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The Significance of Nanofluids as Working Fluids in Energy Extraction Process on Geothermal Heat Exchanger System Utilizing Abandoned Oil Wells: A Review

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ABSTRACT - Geothermal energy offers significant potential as an environmentally friendly renewable resource; however, large-scale deployment remains constrained by high drilling and infrastructure costs. Repurposing abandoned oil and gas wells as geothermal heat exchanger systems has emerged as a promising alternative, yet research on the application of nanofluids in such systems remains limited and fragmented. This review employs a narrative synthesis approach to analyze more than 80 peer-reviewed studies related to wellbore geothermal heat exchangers, working fluids, and nanofluid thermal enhancement mechanisms. The review identifies a clear knowledge gap regarding the integration of nanofluids into geothermal heat extraction processes in deep coaxial and U-tube systems, particularly with respect to long-term stability, pressure drop, and techno-economic feasibility. Findings indicate that nanofluids, especially metal-oxide and hybrid formulations, can substantially enhance thermal conductivity and heat transfer performance, with TiO_2- and CuO-based nanofluids showing the most promising results. However, challenges remain in optimizing concentration, ensuring stability, and mitigating increased pumping power. Overall, this review provides a consolidated understanding of existing research and highlights key directions for future development to improve heat extraction efficiency in geothermal systems utilizing abandoned wells.

Keywords: geothermal, nanoparticle, nanofluid, thermal performance.

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INTRODUCTION

Geothermal is energy deposited in the earth in the form of heat (Nian & Cheng, 2018b. This energy stockpiled in the form of natural steam or hot water has been exploited for several periods of time to produce electrical energy, and has been extensively used both directly and indirectly (Bu et al., 2012). In direct use, geothermal energy can be used for space heating, heating an area, as well as in various industries such as agriculture, and greenhouses (Nian & Cheng, 2018a). This direct use is usually produced from shallow geothermal energy sources and has low enthalpy (Ciriaco et al., 2020. Meanwhile, indirectly, this thermal energy is converted into mechanical energy through steam turbines which are then transformed into electrical energy with an electric generator (Allahvirdizadeh 2020). In Indonesia, early and continued efforts supporting geothermal exploration and development have also been reported, including the utilization of remotely sensed data to support geothermal, oil, and gas activities (Husen 1995).

As one of the renewable energies, the usage of geothermal energy is already relatively wide even though it still has the potential to be amplified, especially its use to produce electrical energy on a large scale. Its role as an alternative energy to replace fossil energy is progressively expected because of its environmentally friendly nature as well as renewables. In practical exploration stages, integrated geophysical interpretation is commonly used to delineate subsurface structures controlling geothermal systems (e.g., faults, basement configuration, and intrusive bodies) and to estimate reservoir depth, supporting early-stage prospect evaluation (Wijanarko et al., 2021). Globally, energy generated from geothermal in 2014 was reported at 73,549 GWh with an installed power generation capacity of 12,600 MWe, and a study in Europe predicts a very rapid increase in geothermal energy utilization by 2050 (Allahvirdizadeh 2020).

In spite of having many advantages over fossil energy, both from availability and environmental impact, the application of geothermal energy still has challenges both in technical and economic aspects (Allahvirdizadeh 2020). Geothermal well drilling activities deal with harsh underground conditions, such as high pressures and temperatures, therefore requires strong technical considerations in the selection of materials used to drill, such as drill pipes, casings, and cementing processes (Mohamed et al., 2021). Drilling cost is frequently reported as a dominant cost component in geothermal development and becomes a key barrier to accelerate deployment (Suranta et al., 2023). To reduce exploration risk and drilling cost, approaches such as slimhole continuous coring have been proposed to improve subsurface data acquisition while maintaining operational efficiency (Hasibuan et al., 2020). In addition, operational issues such as mineral scaling in geothermal wells may reduce production efficiency and require appropriate mitigation strategies (Candra et al., 2025), while geochemical exploration techniques targeting surface manifestations (e.g., Hg–As–H_2S anomalies) are also widely applied to validate geothermal prospects (Andriani et al., 2022).

This challenge has been responded with a series of studies to extract geothermal energy by utilizing oil or gas wells that will or have been abandoned, thus significantly reducing the allocation of drilling costs. This idea was introduced by Kujawa et. al. (2006) with the object of research of the Jachowka K-2 well (Kujawa et al., 2006), which was then followed by some researchers since this idea would noticeably reduce nearly 50% of the total geothermal project (Bu et al., 2012). Caulk and Tomac (2017) investigated the feasibility of Enhanced Geothermal System (EGS) and deep Borehole Heat Exchanger (BHE) installations in abandoned wells across California by constructing mathematical models for the various well depths and thermal gradients of the crust encountered in Santa Barbara, Santa Clara, and Monterey. In all cases, the mitigation of drilling costs corresponds to a reduction in the cost of the EGS project by 42% e 95% (Caulk & Tomac 2017).

Statistically, there are around 20 – 30 million oil wells that have been bolted worldwide (Nian & Cheng, 2018b). In California solely there are reportedly about 147,000 oil wells that are no longer active and must be abandoned (Kujawa et al., 2006. This data will still increase from the number of wells that must be closed and abandoned from various countries (Caulk & Tomac 2017; Nian & Cheng 2018b). Considering the large number of oil and gas wells that have run out of economic life and must be abandoned, the opportunity to operate them to extract geothermal energy is increasingly promising.

To address these challenges and to enhance the feasibility of geothermal energy extraction from abandoned wells, recent research has highlighted the potential role of advanced working fluids, particularly nanofluids, which offer substantially improved thermophysical properties compared to conventional fluids (Rowi et al., 2025). Despite growing interest in abandoned-well geothermal systems and the notable advantages of nanofluids in heat transfer applications, the integration of these two topics has not been systematically reviewed. Therefore, this paper aims to consolidate existing studies on geothermal heat exchanger configurations, working fluid characteristics, and nanofluid-based thermal enhancement mechanisms. Specifically, the review examines key parameters affecting heat extraction performance including well geometry, operating conditions, fluid thermal conductivity, and nanoparticle behavior, while identifying prevailing knowledge gaps and unresolved technical challenges. By synthesizing current findings, this review provides a clearer understanding of opportunities for improving geothermal system efficiency and outlines research directions critical for advancing the use of nanofluids in repurposed oil and gas wells.

METHODOLOGY

This paper adopts a narrative review approach to synthesize studies related to geothermal heat extraction from abandoned oil and gas wells, heat exchanger configurations, and the application of nanofluids as working fluids. A narrative review was selected because the existing literature spans diverse methodologies, including numerical modeling, experimental investigations, material characterization studies, and techno-economic evaluations which are not directly comparable through a systematic or meta-analytic framework.

The literature reviewed in this study was identified through searches conducted from Google Scholar database. The search process covered publications from 2000 to 2023, with the keywords and combinations used in the search included: “geothermal” AND “heat exchange” AND (“nanofluid” OR “working fluid”) AND “thermal conductivity”.

RESULT AND DISCUSSION

Abandoned oil wells to extract geothermal energy

The use of abandoned oil or gas wells to gain geothermal energy is a new way that is believed to produce efficiency in many ways, such as creating new wells along with their supporting facilities, which are the biggest costs in a geothermal energy acquisition project. Nevertheless, the produced energy is still limited, this idea taps research opportunities on how to improve the performance of the heat exchanger system to facilitate better extraction of geothermal energy by using abandoned oil or gas wells.

The heat transfer process that occurs in a downhole geothermal double pipe heat exchanger system is generally described as a conductive heat transfer along the formation rock, the heat is then conductively transferred to the cement block surrounding the pipe (Caulk & Tomac 2017). Moreover, a conduction also occurs along the thickness of the outer pipe. A forced convection heat transfer occurs in the fluid in the annulus when the fluid is flowing down to the bottom of the well while heated gradually correspond to geothermal temperature gradient (Song et al., 2018), which then the fluid flows upwards through the inner pipe carrying thermal energy, as shown in Figure 1. At a certain depth, the temperature of the fluid in the inner pipe will be greater than that of the fluid in the annulus. For this reason, insulation is needed on the inner pipe section as the heat transfer resistance from the inner pipe to the fluid in the upper part of the annulus.

In addition to the general thermal processes described above, the geothermal recovery potential of abandoned wells is strongly influenced by several physical parameters. Well depth determines the reachable geothermal gradient, where deeper wells generally provide access to higher temperature zones and therefore higher heat extraction rates. Similarly, the diameter of the casing, the spacing of the annulus, and the insulation characteristics affects both conductive heat transfer from the formation and convective behavior within the working fluid. Variations in regional thermal gradients also play a critical role, as higher gradients improve steady-state outlet temperatures and overall system efficiency. Studies such as those by Kujawa et al. (2006); Bu et al. (2012); and Caulk & Tomac (2017) consistently highlight these parameters as decisive factors in determining heat recovery performance. Kujawa et al. (2006) commenced a study to assess the possibility and usefulness of accessing geothermal energy from an existing production well, namely the Jachowka K-2 well, by modeling a double-pipe heat exchanger utilizing abandoned wells. The produced heat is relatively lower compared to the actual Geothermal well, hence it still requires a boiler to reach the required water temperature in the heat distribution circuit (Caulk & Tomac 2017). Another study was carried out by Bu et. al. (2012) to resolve the feasibility of using oil wells that have been abandoned as heat exchangers to generate geothermal energy.

The economic aspect has been considered in the study following a 10-year technical modeling. This study was linked and compared to the work previously done by Kujawa et. al. The outlet temperature increases when the flow rate is low, since the heat loss from the rock to the fluid is immediately compensated by the conduction that occurs in the rock when the flow rate is low (Bu et al., 2012).

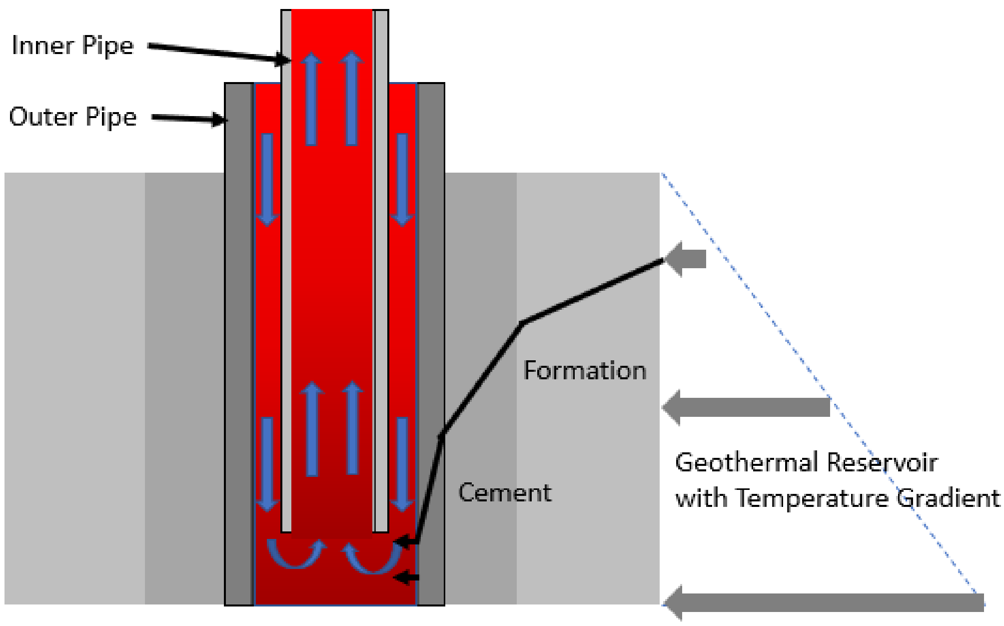

Figure 1. Schematic illustration of heat transfer and fluid flow in a double-pipe heat exchanger system. The working fluid flows downward through the outer pipe and upward through the inner pipe, enabling counter-current heat exchange with the surrounding geothermal reservoir through the cemented wellbore and formation.

Cheng et al. (2013) examined the effect of heat transfer from rocks to fluids on the generation of geothermal energy from abandoned wells using isobutane as a working fluid. The temperature of the Isobutane at the outlet decreases when the circulation time is longer, until it approaches a steady state. The produced energy depends on the heat generated and the temperature at the outlet. By increasing the velocity of the fluid in the inlet also increases the heat generated but the outlet temperature is lower. So that the optimal inlet speed must be determined to obtain optimal heat (W. L. Cheng et al., 2013). Cheng et al. (2014) analyzed a wide variety of working fluids in geothermal systems from abandoned oil wells, considering transient heat displacement in rocks, fluid momentum, and energy equations. The results showed that the geothermal energy from abandoned oil wells with a depth of less than 3000 m was not economically adequate to be exploited due to the low efficiency of power plants (W. L. Cheng et al., 2014). Hu et. al. (2020) took the case on wells in Canada and researched for operation over a long period of time. With water as working fluid, long duration causes a large temperature difference, so it is necessary to find a cutoff point duration where the heat energy result is still optimal (Hu et al., 2020). Alimonti and Soldo (2016) emphasized the importance of considering changes in the properties of the fluid inside the heat exchanger, so that a working fluid that has better thermal conductivity will produce more energy (Alimonti & Soldo 2016; W. L. Cheng et al., 2013, 2014; Hu et al., 2020).

Noorollahi et. al. (2015) conducted a study on the heat transfer between rocks and working fluids using well geometry and system temperature gradients and taking into account the thickness of rock layers in the process of generating thermal energy. The results of the carried out numerical simulations showed that in addition to thermal gradients and time flow rates, well geometry and internal/external pipe sizes play an important role in the heat extraction rate. A larger pipe size can increase the extraction rate but cause a decrease in pressure. With the small inner pipe diameter and the limitation of the pipe design for injection and extraction, a low time flow rate and higher pump power requirements are generated (Noorollahi et al., 2015). Song et. al. (2018) examined the effect of cement in heat transfer in double pipe systems, where cement with high thermal conductivity will greatly help the process of heat transfer from rock to casing which is then passed to the fluid to heat the fluid when injected into the annulus (Song et al., 2018). Templeton et. al. (2014) developed a model for simulating the transfer of heat through the surrounding rock masses to the heat exchanger, as well as the heat transfer that occurs inside the double-pipe heat exchanger (Templeton et al., 2014). The proposed model is able to provide constant power, by adjusting the temperature of the inlet fluid so that the difference between the temperature of the inlet fluid and the outlet remains constant. With this model, the feasibility of extracting geothermal energy from abandoned petroleum wells can be carried out (Noorollahi et al., 2015; Song et al., 2018; Templeton et al., 2014).

Evaluation of key parameters affecting the performance of abandoned oil wells used for double pipe heat exchangers to obtain optimal design and operating parameters by adopting the Taguchi statistical method was carried out by Cheng et. al. (2019). This evaluation offers confidence in the operational parameters, whereby the optimal combination of parameters can be proposed to design and operate a double pipe heat exchanger system converted from abandoned oil well (S. W. Y. Cheng et al., 2019). Gharibi et. al. (2018) performed a comprehensive study on the U-tube heat exchanger to extract geothermal energy through numerical simulation using real well data. The study was conducted to see the effect of four parameters, namely the mass flow rate, fluid inlet temperature, insulation length, and pipe diameter on the heat exchanger. Unsteady condition was preferred in this simulation to represent changes in rock temperature following a linear pattern, the is relevant to actual conditions (Gharibi et al., 2018).

Harris et. al. performed an approach to exploit directionally drilled wells for geothermal energy extraction purpose. Since wells are often drilled in close proximity to each other, two wells can be connected through a relatively small amount of additional drilling work to create a continuous loop. The outcomes of his research showed that a system with a vertical well of 4000 m and a horizontal section of 4800 m can produce about 2 MW of thermal energy and 200 kW of power using an organic Rankine cycle (Harris et al., 2021).

A comprehensive evaluation of the feasibility to convert an abandoned oil well in Malaysia into a geothermal energy extraction plant was carried out by Kurnia et. al. (Kurnia et al., 2021) by looking at both technical aspects and economic considerations. In addition to heat losses during distribution, the scattered abandoned oil wells render additional costs for piping and pumping as well as maintenance costs, in spite of capital reduction from cost to drill new wells.

Given the thermal limitations inherent in wellbore heat exchanger geometries, the selection of an appropriate working fluid becomes increasingly important. Enhancing the thermal conductivity and heat transfer capability of the working fluid, such as through the use of nanofluids, offers a promising pathway to further improve the efficiency of geothermal energy extraction from abandoned wells.

Geothermal heat exchangers systems construction

The construction of a heat exchanger has influence to the performance of heat exchange, such as contact area where the working fluid interface meets the components of the heat exchanger (Hu et al., 2021). In heat exchanger systems for geothermal wells, there are two types, i.e. U-Pipe and Coaxial Double-Pipe (Morchio et al., 2022), where each type can be made single or double.

Most of the geothermal heat exchanger system is vertically oriented since it is a conversion of vertical oil wells, and flow boiling heat transfer occurs as the working fluid takes heat from the rock when it is circulated into the well. In their study, Kumar and Hardik (Kumar & Hardik 2022) concluded that the orientation of the pipe does not affect the heat displacement in single-phase flow boiling. Orientation becomes significant when the quality of steam is greater than 0.05. The heat transfer coefficient mainly depends on the quality of the steam and the heat flux in the flow boiling, where for all orientations, if the quality of the steam increases, then the average heat transfer coefficient also increases. In addition to the quality of steam, the heat exchanger orientation turned out to affect pressure fluctuations in flow boiling, and it has more effect on the horizontal orientation than for vertical one (Kumar & Hardik 2022).

U-Pipe type heat exchanger

U-pipe heat exchangers are the most common type used to extract heat from shallow wells for heating and cooling of spaces. The U-tube heat exchanger is placed in the well before the well is filled with a certain material with the desired thermal conductivity to improve the heat transfer from the formation to the heat exchanger (Lyu et al., 2017). Typically, the working fluid circulating inside a closed-loop U-pipe heat exchanger extracts geothermal heat from the reservoir and flows back to the surface (Figure 2).

Researchers have conducted numerous studies to assess the geothermal production potential of abandoned wells with u-tube and double-pipe heat exchanger techniques (Bu et al., 2012; Hu et al., 2021; Kujawa et al., 2006; Lyu et al., 2017; Noorollahi et al., 2015; Templeton et al., 2014). The studies established different mathematical models for estimating heat extraction by conducting case studies and assessing geothermal potential in abandoned wells. Despite the different cases, they concluded that main parameters affecting heat transfer performance are the fluid injection temperature, injection rate, insulation type, well hole temperature and working fluid selection.

Numerical studies of U-tube heat exchangers for extracting geothermal energy were conducted by Gharibi et. al. (Gharibi et al., 2018) by using actual well data in Southern Iran, to see the effects of four parameters, i.e. mass flow rate, fluid inlet temperature, insulation length, and pipe diameter. This study found that the rate of the working fluid at inlet has an important influence on the performance of the U-tube heat exchanger, where the optimal flow rate of 0.03 m/s at an inlet temperature of 288.16 K results in a maximum outlet temperature of 324.13 K. In addition, the diameter of the U-pipe is also a factor that has a significant.

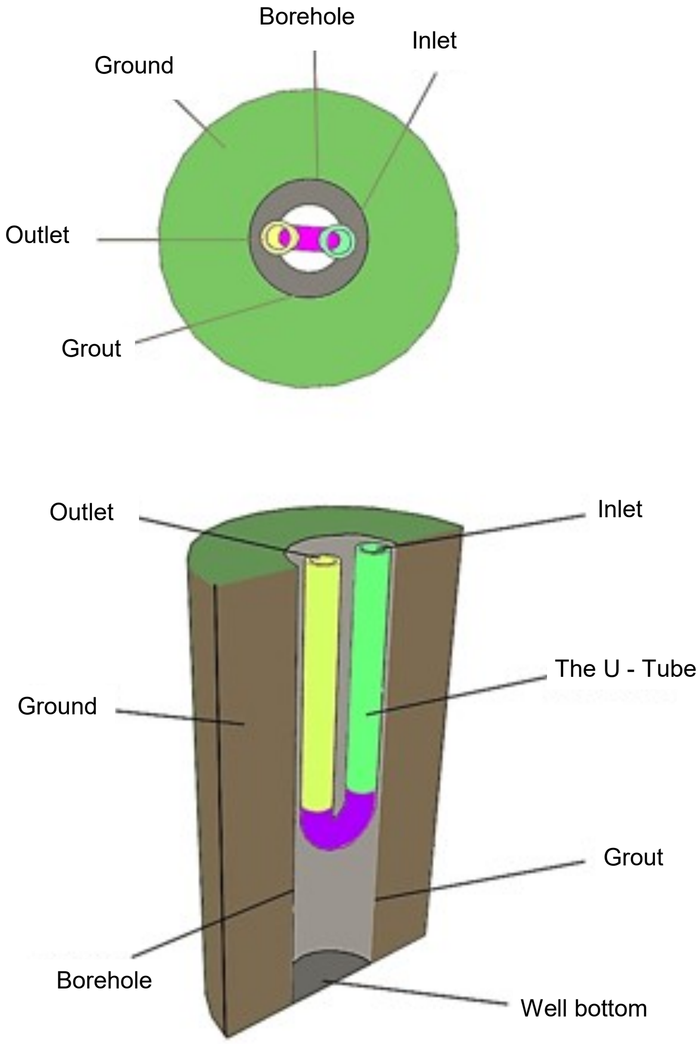

Figure 2. Schematic diagram of an underground single-pipe U-pipe heat exchanger.

The long-term performance of shallow-buried U-tube heat exchangers (SBHE) systems was studied using models to analyze and estimate SBHE performance. This study directed in Illkirch (Alsace region) replied that the soil around SBHE is closely related to the imposed heat load. The performance of SBHE with a constant inlet temperature over a 5-year period shows that the greatest difference of the extracted energy occurred during the first two years, and SBHE was able to provide stable energy for various uses after the 4th year (Tang & Nowamooz 2018).

Double-Pipe Heat Exchanger

This method uses a well as a coaxial double-pipe heat exchanger, where the existing casing serves as the outer pipe and Tubing as the inner pipe. The working fluid is injected into the Casing-Tubing annular and flows into the depths of the well while absorbing heat from the surrounding formations. Once the pumped fluid reaches the bottom of the well, it flows upwards towards the Wellhead through Tubing. The tubing must be thermally insulated to diminish the heat transfer between the fluid in the Tubing and the fluid present in the annular due to temperature difference. The returned fluid will be collected in the Wellhead where the heat will be used according to its purpose. Figure 3 shows the cross-sectional scheme of the coaxial double pipe heat exchanger (Beier et al., 2014). The performance of a coaxial double-pipe heat exchanger is generally influenced by three main factors namely: heat transfer coefficient, temperature difference, and contact area (Hu et al.,

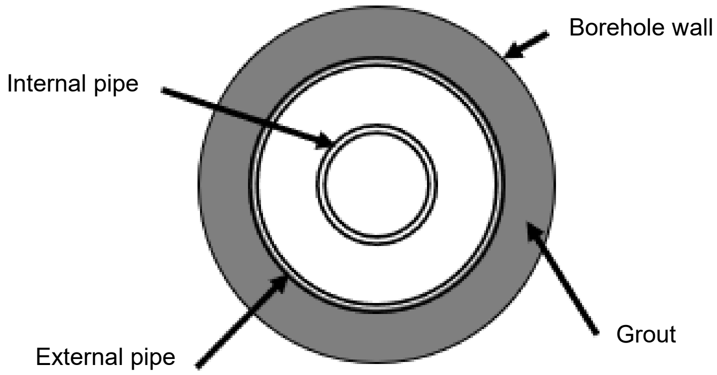

Figure 3. Cross section of coaxial double-pipe heat exchanger.

2021). Compared to the U-Tube method, the Double Pipe method has a larger surface area for heat exchange and can accommodate more fluid volumes for heat exchange. Jalili et. al. compared three geometric shapes of heat exchangers for geothermal systems, i.e. U type, double U type, and Coaxial type, where it was found that coaxial type provides the best performance compared to the other two types (Jalili et al., 2018). In addition, with the same injection rate, the fluid flow rate in the double-pipe geometry is lower, so it requires lower hydraulic pressure to circulate the fluid, and therefore requires lower pumping energy. On abandoned wells, double-pipe heat exchangers will save time and costs since the outer pipes (casings) are already in place.

The geometry of the pipe has a great effect on the heat displacement that ultimately correspond to generated energy. A larger pipe size will increase the mass flow rate as well as lower the pressure (Figure 10). At a certain diameter ratio (Di/Do = 0.7), the total flow pressure loss in the heat exchanger is minimum (Daneshipour & Rafee, 2017. A statistical study with the Taguchi method, found that good lower hole curvature plays an important role in optimizing the performance of borehole heat exchanger. In particular, a curvature of 500 mm is preferred for higher temperatures output and heat transfer rates, while a curvature of 800 mm is recommended for lowering the pressure drop and producing a higher CoP (S. W. Y. Cheng et al., 2019). The inner pipe type of the spiral has the effect of increasing a certain heat displacement, wherein the larger the spiral lump, the smaller the spiral pitch, the more obvious the effect of increasing the heat displacement of the corresponding spiral pipe (Li et al., 2020).

Pokhrel et al. (Tang & Nowamooz 2018) conducted experiments and computations on a coaxial borehole heat exchanger system on a 500 m deep well, where higher mass flow rates resulted in higher power outputs and thus generated more energy. However, the problem of higher pumping power requirement remain exists. The thermal conductivity of rocks is also a dominant factor. In their research, Gordon et. al. (Gordon et al., 2018) varied the diameter of the inner pipe but remains in the same shape.

With variations in the inner diameter, it is found that there is an influence on the performance of the heat exchanger system and can even balance the pressure drop. Numerical studies by adopting the finite volume method carried out by Jia et al. (Jia et al., 2022) predicted the performance of coaxial BHE (double pipe) and simultaneously considered the different structural parameters of BHE, geological formations and modes of operation to solve the problem of the very large diameter-length ratio of BHEs.

The thermal conductivity of soils and rocks was found to play an important role in predicting BHE performance. Therefore, with a relatively accurate thermal conductivity value, this method can predict the performance of coaxial BHE at possibly higher accuracy.

A performance-oriented comparison of common heat exchanger configurations indicates that U-pipe designs generally offer simpler installation but smaller heat transfer areas, while coaxial double-pipe systems provide larger contact surfaces, improved heat recovery, and lower hydraulic losses for the same flow rate. Single-pipe systems, although structurally simple, typically yield lower outlet temperatures due to limited thermal interaction. Previous numerical and experimental studies demonstrate that coaxial arrangements tend to outperform U-pipe systems in terms of thermal efficiency, especially in deep wells where conductive heat flux from surrounding formations is substantial.

Comparative analyses in the literature indicate that the effectiveness of different heat exchanger configurations strongly depends on the well geometry and local thermal conditions. U-tube heat exchangers, while easier to install, often exhibit higher pressure drops and lower thermal efficiency in deep or large-diameter wells. In contrast, coaxial double-pipe systems generally provide larger heat transfer areas, more stable flow patterns, and improved thermal recovery in deep abandoned oil wells, particularly where geothermal gradients are moderate. Studies such as those by Bu et al. (2012), Gharibi et al. (2018), and Jalili et al. (2018) consistently report superior heat extraction performance for coaxial configurations compared to single-pipe and U-tube arrangements. These findings suggest that coaxial systems are often more suitable for maximizing heat recovery under diverse geological settings.

The geometry of the heat exchanger also has important implications for nanofluid performance, as enhanced thermal conductivity can only be fully utilized when sufficient surface area, flow stability, and residence time are available. Coaxial systems, with their larger contact area and lower hydraulic losses, may be particularly advantageous for nanofluid applications, allowing improved convective heat transfer and reduced sedimentation risk compared to narrower U-tube designs. These considerations form an important link between heat exchanger configuration and the potential benefits of nanofluid-based working fluids.

Pipe insulation and coating

Gharibi et. al. (Gharibi et al., 2018) settled in his numerical study on the U-pipe heat exchanger, that partial isolation of the outlet pipe is necessary since the working fluid flowing to the surface has a higher temperature than the surroundings, so that the heat loss of the working fluid traveling up to the surface can be controlled. The optimal insulation length for different speeds and temperatures of water inlets almost does not vary.

Guan et. al. (Li et al., 2020) in his study that the better the insulation performance of the inner pipe, the more favorable the increase in heat displacement. Nevertheless, the incremental heat transfer rate in total is insignificant. Harris et. al. (Harris et al., 2021) several simulations to explore the effects of various insulation thicknesses on performance. It was found that 3 cm thick of insulation provides a marginal increase in performance, with a 4% increase in electricity production on the basis case. Song et. al. performed simulations and got the idea that the outlet temperature decreased dramatically at an early stage, and then remained relatively stable. There is a critical value for the flow rate to obtain higher thermal power with proper pressure drop. Insulated pipes can significantly reduce heat loss from the working fluid in the central pipeline. The optimal insulation measures that determine the

Table 1. Performance comparison of U-Pipe and coaxial heat exchangers in abandoned wells

Configuration	Advantages	Limitations
U-pipe	Simple installation; widely used	Lower heat transfer area; higher pressure drops
Double-pipe coaxial	Better thermal performance; lower pumping power	Requires good insulation; geometry-dependent
Single pipe	Simplest geometry	Lowest thermal efficiency

effect of heat insulation and costs can be taken into account (Song et al., 2018).

Armstrong et. al. (Armstrong et al., 2021) examined the improvement of heat transfer and stability of nano fluids with copper pipes coated with silver nanoparticles. It resulted a good increase in the overall heat transfer coefficient for the increase of identified mass flow rate, and the result compared with the performance of copper pipes without layers. There is minimal resistance to thermal conductivity since the collaboration of silver and copper particles increases conductivity in the nano-level, though it has a one-minute increase in the thickness of the copper tube.

In his study, namely the 3-D numerical model and experiments on a corrugated tube with a combination of pitch and wave height, Corcoles (2020) figure out that in a double-pipe heat exchanger system, the high pitch and wave height of the inner pipe have an influence on heat transfer and pressure reduction, not take the viscosity factor into account in this study (Córcoles et al., 2020).

Working fluid on the geothermal heat exchanger systems

The organic Rankine cycle is adopted for the process of single-cycle geothermal energy (W. L. Cheng et al., 2014, as shown in Figure 4 (W. L. Cheng et al., 2013, wherein boilers and pumps are replaced by double-pipe heat exchangers, and heating of the working fluid occurs at the time of its circulation from the annulus to the bottom of the well. The Rankin cycle is strongly influenced by the working fluid, and even more for abandoned oil wells. Kujawa et al. (Kujawa et al., 2006) using Water as the working fluid by varying the flow rate of 2 and 10 m3/h, injection temperature 25°C, depth 3950 m. Analytical computation to estimate the temperature at the output and heat energy

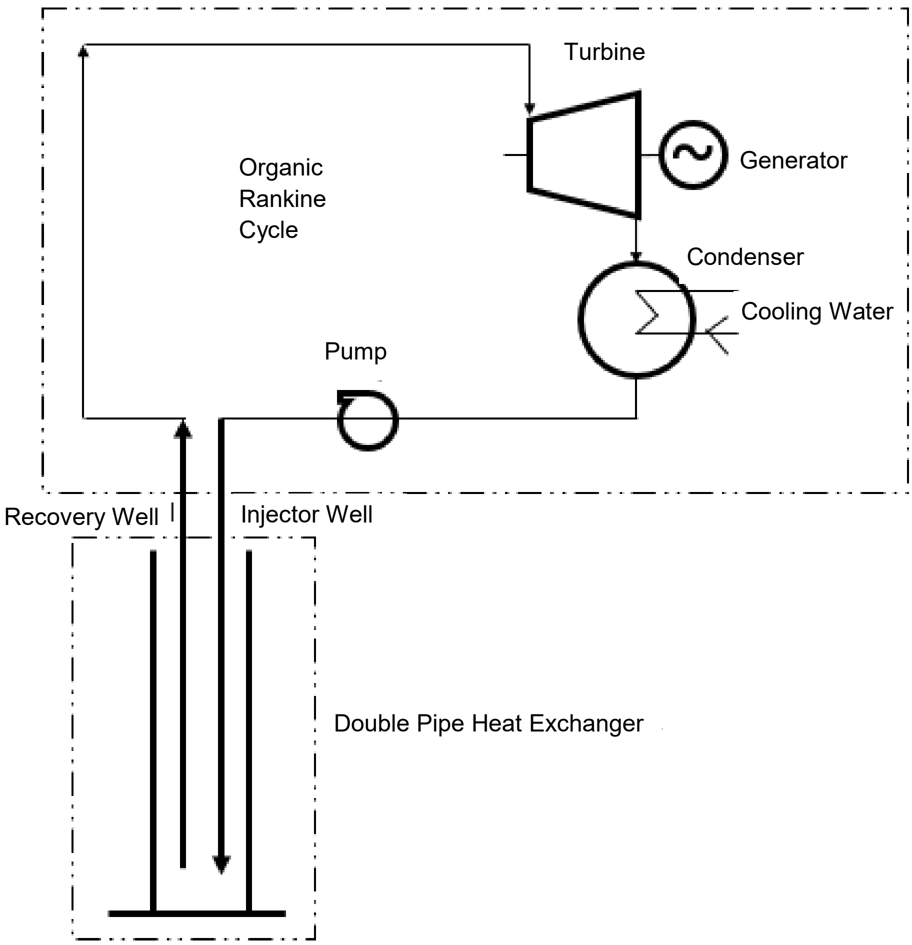

Figure 4. Geothermal power plant structure diagram.

produced gave a maximum temperature result of 86.6°C at a flow rate of 2 m3 / h, and the generated power of Q = 140 kW. However, the maximum generated power of 644 kW, was produced at a flow rate of 20 m3 / h though the output temperature was 53.0°C. Bu et al. (Bu et al., 2012 it also uses Water as the working fluid. With an injection temperature of 30°C and a flow rate of 2.13 m3/h it provides an output temperature of 88.25°C and produces a power of 148.88 kW. Cheng et al. (W. L. Cheng et al., 2014) uesed refrigerant as the working fluid and got R134a and R245fa were more suitable than R600a, R600, propylene, R290 and R143a for geothermal power plants using abandoned oil wells. The overall configuration of the geothermal power plant system considered in this study is illustrated in Figure 4.

Different working fluids exhibit distinct thermophysical characteristics that directly influence geothermal system performance. Water provides high specific heat capacity but moderate thermal conductivity, while organic fluids used in ORC cycles offer favorable boiling characteristics for low-temperature geothermal sources. Refrigerants such as R134a or R245fa may enhance cycle efficiency under certain conditions but require careful management of environmental impacts. In contrast, nanofluids offer significantly improved thermal conductivity, heat transfer coefficients, and critical heat flux compared to base fluids, which can increase outlet temperatures and overall heat extraction rates in downhole systems.

Nanofluids as working fluids

The heat transfer coefficient of forced convection for a fluid flow is of great importance in heat transfer applications. However, the efficiency of heat displacement by using conventional fluids has challenges with the equipment, particularly with regards to contact areas. Considering the limitations in heat exchanger equipment, efforts to improve heat transfer performance are carried out from the view of the working fluid.

Therefore, the thermal conductivity of the working fluid should be enhanced so it will augment heat transfer performance. This method will be more economical than upgrading the heat exchanger system equipment.

One of methods to improve the thermal conductivity of a fluid is to disperse nano-sized metal particles in a base fluid, such as water, oil or glycol (Menni et al., 2020). The use of metal particles is based on the fact that the thermal conductivity of metals is much higher than liquids, therefore by increasing thermal conductivity will increase the rate of heat transfer. The dispersion of nanoparticles to the base fluid can also increase critical heat flux up to 200% (Hegde et al., 2010), therefore will improve the heat transfer performance in a system that is limited by critical heat flux. Fluids containing dispersions of nanoparticles are hereinafter referred to as nanofluids, and these fluids promise good rheological properties, more stable, and have higher thermal conductivity. Increasing the heat transfer coefficient by utilizing nanoparticles can significantly minimize the size of heat transfer equipment, which is highly desirable (Menni et al., 2020; Returi et al., 2019).

However, the dispersion of nano-sized particles in the base fluid still leaves other problems in operations, including the increase in pump power requirements, and the potential for blockage in or erosion of the channel through which it passes, although nano fluids are known to have properties that relatively do not clog the channels through which they pass compared to other fluids (Raj et al., 2017). Hozien et. al. conducted a study of nano-fluids characteristics with regards to heat transfer coefficient and pressure drop in the helical double-pipe heat exchanger (Hozien et al., 2021). The results of similar studies are tabulated below.

Nanofluids outperform conventional working fluids primarily through increased thermal conductivity, enhanced Brownian motion effects, and improved convective heat transfer coefficients. Several studies have reported heat transfer enhancements ranging from 20% to over 70% depending on nanoparticle type, concentration, and flow conditions. However, practical considerations such as long-term stability, sedimentation, potential erosion of pipe surfaces, and increased pumping power must also be considered when selecting nanofluids for geothermal applications. These trade-offs emphasize the importance of optimizing

Table 2. Study of nano fluids characteristics as working fluids

Nanofluids	Concentration	Characterization
Al/Water	0.78% to 7.04%	0.37% to 3.43% Heat Transfer enhancement
Al/Water and Cu/Water	0.55%, 1.12% and 2.23%	Thermal conductivity increases by 22% for Al/Water and 26% for Cu/Water
Al_2O_3/Water	~0.5%, 1% and 2%	Increasing nano particles concentration increases heat transfer coefficient
CuO/Water	0 to 0.5%	Heat transfer coefficient increases with increasing volume concentration and flow rate. At 0.5%, HT coefficient increases by 77.5%
PANI/Water	0.1% and 0.5%	10.25% at 0.1% volume concentration, and 69.62% at 0.5% volume concentration
Carbon Nanotubes/Water	0.1%, 0.3%, and 0.3%	Pressure drop increased by 16%, 30%, and 42%, and Nusselt number increased by 28%, 52%, and 66%
SiO2/Water	0.01% to 0.25%	28.71% Heat Transfer enhancement higher than base fluid; pressure drop 62.60% higher than base fluid
TiO_2-SiO_2	0.5% up to 2.5%	Enhanced Heat Transfer by 254.4% at 2.5% volume concentration and 1.5 pitch ratio
ZnO	0.05% to 0.5%	Nusselt number enhanced up to 18.6% at 0.5% volume concentration and 50°C
MWCNT/Water	0.2%, 0.4%, and 0.6%	Increase in Nusselt number up to 30% at 0.6% volume concentration. Pressure drop increased up to 11%

nanoparticle concentration and ensuring compatibility with geothermal wellbore environments.

Numerous studies on nanofluids sum up hat the thermal conductivity of nanofluids is influenced by several factors including the type of nanoparticles, particle size, particle shape, volume fraction, and others (Raj et al., 2017; Returi et al., 2019). Particle types that are widely used to make nano fluids include Ceramic Oxides, Metal Carbides, Nitrides, Metals, Non-Metals, and Layers; while the basic fluids commonly used to disperse nanoparticles are Water, Ethylene Glycol, Oil, Bio-fluid, and Polymer solutions (Verma & Tiwari, 2017).

Various studies on the influence of volume fractions to the heat transfer rate is still inconclusive. Menni et. al. deduced that the volume fraction has a role in increasing the heat transfer rate, but causes a fairly high pressure loss at particle concentrations greater than 5% (Menni et al., 2020. Therefore, research on the effect of nanoparticle concentration on the heat transfer rate still leave rooms for development so that a relationship can be drawn between nanoparticles concentration to the heat transfer rate with certain applications.

As a heat transfer medium, TiO_2 nanoparticles is considered promising due to many advantages such as harmless to health, environmentally friendly, stable chemical and physical properties, excellent dispersion, economical, and can be applied on a large scale (Das et al., 2016; Zhong et al., 2020. TiO_2 nanoparticles are also known to have high thermal conductivity (Singh Rajput et al., 2019).

Particle size variations

Akbari et. al. concluded that the use of solid nanoparticles with smaller diameters had a good effect on increasing heat transfer and decreasing pressure loss (Akbari et al., 2016). With an increasingly small size, dispersing these particles into the base fluid will increase the surface area per volume, thereby increasing the heat transfer rate.

Concentration variations

The addition of nanoparticles to the base liquid leads to an increase in its heat transfer coefficient. The Nusselt number of the working fluid increases with an increase in the volume concentration of the nanofluids much higher than that of the base fluid (Kristiawan et al., 2020). Akhgar et. al. elaborated in his research that an increase in temperature and volume fractions increases the thermal conductivity of nanofluids, whereas an increase in volume fractions turns out to be more effective in increasing thermal conductivity than temperature (Akhgar & Toghraie 2018). In their research, Rahmati et. Al. (Rahmati et al., 2017) showed that, an increase in the nanoparticles volume fraction and the slip rate coefficient led to a significant increase in heat transfer. Besides, the increase in the slip velocity coefficient has a great effect on reducing the friction factor of the horizontal microtube wall.

Khodadadi et. al. conducted rheological behavior studies of MgO-Water nano fluids at different temperatures ranging from 25°C to 60°C and different volume fractions ranging from 0.07% to 1.25%, by measuring viscosity at shear rates from 6,115 s-1 to 73.38 s-1. The results showed that base fluids behaved Newtonian and nanofluids exhibited non-Newtonian behavior. The results obtained also showed that viscosity increases with an increase in the solid volume fraction of nanoparticles and decreases with increasing temperature (Khodadadi et al., 2019).

Hybrid nanofluids

A hybrid nanofluids is an mixture of two or more different nanoparticles that form a composite (Raj et al., 2017; Vallejo et al., 2022), since a material does not necessarily have the desired properties for a particular application. When two or more nanoparticles that have different physical and chemical properties are homogeneously mixed, a fluid will be formed that has physical and chemical properties that mono nanofluids do not have (Dhinesh Kumar & Valan Arasu 2018). Research on hybrid nanofluids is a new concern because by combining two or more nanoparticles are processed better thermal properties compared to nano fluids formed from one type of nanoparticles (Returi et al., 2019; Raj et al., 2017).

Among the studies comparing single nanofluids with hybrids reported an increase in heat transfer rates of up to 30% (Returi et al., 2019). Research conducted by Suresh et. al. against Al_2O_3-Cu hybrid nanofluids dissolved in the de-ionized water base fluid indicates an increase in viscosity and thermal conductivity with an increase in the concentration of nanoparticles (Suresh et al., 2011). In terms of specific heat capacity, hybrid nano-fluids exhibit a lower specific heat capacity than the base fluid, i.e. water, as studies conducted on TiO_2-CNT hybrid nano (Adun et al., 2021). Adun et. al. concluded that in the interests of rapid heat absorption and release, hybrid nano-fluids with low specific heat capacity are required, while for heat storage a high value of specific heat capacity is required. For this reason, the utilization of hybrid nano fluids must be adjusted to the required characteristics (Adun et al., 2021).

The performance of hybrid nanofluids is largely determined by chemical properties such as purity, solubility and compatibility, as well as the geometric parameters of nanoparticles like the shape and size, so the preparation phase greatly affects the performance of the synthesized nanofluids (Muneeshwaran et al., 2021). However, hybrid nano fluids still have challenges in terms of stability, where the issue is also still the object of research for mono nanofluids.

Synthesis NanoFluids

The synthesis process is the earliest stage in nanofluids research, where in this phase the nano fluid solution is prepared from nanoparticles. There are two methods that are commonly used in preparing nanofluids solutions, namely the ""one-step" method and the "two-step" method. Compared to the "one-step" method, the "two-step" method is believed to be an easy and fast method of preparing nano fluids in large (Das et al., 2016). The nanofluids stability is influenced by the homogeneity of the dispersion of nanoparticles in the base fluid, which is a very critical phase in the application stage of nanofluids. Nanoparticles have a tendency to coagulate and cluster, so if dispersion does not occur properly, this clumping will increase the rate of precipitation which ultimately decreases its thermophysical properties (Kristiawan et al., 2020) such as viscosity and thermal conductivity (Asadi et al., 2019).

This instability in nano fluids is the same as that of any solid dissolved in a liquid, where there is a Van der Waals attraction force as well as a gravitational force that occurs at the molecular level (Chakraborty & Panigrahi 2020). Clumping or settling occurs when the tensile force of van der Waals is greater than the repulsive force of the electric double layer so that a collision occurs as a result of Brownian movement, and stability occurs if the repulsive force of the electric double layer is greater than the tensile force of Van der Waals (Jama et al., 2016).

Various methods, both mechanically and chemically, have been developed to maintain the stability of nanofluids. Sonication is mechanical methods that widely used to maintain the stability of nanofluids and is considered the most effective due to its capability to maintain the stability of nanofluids for at least two weeks (Asadi et al., 2019). A chemical method widely used to maintain the stability of nano fluids is by adding surfactants in the solution, especially for nanofluids produced from two-step processes. The present of surfactants lower the surface tension in nanofluids thereby increasing the stability of the solution (Jama et al., 2016. Nevertheless, the use of surfactants for the stabilization of nanofluids still has challenges to be solved. The presence of a foam layer of surfactant causes the conductivity medium to be contaminated, so it can diminish the thermal conductivity of nano (Jama et al., 2016).

In addition to adding surfactants, pH adjustment of the solution also influences the stability of the nanofluids. The stability of the nanofluids is highly dependent on the electro-kinetic properties of the solution, the magnitude of which is measured by the value of the zeta potential. A solution with high zeta potential indicates the stability of the solution, while low zeta potential gives an indication of coagulating. Research conducted by Chakraborty (Chakraborty 2019) on TiO_2 nano fluids showed that the pH value of the solution is directly proportional to the zeta potential value, where by setting the pH greater than 7, by dripping Sodium Hydroxide (NaOH) solution, providing better stability of the TiO_2 nanofluids.

In addition to using a zeta potential analyzer to measure the value of zeta potential, nanofluids stability can also be measured by using TEM (Transmission Electron Microscope) to see the image of accumulated nanoparticles distribution. The measurement can be performed by using DLS (dynamic light scattering) to quantity the average of nanofluids distribution and can also be conducted by calculating the deposition rate over a certain time interval (P(t)). Sedimentation experiments conducted by Zhang et. al. (Zhang et al., 2022) TiO_2-Water nanofluids exhibited uniform values from stability measurement using TEM, DLS, zeta potential analyzers, and deposition rates for 30 days.

Characterization of nano fluids

Thermal Conductivity. Thermal conductivity indicates the heat transfer rate, where the higher the thermal conductivity of a fluid, the higher the heat transfer rate. In general, the base fluid has a low thermal conductivity, which will be increased by adding nanoparticles. Nanoparticles, both metallic and non-metallic, oxides, carbides, carbons, will all improve thermal conductivity in the heat transfer working fluid (Soltani & Akbari 2016). Thermal conductivity increases by increasing the concentration of nanoparticles in the base fluid (Khodadadi et al., 2019). Adriana reports that in many studies, the thermal conductivity of nano fluids is strongly influenced by the nanoparticle material itself, i.e. the shape and size of the nanoparticles, the concentration of nanoparticles in volume, temperature, and also the additives added in nanofluids (Minea 2017).

High thermal conductivity is the most desirable characteristic of the working fluid in the process of generating geothermal energy, because nanofluids as working fluid are expected to immediately absorb heat from rocks. The heat transfer coefficient is also influenced by the thermal conductivity of the working fluid. Daneshipour and Rafee compared between Al_2O_3-Water and CuO-Water nanofluids as working fluids on double pipe heat exchanger systems and found that CuO-Water produces higher thermal conductivity than Al_2O_3-Water, since CuO nanoparticles have higher thermal conductivity (Daneshipour & Rafee, 2017).

The addition of surfactants to maintain the stability of nano fluids is recognized to have influence on thermal conductivity. Nevertheless, SDBS type surfactants (sodium dodecylbenzene sulfonate) can improve the thermal conductivity of CuO-Water nanofluids and Al_2O_3-Water if added at optimal concentrations (Gonçalves et al., 2021). Studies of the effect of surfactants with CNT-Water nanoparticles showed that the addition of CNTs to water still showed an increase in the thermal conductivity of the solution, although it was carried out on different types and ratios of surfactants (Almanassra et al., 2020).

Density. Density is a physical property that has an influence on the properties of heat transfer. The density of nanofluids has a linear correlation with volume fractions but is inversely proportional to temperature (Jama et al., 2016). Stacy et. al. conducted experiments with aluminum nanoparticles to see the effect of density on thermal conductivity, and found that thermal conductivity increased linearly against the increase in density (Stacy et al., 2014).

Viscosity is one of the very important physical properties of a fluid, besides affecting pumping and load-carrying ability, this property also determines the convection heat transfer coefficient (Jama et al., 2016). When nanoparticles are dissolved in a base fluid, it will cause an increase in the viscosity of the fluid. The increase in viscosity exerts a negative influence on the heat transfer process, so the influence of nanoparticles in relation to the viscosity of the nanofluids must be reduced. Soltani and Akbari refer to several studies of hybrid nanofluids and obtain a significant increase in viscosity with the addition of nanoparticle (Soltani & Akbari, 2016. In many studies it was concluded that in addition to the shape, size and concentration of nanoparticles, the viscosity of nano fluids is also a function of temperature (Khodadadi et al., 2019).

Specific heat capacity. The specific heat capacity of nanofluids indicates the heat storage capacity of the fluid. The specific heat capacity value is required to calculate the Nusselt number, the Prandtl number, and other important factors in the effort to improve heat transfer (Adun et al., 2021). Generally, nanoparticles exhibit lower specific heat capacity than other fluids, and therefore will reduce the amount of heat required by nanofluids to reach a certain temperature. Nanofluids store heat more easily, so these fluids will be excellent for storing the heat received from the heat of the rocks through which they pass. Nusselt Numbers. Piasecka et. al. (Piasecka et al., 2021) examined the heat transfer boiling and found a correlation after comparing the Nusselt numbers of the experimental results with the predicted ones, which gave the least average error for subcooled boiling conditions, while in saturated boiling a new correlation was proposed because no satisfactory results were achieved using existing correlations. Rajput et. al. conducted research on the effect of Al_2O_3 and TiO_2 nano fluids on Shell/Tube and Double Pipe heat exchangers, by varying the flow rate and concentration, resulting in a significant increase in the Nusselt number for both heat exchanger systems, proportional to the concentration of nanoparticles in water (Singh Rajput et al., 2019). Research conducted by Daneshipour and Rafee (Daneshipour & Rafee 2017) using Al_2O_3-Water and CuO-Water nanofluids as working fluids in double pipe heat exchange systems concluded that the Nusselt Number increases with increasing volume fractions of nanoparticles in solution.

Operation condition

Double pipe heat exchangers are basically circulating the fluid pumped through the annulus of the inner pipe-outer pipe, down to the bottom of the well, then the fluid that reaches the bottom of the well enters the inner pipe up to the surface of the well to be utilized for heat flux. As long as the fluid flows in the annulus, there is a transfer of heat from the rock formation to the fluid in the annulus whose magnitude corresponds to the thermal gradient of the rock, so that the highest temperature occurs at the bottom of the well. When the fluid flows to the surface through the inner pipe, there is a heat transfer from the fluid inside the pipe because the temperature of the fluid inside the pipe becomes higher than the temperature outside the pipe, so to prevent heat loss, an insulation needs to be installed in the inner pipe (Kujawa et al., 2006).

Beier et. al. (Beier et al., 2012) developed an analytical borehole model to calculate the vertical temperature profile of the circulating fluid and the heat transfer rate, and compared the results with field data. The model built is proven to be able to estimate the thermal resistance of the borehole by taking into account the vertical temperature profile rather than relying on average temperature estimates. With identical results, this modeling can be used to estimate the vertical temperature profile of a coaxial heat exchanger system to extract heat energy. Kujawa et. al. made a model of a well with a depth of 3950 m; outer pipe diameter 244.5/222.0 mm; deep pipe diameter 60.3/50.7 mm; deep pipe insulation length 600 m. By varying the inlet fluid rate (V) 2, 10, 20 m3/h and the temperature at the time of inlet (T1) 10, 15, 20 and 25°C. At a low fluid flow rate, which is 2 m3/h and an inlet temperature of 25°C, the output temperature (T_2) is at highest at 86.6 °C but the heat power generated is lowest at Q = 140 kW. Then at a fluid flow rate of 20 m3/h, the lowest external temperature (T_2) is 53.0°C with the highest heat power Q = 644 kW.

Physical mechanism

Vertical flow boiling is a flow that will occur in the research to be carried out, where fluid will be pumped from the annulus to the bottom of the well and then flows upwards through the inner pipe, and this fluid is in a hot state or even a boiling condition. Zhou et. al. (Zhou et al., 2021) investigate the vertical two-phase water-vapor flow regime upwards under heating conditions at different pressures through single-sided visualization in a narrow rectangular channel with a large aspect ratio. The results showed alignment with Hosler, while wide differences were observed when compared to the water-air two-phase experimental data.

In his experimental studies, Lin et. al. (Lin et al., 2021) examined the effect of heterogeneous wetting surfaces on the microchannel flow boiling process, and found that during the boiling process, the dominant heat transfer mechanism was the nucleate boiling, with many nucleate places between the hydrophilic/hydrophobic lines. Jhia et. al. (Jhia et al., 2022) utilizes machine learning techniques to identify flow regimes and extend them to steam-water (two-phase) flows.

By using the global flow regime identified by SOM as a reference and the flow displays the dataset as input data, the trained model can classify the flow regime with an accuracy of more than 90%. Liu et. al. (Liu et al., 2018) conducted flow boiling refrigerant experiments R600a, R227ea and R245fa in vertical rectangular mini-channels and obtained visualization results of flow patterns and bubble behavior. Bottini et. al. (Bottini et al., 2020) visualized flow in flow boiling which shows the development of bubbly and slug flows in an accelerated channel for low-pressure conditions. Local two-phase measurements show substantial void generation for low-pressure conditions that match the acceleration of flow through the gas interface speed.

Outlook and opinion

The literature review highlights several key directions for future research and development in the use of nanofluids within geothermal heat exchanger systems, particularly those utilizing abandoned oil wells. One important area is the advancement of studies focused on repurposing abandoned oil wells into geothermal systems by analyzing various geometrical configurations and working fluids, with the ultimate aim of optimizing heat production despite the typically lower temperature gradients found in such wells compared to traditional geothermal reservoirs. Continued exploration of nanofluids as working fluids is vital due to their excellent thermal conductivity, which can enhance the rate of heat absorption from surrounding geological formations and prolong heat retention before the fluid is cycled to the surface for energy generation.

Furthermore, the investigation of hybrid nanofluids is encouraged, as their unique composite nature offers superior thermophysical properties compared to mono nanofluids, potentially leading to improved heat transfer efficiency and fluid stability under subterranean conditions. A comprehensive techno-economic analysis is also essential to determine the viability of converting abandoned wells into functional geothermal systems, factoring in capital expenditures, energy return on investment (EROI), lifecycle costs, and possible environmental or regulatory limitations.

Robust simulation models and the development of field-scale prototypes are necessary to validate laboratory-scale results and to identify practical challenges such as scaling, corrosion, and mechanical degradation during long-term operation. The integration of wellbore geothermal systems into hybrid renewable energy solutions, such as solar-geothermal or geothermal-biomass systems, could further enhance energy output and reliability, particularly in isolated or off-grid locations.

Additionally, there is a need to explore advanced materials for heat exchanger components that can endure high pressure, repeated thermal cycling, and chemically harsh environments, thereby extending the system's operational lifespan and performance. Lastly, policy development and incentive mechanisms should be examined to promote the transition of abandoned oil wells into sustainable geothermal energy assets, aligning such efforts with broader goals of global decarbonization and the circular economy.

Future research should prioritize long-term field validation of nanofluid performance in deep geothermal wells, particularly concerning stability, corrosion effects, and pumping-energy requirements. Economic assessments are also needed to evaluate lifecycle cost trade-offs associated with nanofluid preparation, maintenance, and recovery. Additionally, integrating abandoned-well geothermal systems with hybrid energy technologies - such as solar-assisted RC systems or heat-storage modules - may further improve overall efficiency and grid resilience. Advances in computational modeling, including multiphase flow simulation and machine-learning-based prediction tools, could significantly enhance design optimization.

CONCLUSION

The utilization of abandoned oil or gas wells can produce energy though the magnitude yet to be equivalent to an actual geothermal well. However, with the large number of abandoned oil and gas, it can produce energy at economic value. The result from various research shows that there are parameters that significantly affect the heat transfer performance of double-pipe and U-pipe heat exchangers in abandoned oil wells. The three influential parameters are fluids injection temperature, fluids injection rate, and fluids thermal conductivity . Geometry factors have a role in obtaining the optimal heat transfer coefficient but require equipment modification that will affect the economic aspect. Nanofluids as superconductors is proven to be able to increase the thermal conductivity of the working fluid which ultimately increases the heat transfer coefficient without having to make geometry alterations. Hybrid nanofluids have a great opportunity to response the challenges faced by mono nanofluids in terms of long-term stability, pump pressure drops, and improved thermophysical characteristics. This review highlights that abandoned oil and gas wells represent a technically viable and economically attractive pathway for geothermal energy extraction. The choice of heat exchanger configuration, working fluid characteristics, and operating conditions all play decisive roles in determining system performance. Nanofluids, in particular, offer substantial enhancements in thermal conductivity and heat transfer rate, making them promising candidates for improving geothermal heat extraction efficiency.

However, challenges such as long-term stability, erosion, and increased pumping power must be addressed. Future work should focus on optimizing nanofluid formulations, validating performance under real wellbore conditions, and developing integrated techno-economic frameworks for practical implementation.

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GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbol	Definition	Unit
BHE	Borehole Heat Exchanger	-
TEM	Transmission Electron Microscope	-
CHF	Critical Heat Flux	-
EGS	Enhanced Geothermal System	-
EROI	Energy Return On Investment	-
Nu	Nusselt Number	-
ORC	Organic Rankine Cycle	-
SBHE	Shallow-Burried U-tube Heat Exchangers	-

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