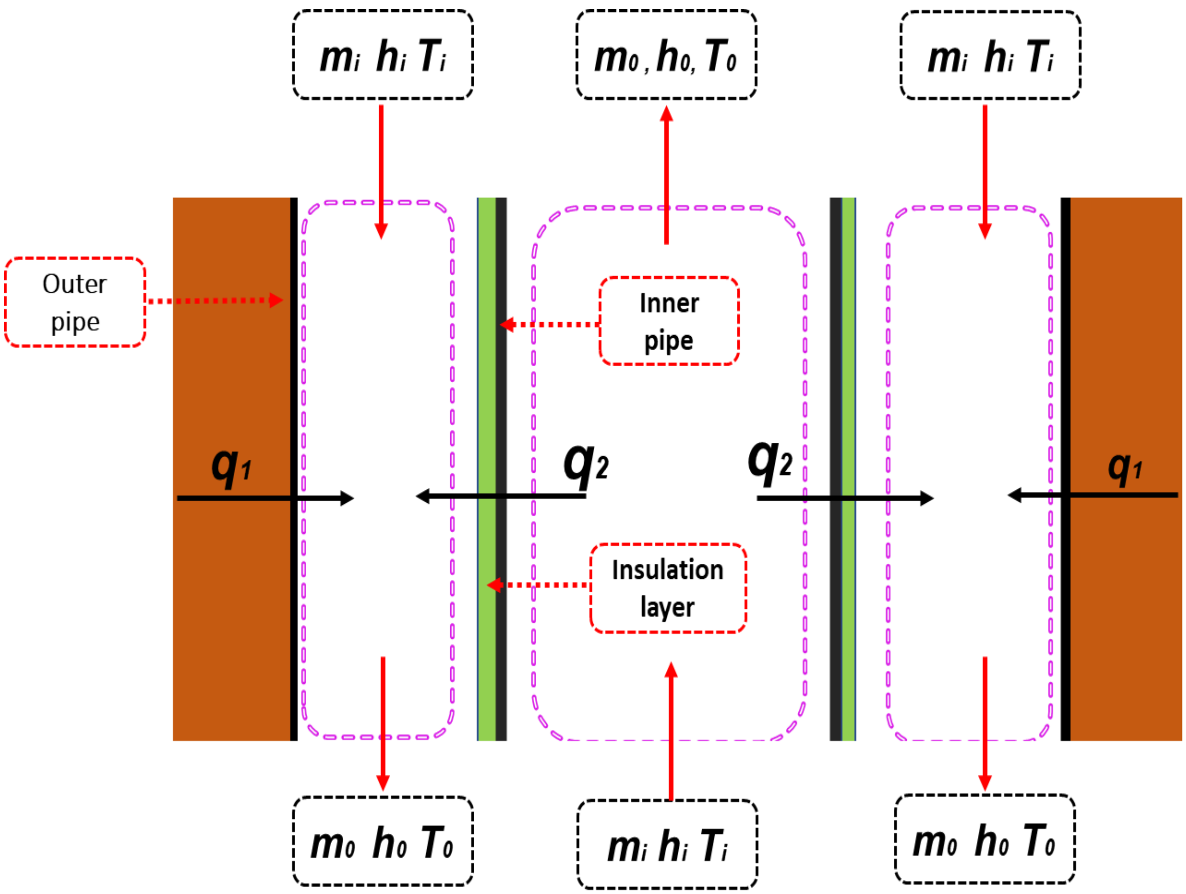


Fig.15 The chart of the heat flow of the system

There are 2 heat flow directions. The first one is that the heat moves from the hottest rocks to the annulus which is equal to q_1 whereas the second flow direction is from the inner pipe to the annulus or vice-versa (q_2), (Fig. 15). It is assumed that the well is divided the sections (for each 50 m). The output parameters of the working fluid in every section are input parameters for the next one.

Other assumptions are made for the structure of the model:

- The flow condition is a steady-state condition for the first part.
- The flow rate of the circulating fluid is constant.

- The temperature profile of the rock formation is considered linear
- q_2 is not taken into account due to the inner pipe is being insulated.

The parameters and thermal properties of the downhole heat exchanger (DHE) are taken from the different works of literature and are indicated in Table 3. The insulation material is selected as glass wool. The length of the well, inner pipe diameter and tube materials are chosen as variables to evaluate their impacts on heat extraction rate.

Table 3. The parameters and properties of the downhole heat exchanger.

Parameter	Unit	Value	Reference
Inner pipe diameter	m	0.0779	Alimonti and Soldo, 2016
Insulation thickness	m	0.002-0.012	Yildirim et al, 2019
Annulus diameter	m	0.1504	Alimonti and Soldo, 2016
Geothermal well diameter	m	0.1778	Alimonti and Soldo, 2016
Pipe thermal conductivity	W/m K	4-231	Yildirim et al, 2019
Insulation (glass wool) thermal conductivity (kins)	W/m K	0.043	Yildirim et al, 2019

3.5 Heat transfer in the casing and inner pipe

In the annulus section, the working fluid is directly contacting with the wall which consists of a steel casing. Also, there is the cement between the casing and rock wall as well as between other casings. The assumption is that the heat is transferred from the rock formation to the wall by conduction and between the wall and the circulating fluid by convection.

On the other hand, in the upward flow, the working fluid which is heated at the bottom of the well enters in the inner tube. After that step, the heat transfer occurs only along the wall of the pipe until reaching to the surface

3.5.1 Rock formation and casing

There are few types of thermal resistances (TR) that play crucial role in heat transfer. One of them is conductive thermal resistance in the rock and it can be found by the equation below:

$$R_{conductive} = \frac{\ln \frac{2\sqrt{A_S \times t}}{r_w}}{2k_s} \tag{3.2}$$

where:
k_s is the thermal conductivity of rock [W/ m K]
A_s is the thermal diffusivity of rock [m^2/s]
t is the elapsed time [s]
r_w is the radius of the well [m]

Additionally, the thermal diffusivity can be expressed as: [86]

$$A_s = \frac{k_s}{\rho_{rock} \times c_p} \tag{3.3}$$

In the equation above:
ρ_{rock} is the density of the rock [kg/m^3]
c_p is the specific heat of the rock [J/ kg K]

The conductive heat transfer coefficient can be shown as:

$$\frac{1}{h_{cd}} = \frac{D_w \times \ln\frac{4\sqrt{A_s \times t}}{D_w}}{2k_s} \tag{3.4}$$

Where;
h_{cd} is conductive heat transfer coefficient [W/ m^2 K]
D_w is the diameter of the wellbore.

Due to having negligible differences between casing and wellbore diameter, D_w=D_c can be considered.

3.5.2 Casing and working fluid

There is a circulation of working fluid through the annulus because of forcing by convection. The values of the connective heat transfer coefficient are strongly dependent on the geometry of downhole heat exchanger, and the properties of the working fluid. For an indication of those dependencies, the dimensionless formulas in equations 3.5 is used:

$$\mathrm{Re} = \frac{\mathrm{D\,w\,\rho}}{\mu} \; ; Pr = \frac{\mathrm{Cp}\,\mu}{\mathrm{k}} \tag{3.5}$$

where:
Re, Pr are standing for Reynolds and Prandtl numbers, respectively.
D- diameter of the tube [m],
ρ – the density of the fluid [kg/m^3],
μ - dynamic viscosity of the fluid [Pa s],
c_p – specific heat capacity of the fluid [J/ Kg K],
k- thermal conductivity of the fluid [W/ m K].

Depending on some properties, it is known that if Re ≤ 2300, the flow is fully laminar whereas it is turbulent when Reynolds number is higher than 2300 [87].
Then, h which is called convective heat transfer coefficient can be found from equation 3.6:

$$h_{cv} = \frac{\mathrm{Nu\,K}}{\mathrm{Dh}} \tag{3.6}$$

Where:
h_{cv} is conductive heat transfer coefficient [W/ m^2 K]
D_h is the hydraulic diameter [m],
k is the thermal conductivity of working fluid [w/m K].
According to the Dittus-Boelter equation, the turbulent flow is assumed inside the pipes [44]:

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad (3.7)$$

The total resistance of the casings can be removed in comparison with rock thermal resistivity. As a result, the total heat transfer coefficient can be written as a sum of the heat transfer coefficient:

$$K_t = \frac{1}{h_{cd}} + \frac{1}{h_{cv}} \quad (3.8)$$

K_t is the total heat transfer coefficient [W/m K]

The following equation illustrates the heat flow in the downward pipe [29]:

$$Q_{annular} = \pi D_w K_t \left(Tw(z) - T_{fluid\text{-}down}\right) \Delta z \quad (3.9)$$

Where:

D_w is the external diameter of the borehole [m]
T_w is the temperature of the rock at depth z [^{0}C]
$T_{fluid\text{-}down}$ is the temperature of working fluid in the annular pipe [^{0}C]
Δz is the length of the pipe [m]

3.5.3 Inner pipe and working fluid

The equations for upward flow will have differences compared to downward flow:

$$Q_{inner} = \pi D_t K_{t\,o} (T_i - T_o)\, \Delta z \quad (3.10)$$

D_t is the diameter of the inner tube [m]
$K_{t\,o}$ is the total heat transfer coefficient [W/m K]
T_i is the temperature of the working fluid in the inner tube[°C]
T_o is the temperature of working fluid in the annular pipe [°C]
Δz is the length of the pipe [m]

The total heat transfer coefficient for upward flow which has direct relations with insulation thickness can be expressed as equation (3.11):

$$\frac{1}{K_{to}} = \frac{r+t}{r} \times \frac{1}{h_i} + \frac{r+t}{r+t/2} \times \frac{t}{k_{ins}} + \frac{1}{h_o} \quad (3.11)$$

r is internal radius of inner pipe [m]
t is insulation thickness [m]
k_{ins} is the thermal conductivity of insulative material [W/ m K]

h_i and h_o are the convective heat transfer coefficients for inner and outer pipe, respectively [W/ m^2 K].

$$h_i = \frac{Nu \times k_{ins}}{D_t}$$

$$h_o = \frac{Nu \times k_{ins}}{2(r+t)} \qquad (3.12)$$

3.6 The calculation of pressure drop

In vertical cylinder pipe, the pressure drop can be known by 3 components:

- Hydrostatic pressure drop because of gravity
- Pressure drop due to friction
- Kinetic pressure drop

The third one is very negligible and it can be neglected during the calculations. When the working fluid flows towards the bottom of the well, frictional forces appear against the flow direction. However, that type of frictional loses due to forces is being tackled by the helping of hydrostatic column. Hydrostatic or gravitational pressure drop is dependent on the density of fluid as well as fluid properties and frictional pressure drop [88].

After neglecting the kinetic pressure drop, ΔP in a cylindrical pipe is equal to the sum of gravitational and frictional pressure loses (Fig.16), so it can be obtained by using equation 3.13:

$$\Delta P = \rho g L + (f \rho L u^2) / 2Dh \qquad (3.13)$$

The gravitational pressure drop can exist in an open system, thus when there is a closed system, it will be eliminated. From another point of view, the downhole heat exchanger is being gained heat by hot rock formation, so the density varies as increasing temperature and pressure, as a consequence, pressure drop due to gravity occurs.

Kinetic pressure drop can exist at the bottom of the DHE because of changing flow area. The final formula to calculate pressure drop at the bottom part of DHE can be written as in equation 3.14:

$$\Delta P = \rho g L + (f \rho L u^2) / 2Dh + \frac{1}{2} \rho \Delta u^2 \qquad (3.14)$$

Where:
ρ is the density of working fluid [kg/m^3]
L is the length of DHE [m]
f is the friction factor
u is the velocity of the working fluid [m/s]
D is the diameter of the pipe [m].

In addition, pressure output (P_0) will be found from equation 3.15:

$$P_0 = P_i - \Delta P \qquad (3.15)$$

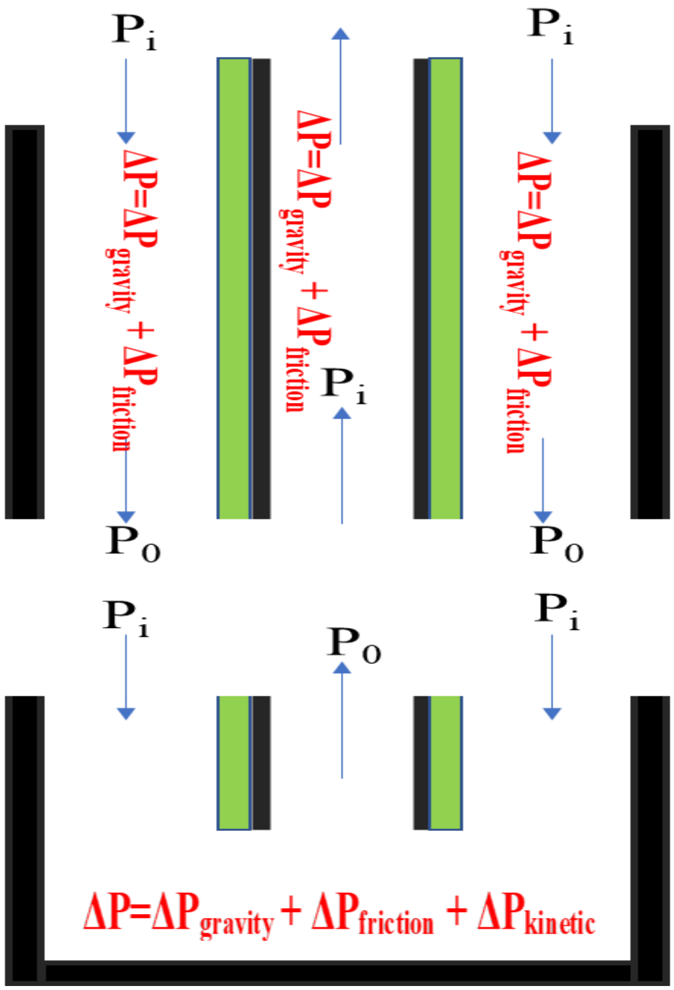


Fig.16 Pressure drops within the downhole heat exchanger

3.7 Power generation system

The heated working fluid which comes from DHE is sent to the power plant to produce electricity. The power plant operates on the Rankine cycle. The turbine, generator system, condenser and pump are the crucial component of the power plant.

According to the turbine, the energy balance can be written as equation 3.16:

$$\dot{W}_{tur} = \dot{m}_{fluid}\, \eta_t\, (h_1 - h_2)\eta_g \tag{3.16}$$

Where:

$\dot{m}_{fluid}$ is the flow rate of the working fluid [kg/s]

η_t is the turbine efficiency

η_g is the generator efficiency,

h_1 and h_2 are the in and out enthalpy of the turbine

$\dot{W}_{tur}$ is the generated power [kW]

In generator, the conversion of mechanical energy into electricity is occurred with high efficiency. 95 % of generator efficiency is assumed in the Thesis.

The role of the condenser in the power plant is to convert the steam into a liquid phase by cooling water. The performance of it is very significant because its temperature and pressure have more impacts on the efficiency of the turbine. The equation below illustrates the connection between the mass flow rate of the cooling water and working fluid [85]:

$$m_{cw}(h_x - h_y) = \dot{m}_{fluid}(h_2 - h_3) \tag{3.17}$$

Regarding the pump, the power needed to it can be found the equation (3.18):

$$\dot{W}_{pump} = \dot{m}_{fluid}\,(h_4 - h_3)\,/\eta_{pump} \tag{3.18}$$

η_{pump} is the pump efficiency.

As a consequence, the net power generated and the thermal efficiency (cycle performance) can be expressed as below:

$$\dot{W}_{net} = \dot{W}_{tur} - \dot{W}_{pump} \tag{3.19}$$

$$\eta_{thermal} = \frac{\dot{W}_{net}}{Q_{in}} \tag{3.20}$$

3.8 Sensitivity analysis

For analyzing the feasibility of power generation from abandoned hydrocarbon wells using DHE, a sensitive study is carried out. Mass flow rate, insulation thickness, depth of DHE, diameters of the pipes, temperature gradient and type of working fluids are taken into account to evaluate the performance of DHE to produce electricity.

Table 4. Main parameters used in the Thesis work [29], [61].

Parameters	**Value**
Temperature gradient	2-5 °C/50 m
Depth	1000-3000 m with increment every 500 m
Diameter of the inner tube	0.0779 m and 0.1214 m
Rock density	2080-3120 Kg/m^3 with an increment of 260 Kg/m^3
Rock specific heat	640-920 with an increment of 80
Rock conductivity	2-3 W/m K with an 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
The efficiency of the generator	95%
Isentropic efficiency of the pump	85%

TableTable 5 indicates the inlet pressures of the different working fluids.

Table 5. Working fluids and inlet pressure [85].

Working fluid	R134a	R22	R125	n-butane
P_{inlet} [kPa]	708.8	1131	1637	290

Chapter 4

Results and discussion

In the final chapter, the thermodynamic analyses of the model are illustrated in detail. This study is made to evaluate the feasibility of DHE for the generation of power. The model is validated by [29] and [85].

The effect of rock properties, geothermal gradient, insulation thickness, the depth of the well, mass flow rate, type of working fluids are investigated in the thesis work. Additionally, the future performance of the system is forecasted. More than 500 simulations done by EES are conducted to the thesis.

4.1 The effect of ground properties

The properties of the rock such as rock conductivity, rock density, specific heat capacity and geothermal gradient play a crucial role in the heat exchange process as well as the efficiency of the power generation.

4.1.1 Rock density

The rock properties have an impact directly on the ground thermal resistance. In Fig.17, the dependences of rock conductive thermal resistance from rock density within the time are indicated. The value of the rock density is taken between 2080 and 3120 kg/m^3 with an increasing 260 kg/m^3 in every step as shown in Table 4.

Fig.17 shows that the conductive thermal resistance of the rock increases significantly during the first year, then it will have a considerable and stable increase over the next years. Moreover, the thermal resistance of the rock which has high density is lower than the resistance of rock with low density.

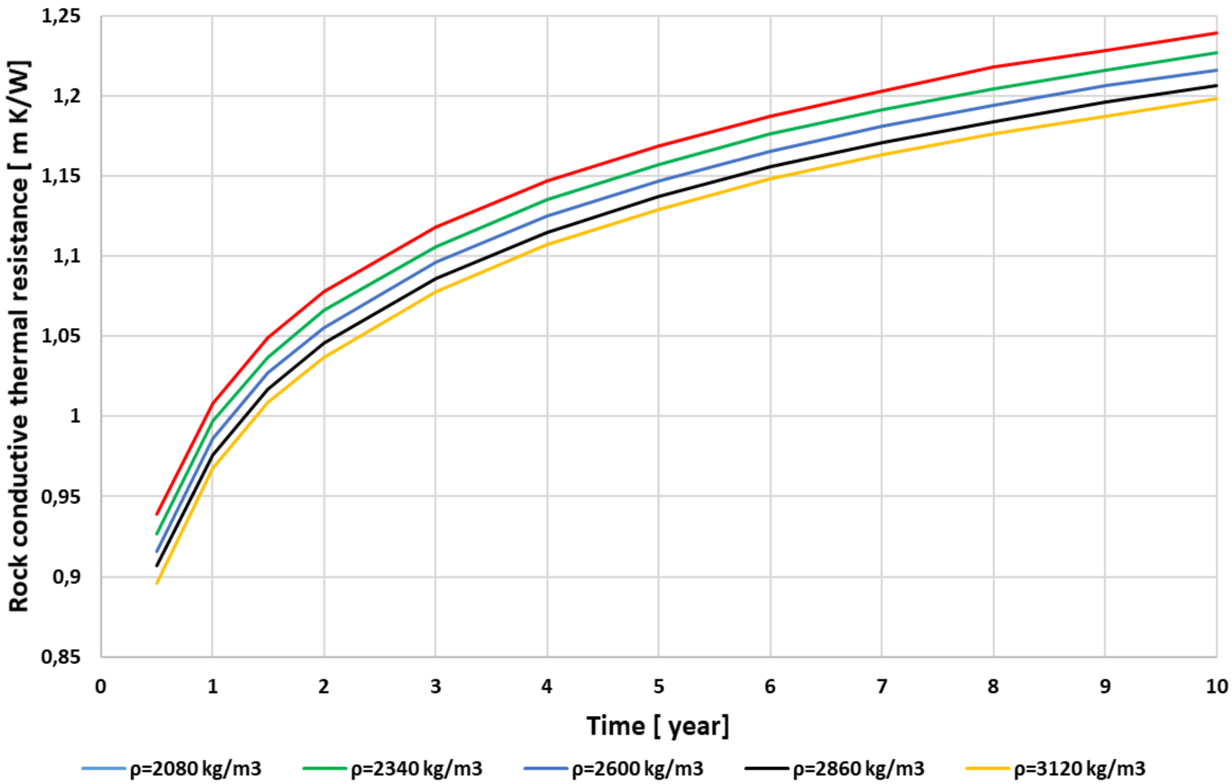


Fig.17 Soil resistance within years depending on the rock density
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, k_{rock} : 2.5 W/m K)

In Fig.18, the relation between rock density and wellhead temperature is illustrated.

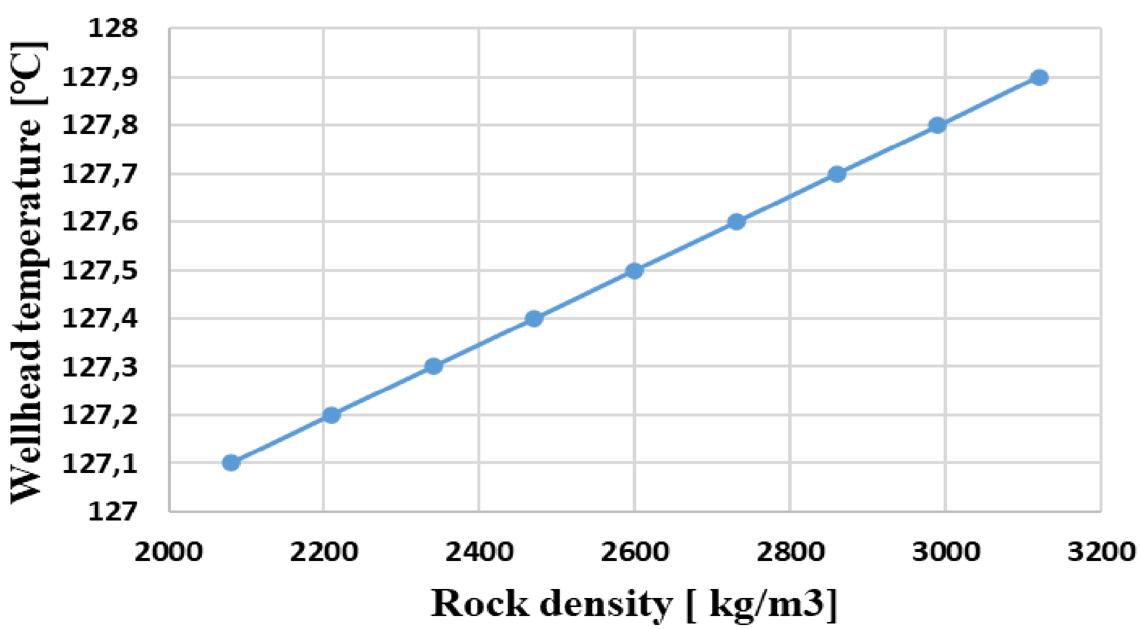


Fig.18 Dependence of the wellhead temperature from rock density
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m)

From the chart above, it can be shown that as increasing the value of rock density, there is a negligible change in wellhead temperature.

4.1.2 Rock specific heat

The impacts of the rock-specific heat on rock thermal resistance and wellhead temperature are very similar to the rock density as can be seen from Fig.19 and Fig.20. Thus, it is estimated that the thermal conductive resistance will have a remarkable increase over the years. In addition, the resistance is high where the rock-specific heat has a high value.

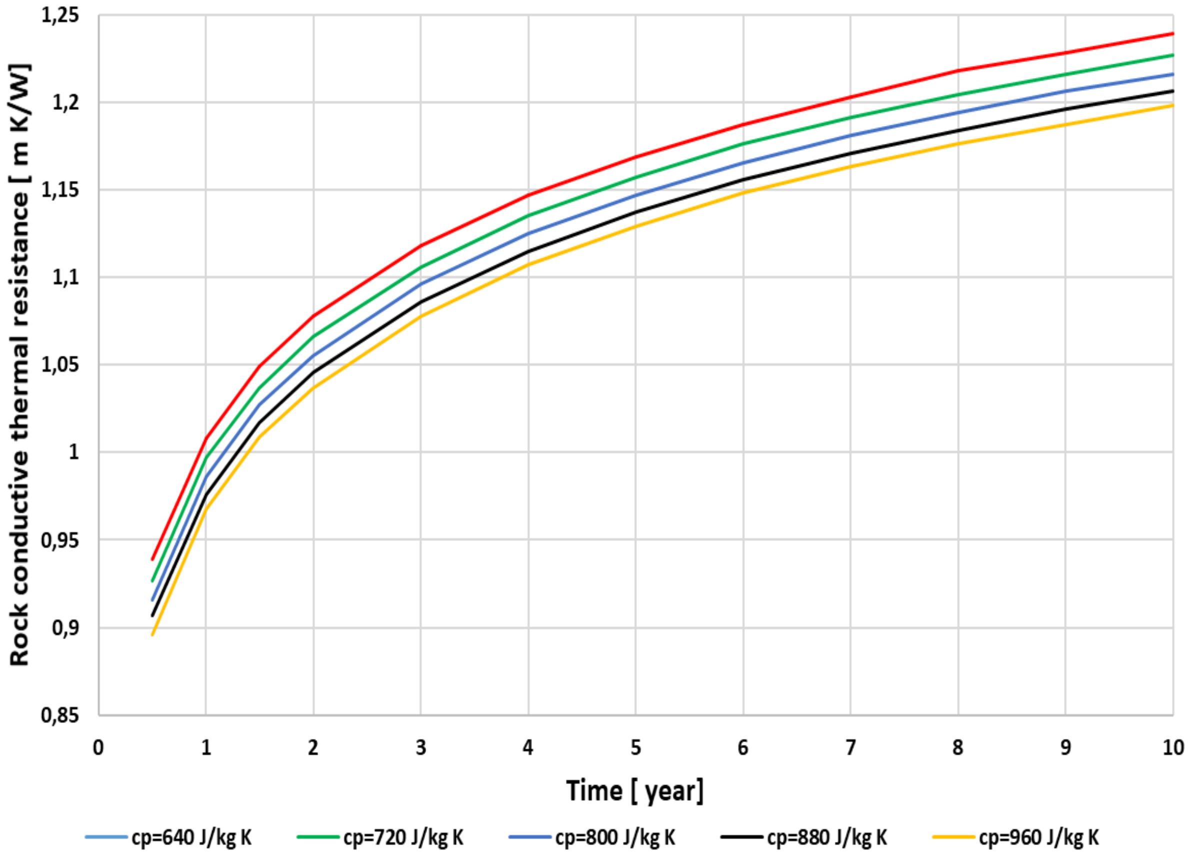


Fig.19 Soil resistance within years depending on the rock specific heat (Working fluid: R134a, m_{fluid} :30 kg/s, ΔT: 3°C/50m, ρ_{rock}: 2600 kg/m^3, k_{rock} : 2.5 W/m K)

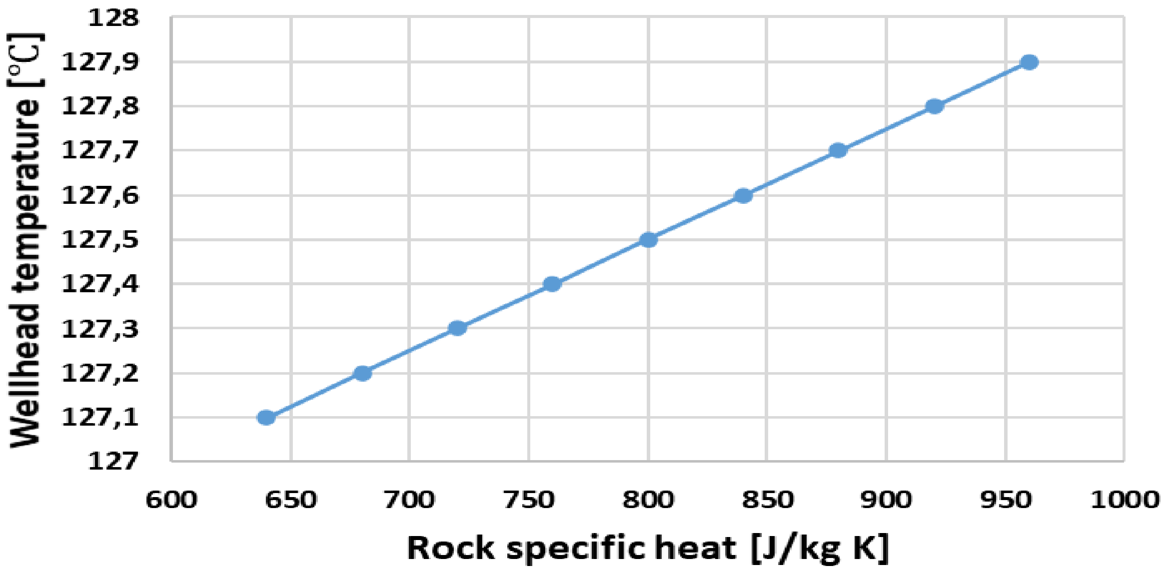


Fig.20 Dependence of the wellhead temperature from rock specific heat.
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, ρ_{rock}: 2600 kg/m^3, k_{rock} : 2.5 W/m K)

As in the rock density, the rock-specific heat does not have any significant impacts on the wellhead temperature.

4.1.3 Rock conductivity

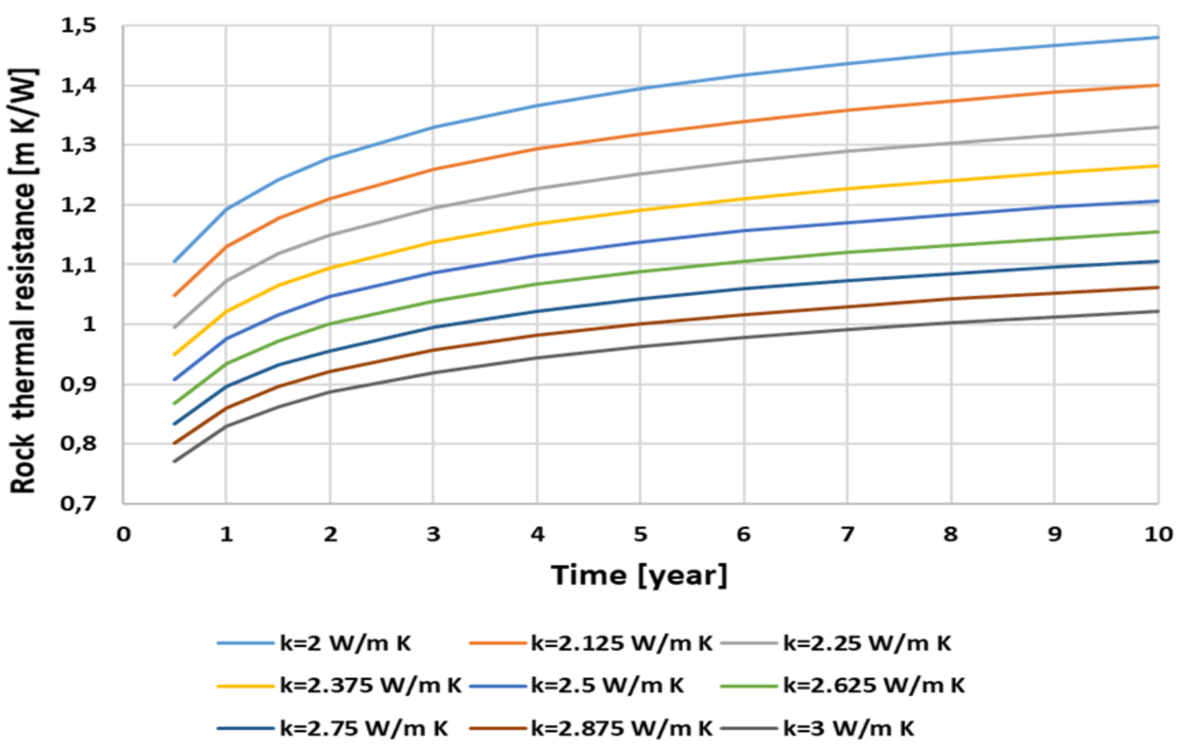


Fig.21 Soil resistance within years depending on the rock conductivity
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock}: 2600 kg/m^3)

According to Fig.21, the thermal resistance has higher variations over the next 10 years as decreasing the value of rock conductivity in comparison with rock density and specific heat.

Rock conductivity has a remarkable impact on the transfer of the heat from the rock as well as the wellhead temperature. In Fig.22, the value of rock conductivity has been taken between 2 and 3 [W/m K] with an increment of 0.125.

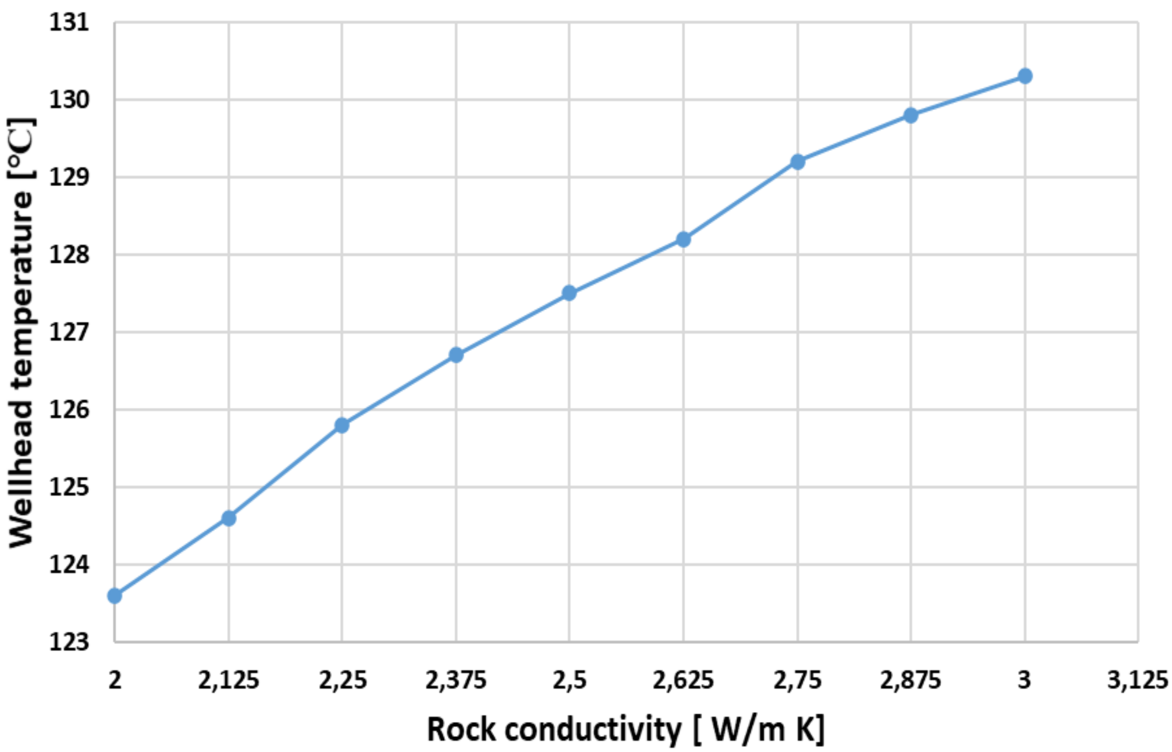


Fig.22 Effect of rock conductivity on wellhead temperature
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3)

As can be seen that from the line graph above, the conductivity of rock can cause a significant temperature variation on the wellhead temperature.

4.2 Geothermal gradient

In most steps of the simulation performed, the geothermal gradient is considered 3°C per 50 m and the surface temperature is assumed 13.89 °C referring to [85]. In some parts of the simulations, the geothermal gradient is taken between 2-5 °C/ 50 m to make a comparison. The assumption is that the gradient is considered linear.

Fig.23 illustrates that in the first 250 m, the working fluid is cooled, then it is heated up to the bottom part. Starting from the bottom, the temperature of the working fluid is declining negligibly until reaching the surface.

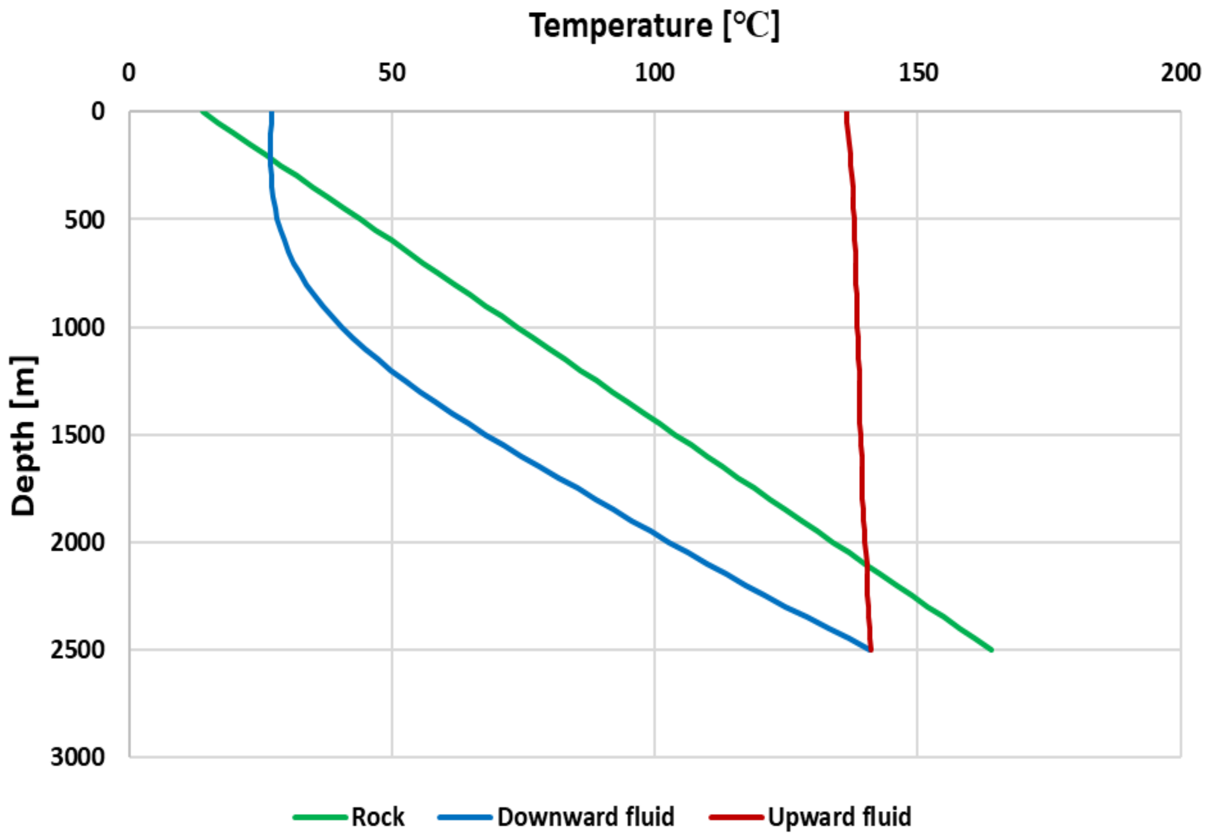


Fig.23 The profile of temperature through the well
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

The effect of the geothermal gradient and depth is investigated based on the net power generation of the plant. As it can be seen from Fig.24, the net power generation of the DHE increases with increasing the gradient and depth. For instance, with changing the depth of DHE from 2000 to 2500 m, the net power increases more than 50 % almost in each temperature gradient.

Moreover, low geothermal gradients (below 3°C/50 m) are not considered to be applied to the DHE, since the energy desired output is less than the energy required output. Thus, the suggested gradient to be applied is higher than 3°C/50 m or taking the depth of the DHE higher than 2000 m.

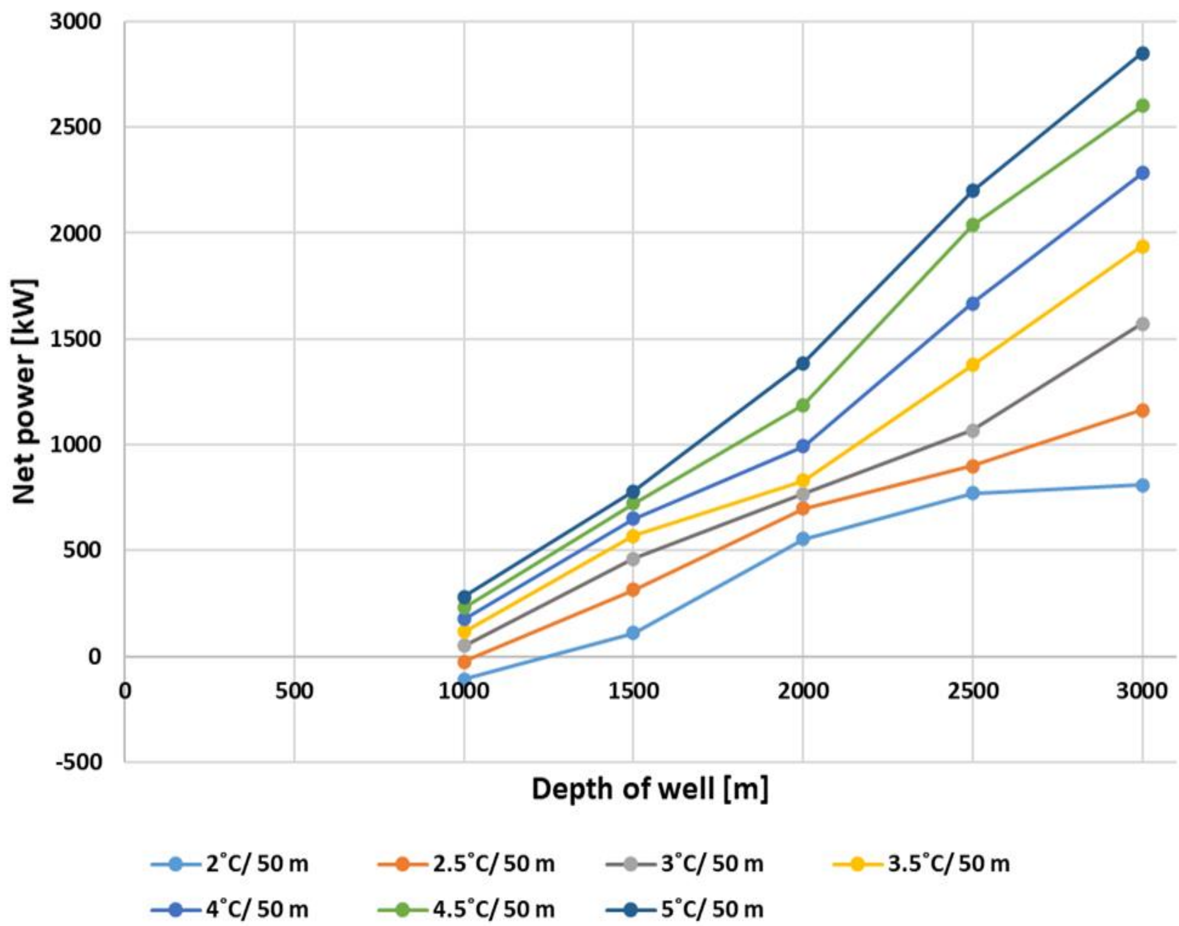


Fig.24 Effect of the geothermal gradient and the depth of DHE to the net power.
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

4.3 Effect of insulation thickness and mass flow rate

In the power generation using DHE, the inner pipe should be insulated to avoid the heat loss of the working fluid during upward flow. The glass wool (k=0.043 W/m K) has been selected as an insulative material. The insulation can be installed at any point according to the heat lost.

The impact of the insulation on the temperature distribution along the well is indicated in Fig.25. It can be seen that even a few millimeters of insulation can prevent the big temperature variation of the wellhead temperature. For example, when the insulated inner pipe is used, the wellhead temperature is between 145-151 ℃ whereas it decreases to 89℃ when the insulation is not be installed on the inner pipe.
In addition, the wellhead temperature in the inner tube increases with improving insulation thickness, because of preventing to transfer of more heat from the inner pipe to the outer pipe by the thicker insulation. However, it should be taken into consideration that the wellbore radius cannot be modified because the well is already present. Thus, a thicker insulation layer can reduce the diameter of the outer pipe. As a result, when the annular space is reduced, the velocity of the working fluid will be increased and it will make a way to more pressure lost and pump power consumption.

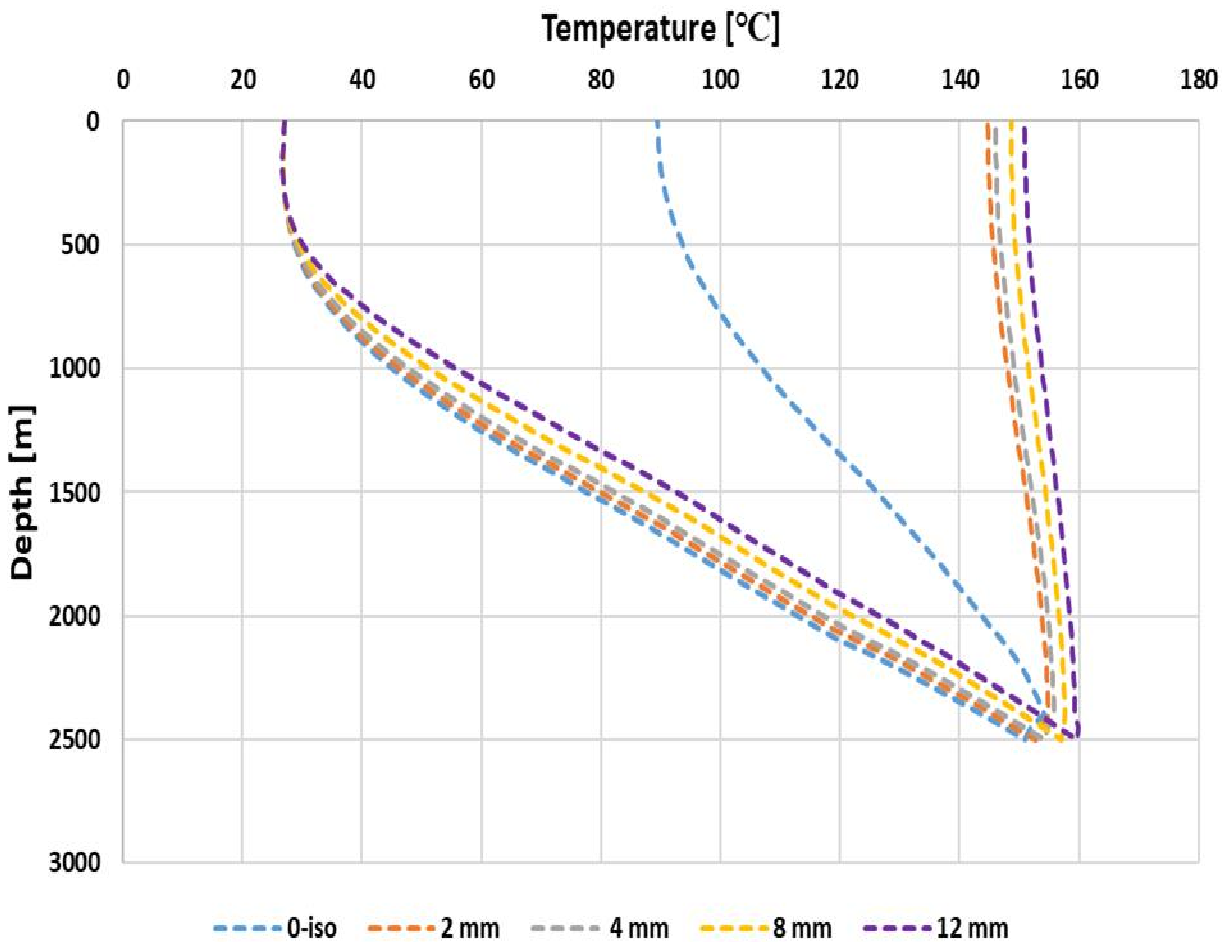


Fig.25 Effect of the insulation thickness
(Working fluid: R134a, m_{fluid} : 30 kg/s, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

The mass flow rate of the working fluid is one of the important parameters in geothermal energy production using DHE from AOGWs. There is a direct relationship between the mass flow rate of the working fluid and insulation thickness on the inner pipe. Thus, as improving the insulation thickness, the volume of the annular space is decreasing. It is mainly affecting to the mass flow rate of the fluid. The effect of insulation thickness on mass flow rate as well as net power is reported in Fig.26.

The mass flow rate is a desirable parameter in the system, thus insulation thickness with low heat lost and high mass flow rate should be selected. As a result, the 8 mm thickness for insulation can be selected regarding the chart below.

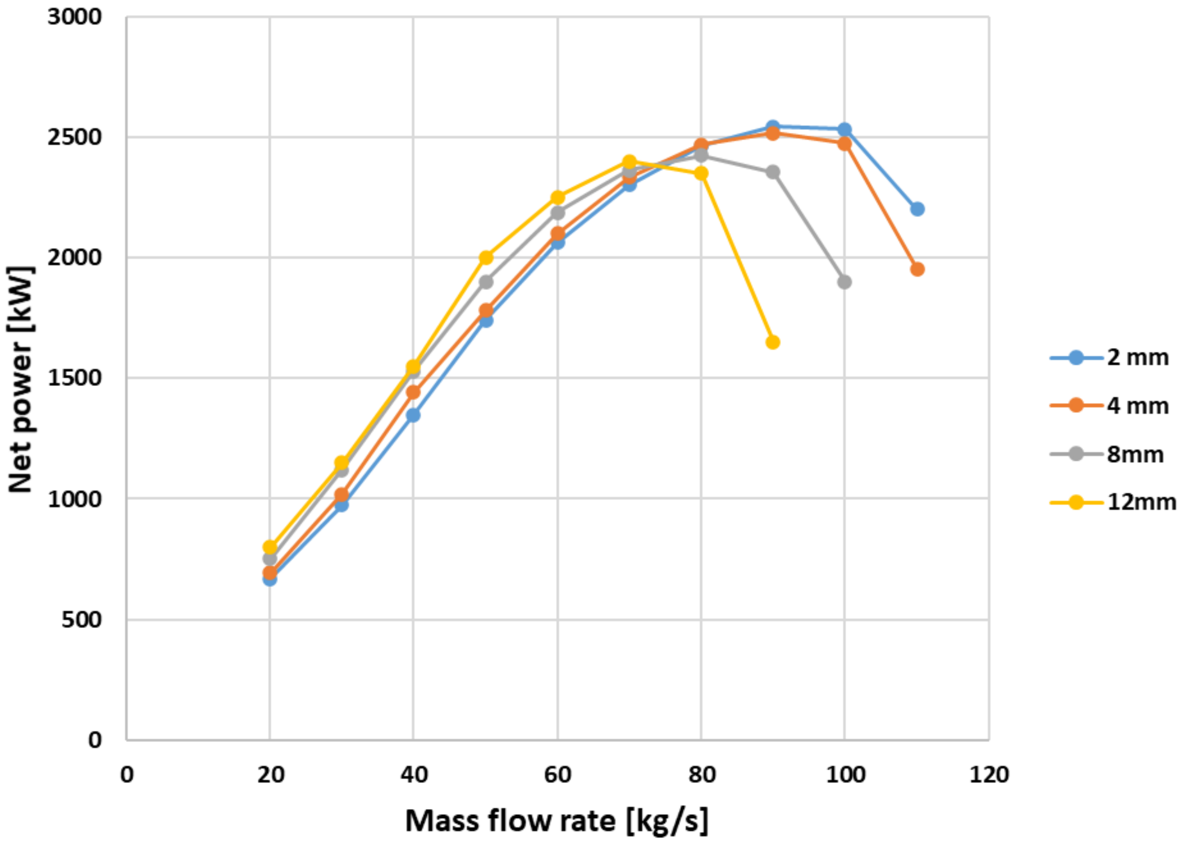


Fig.26 Effect of insulation thickness on the mass flow rate
(Working fluid: R134a, depth: 2500 m, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

4.4 The performance of the DHE system in future

Many simulations have been made considering a short time after starting to generate power. Fig.27 demonstrates that the power reduction in the case of the continuous generation of power over the twenty years from the initial production is indicated. Additionally, the trend of the bottomhole temperature for the future is shown on the line graph below.

As reported in Fig.27, the bottomhole temperature of the working fluid decreases significantly during the first year, then this statistic starts to decline negligibly. The reason for that is the drop of the temperature at the wall of the well.

The trend is almost the same for power reduction. Thus, after decreasing during the first five years, the line of power reduction is appropriate to pseudo-state condition. There is approximately 30 % of reduction on power generation during the next twenty years.

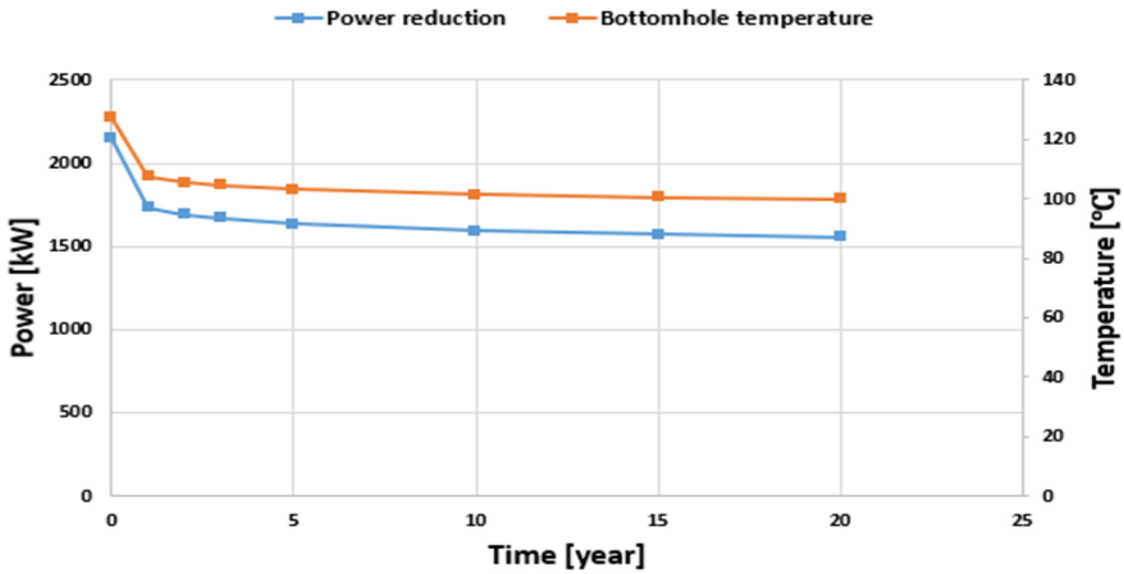


Fig.27 Power reduction and bottomhole temperature depending on time (Working fluid: R134a, depth: 2500 m, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

4.5 The selection of working fluids

The type of working fluids is selected regarding the performance of the DHE system, thermal efficiency, power generation and environmental aspects.

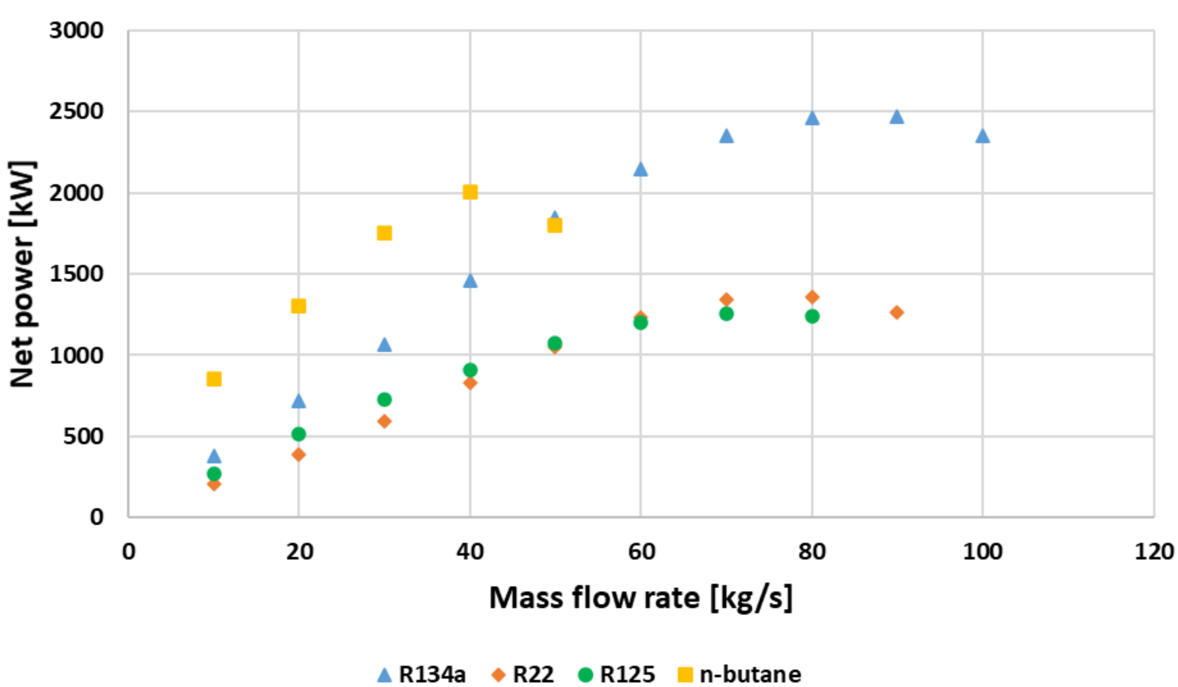


Fig.28 The net power for different working fluids

Fig.28 indicates that the refrigerant fluids can be circulated with a high flow rate in comparison with hydrocarbon working fluids in DHE system. The working fluid R134a gives the highest net power (2467 kW) at mass flow rate is equal to 90 kg/s whereas other fluids have lower net power output. In the other hand, it can be observed that n-butane which is a hydrocarbon fluid can give better performance than others when the mass flow rate is low.

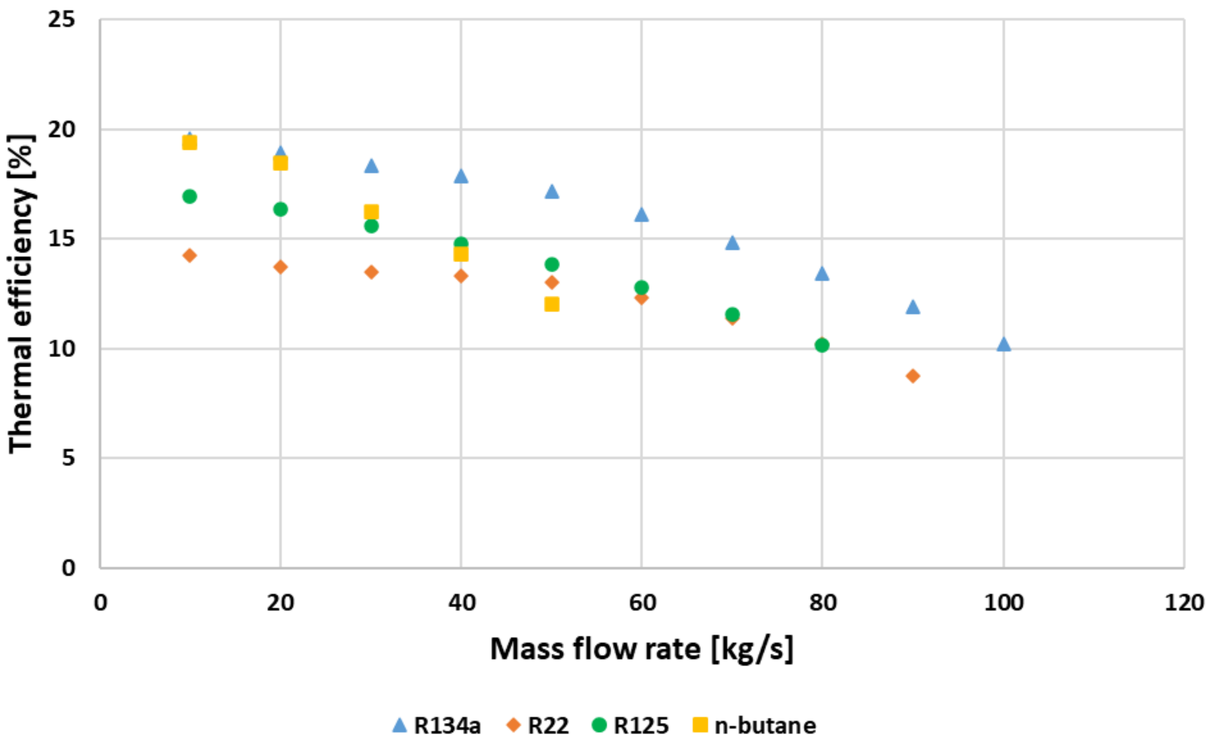


Fig.29 The thermal efficiency depending on mass flow rate
(Depth: 2500 m, ΔT: 3°C/50m, cp_{rock} : 800 J/kg K, ρ_{rock} : 2600 kg/m^3, k_{rock} : 2.5 W/m K)

Fig.29 illustrates the trend of thermal efficiency as increasing the mass flow rate of the different working fluids. It is clear that for all type of working fluids, the thermal efficiency is decreasing as increasing the mass flow rate. While R134a and n- butane shows better performance regarding thermal efficiency, R22 and R125 have lower thermal efficiency trend.

Additionally, the environmental aspects play a crucial role together thermodynamic performance in the selection of working fluids. Thus, however some fluids have considerable performance, they are very flammable and hazardous for the environment. As a result, they are not preferable to operate as working fluid in the DHE system.

Chapter 5

Conclusions

The extraction of geothermal energy resources from AOGWs by the use of DHEs offers great potential for the future global energy scenario. A new thermodynamic model, performed for a geothermal power plant with a coaxial DHE system, has been done by EES software to evaluate the possibility of electricity generation from AOGWs.

The DHE is a well-completion solution that allows harnessing geothermal heat without producing geothermal fluids. Thus, the energy requested by the pump for reinjection and environmental impacts is highly reduced. Moreover, the corrosion and scale problems are neglected because of having no direct contact of the working fluid with the rock formation.

The effects of rock properties, insulation, mass flow rate and the types of working fluids are examined in a complex parametric study. The results showed that among the rock properties, the rock conductivity has a significant role in the generation of power in comparison to the rock density and specific heat. Thus, high rock conductivity means higher wellhead temperature as well as net power. In addition, the higher geothermal gradient and depth of the well are important to improve the performance of the DHE system. Regarding the insulation, it is recommended that the inner pipe should be insulated on the DHE system. Thus, it plays an important role in the prevention of the heat losses and increasing the wellhead temperature.

The performance of the system for the future has been investigated in the paper. As production time is increasing, the power reduction and bottomhole temperature decrease dramatically in the time-span of 5 years, then their trends try to follow the pseudo steady-state condition.

Finally, according to the types of working fluids, the hydrocarbon working fluids show better performance than the refrigerant fluids at low mass flow rates. Therefore, the fluid of R134a is highly recommended to utilize as a working fluid in the DHE systems to obtain better power output. Thus, it gives about 2500 kW power (depth: 2500 m, ΔT: 3°C/50, mass flow rate: 89 kg/s, Dt:0.779 m).

Nomenclature

A_s	: Thermal diffusivity of rock (m^2/s)
c_p	: Specific heat capacity of the fluid (J/ Kg K)
D	: Diameter of the tube (m)
D_c	: Diameter of the casing (m)
D_h	: Hydraulic diameter (m)
D_t	: Diameter of the inner tube (m)
D_w	: Diameter of the wellbore (m)
f	: Friction factor (-)
H	: Convective heat transfer coefficient (W/m^2K)
h_1	: Inlet enthalpy of the turbine (kJ)
h_2	: Out enthalpy of the turbine (kJ)
h_{cd}	: Conductive heat transfer coefficient ($W/ m^2 K$)
h_{cv}	: Conductive heat transfer coefficient ($W/ m^2 K$)
h_i	: Convective heat transfer coefficients for inner (W/m^2K)
h_o	: Convective heat transfer coefficients for outer pipe (W/m^2K)
k	: Thermal conductivity of the fluid (W/ m K)
K	: Thermal conductivity of insulation layer (W/m K)
K_{ins}	: Thermal conductivity of insulative material (W/ m K)
K_s	: Thermal conductivity of rock (W/ m K)
K_t	: Total heat transfer coefficient (W/m K)
$K_{t\,o}$	: Total heat transfer coefficient (W/m K)
L	: Length of DHE (m)

$\dot{m}_{fluid}$: Flow rate of the working fluid (kg/s)

Nu : Nusselt numbers (-)

P_0 : Pressure output (kPa)

P_i : Inlet pressure (kPa)

Pr : Prandtl numbers (-)

$Q_{annular}$: Heat transfer rate in downward flow

Q_{inner} : Heat transfer rate in upward flow

r : Internal radius of inner pipe (m)

Re : Reynolds numbers (-)

r_w : Radius of the well (m)

t : Elapsed time (s)

$T_{fluid-down}$: Temperature of working fluid in the annular pipe (°C)

th : Insulation thickness (m)

T_i : Temperature of the working fluid in the inner tube (°C)

T_o : Temperature of working fluid in the annular pipe (°C)

T_w : Temperature of the rock at depth z (°C)

u : Velocity of the working fluid (m/s)

$\dot{W}_{net}$: Net Power (kW)

$\dot{W}_{pump}$: Pump power (kW)

$\dot{W}_{tur}$: Generated power (kW)

ΔP : Pressure drop (kPa)

Δz : Length of the pipe (m)

$\eta_{thermal}$: Thermal efficiency (-)

η_g : Generator efficiency (-)

η_{pump} : Pump efficiency (-)

η_t : Turbine efficiency (-)

ρ : Density of the fluid (kg/m^3)

ρ_{rock} : Density of the rock (kg/m^3)

μ : Dynamic viscosity of the fluid (Pa s)

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