Review

A Systematic Review of the Design and Heat Transfer Performance of Enhanced Closed-Loop Geothermal Systems

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Abstract: Geothermal energy is one of the primary sources of clean electricity generation as the world transitions away from fossil fuels. In comparison to enhanced geothermal methods based on artificial fracturing, closed-loop geothermal systems (CLGSs) avoid seismicity-induced risk, are independent of reservoir permeability, and do not require the direct interaction between the fluid and the geothermal reservoir. In recent years, the development of CLGS technologies that offer high energy efficiencies has been explored. Research on coaxial closed-loop geothermal systems (CCLGS) and U-shaped closed-loop geothermal system (UCLGS) systems were reviewed in this paper. These studies were categorized based on their design, modeling methods, and heat transfer performance. It was found that UCLGSs had superior heat transfer performances compared to CCLGS. In addition, UCLGSs that utilized CO₂ as a working fluid were found to be promising technologies that could help in addressing the future challenges associated with zero-emission compliance and green energy demand. Further research to improve the heat transfer performance of CLGS, especially with regards to improvements in wellbore layout, equipment sizing, and its integration with CO₂ capture technologies is critical to ensuring the feasibility of this technology in the future.

Keywords: systematic review; heat transfer performance; closed loop; CLGS; enhanced geothermal system

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1. Introduction

Global energy demand and the demand for fossil-based energy are projected to increase through to 2050 as a result of an increasing population and continued economic growth. Consequently, there has been an increasing amount of discussion regarding the transition from fossil-based fuels to renewable energy sources to achieve zero-emission targets. It is predicted that renewable energy will play a pivotal role as the primary source of electricity generation in the near future [1]. Unlike other forms of renewable energy such as wind and solar energy, the energy derived from geothermal sources is considered to be more viable as it is not dependent on solar intermittence or weather conditions [2]. Hydrothermal energy is a conventional energy source that can only be utilized in specific regions located in volcanic basins, such as in the United States of America, Indonesia, and Iceland, among others [3].

The MIT report [4] states that an Enhanced Geothermal System (EGS) could be a promising energy source because it can provide an additional 100 GWe by 2050. There has been a significant amount of research exploring EGS. In particular, several studies have considered a novel use of EGS that utilizes CO₂, which was found to outperform its H₂O counterpart [5]. A numerical study was also carried out to evaluate the heat transfer performance of CO₂ for EGS applications [6]. It was found that CO₂ had a better heat transfer performance than H₂O in terms of its heat extraction rate. Additional studies

were carried out to evaluate the feasibility of using CO₂ as a fluid substitute for water to increase the base load geothermal electricity-generating capacity and conducted a thermal-hydraulic-mechanics study on EGS with various parameters for natural fractures, working fluids, and reservoir stimulation in the context of EGS development [7–10]. They concluded that CO₂ fluids could significantly improve heat production because of their higher heat mining rate compared to water. Son et al. [11] carried out a simulation that compared the critical parameters that affected the heat transfer performance of CO₂ and water; this included variables such as flowrate, inlet temperature, and operating temperature. They concluded that CO₂ was suitable for geothermal reservoirs with lower temperatures below 150 °C. Geothermal simulations of heat extraction utilizing supercritical CO₂ (sCO₂) have been conducted for power production in organic Rankine cycles (ORCs) [12,13]. These studies showed that sCO₂ was an appropriate fluid type for use in ORCs. Further studies investigated the use of CO₂ from CO₂ capture, storage, and utilization (CCSU) technologies for geothermal applications. Arun et al. [14] studied the combination of a coal-based IGCC plant and an EGS for CO₂ sequestration and electricity generation that provided optimum power generation using a mixture of CO₂ and isobutane fluids in an ORC. Some techno-economic studies were also carried out to investigate the economic feasibility of CCSU integration with EGSs [15–18]. Although many researchers have studied EGSs based on artificial fracturing, there are still many challenges that remain unresolved, such as seismic-induced risk, soil and water contamination, its dependence on reservoir permeability, and water drawback. Hence, the feasibility of this field of EGS technology is still undecided [2,19,20].

A closed-loop geothermal system (CLGS) or wellbore heat exchanger (WBHX) was proposed to address the challenges associated with artificial fracturing-based EGSs. This geothermal system does not involve direct contact between working fluid and reservoir, does not require hydraulic fracturing, and does not introduce make-up working fluid into the reservoir. Hence, this technique avoids seismic-induced risks as hydraulic fracturing is not necessary. In addition, the problems associated with soil contamination and water drawback could be significantly reduced because the working fluid does not make direct contact with the country rock. Alimonti et al. [21] published a technical review that focused on coaxial WBHXs, while Sun et al. [22] evaluated U-shaped CLGSs. In contrast, this review paper only discusses the case study in which multiple UCLGS are used for district heating. Furthermore, to the best knowledge of the authors, only a few review papers comprehensively discuss the design and performance of CLGSs in EGSs. Thus, this paper aims to review all publications associated with the design, mathematical modeling, and heat transfer performance of different types of CLGS, as well as compare its performance with different working fluids, i.e., water and CO₂. Specifically, it aims to answer the following three research questions:

- (1) What types of CLGSs were investigated in previous studies? What types of research, designs, and methods were applied in previous studies that evaluate their performance?
- (2) What are the key performance parameters and which of their sensitivity-analysis variables were evaluated in the previous literature?
- (3) Can alternative working fluids such as CO₂ be utilized in CLGSs? How do their heat transfer performances compare with H₂O?

2. Methodology

2.1. Search of Literature

A systematic literature review based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) approach [23] was used in this study. A standard protocol is required to ensure that reliable information and data are collected such that any assessment and analysis produced is of high quality [24]. The articles were retrieved from three reputable databases: Science Direct, Scopus, and Web of Science. These were combined with relevant references from previous review papers. This research process comprises three phases, as described in Figure 1 [23]. The first step involved keyword

identification; this was followed by a comprehensive search of each targeted database after all relevant descriptors were defined (Table 1).

Figure 1. Study methodology flowchart based on PRISMA [23].

Table 1. Search descriptor inputs.

Database	Search String
Scopus	TITLE-ABS-KEY("closed loop *" OR "closed-loop *" OR "borehole *" OR "bore hole" AND geothermal)
Science Direct	"closed loop" OR "closed-loop" OR "borehole" OR "bore hole" AND geothermal
Web of Science	TS = ("closed loop *" OR "closed-loop*" OR "borehole *" OR "bore hole" AND geothermal)

Note: *: any word.

The identified descriptors must be present in either the title, abstract, or keywords. Only publications with the following attributes were included: (1) document type = "research articles"; (2) language = English; and (3) publication year = "2001–2022". Each publication was filtered using the stated exclusion criteria by reviewing the title and abstract of the selected articles. In this way, all irrelevant articles were eliminated unless the technology (the closed-loop wellbore) was used in enhanced geothermal applications.

This methodology identified 2412 publications on Scopus, 33 publications from Web of Science, and 60 publications from Science Direct, for a total of 2505 articles. After screening for relevance (1975), irrelevant records (400), duplicated reports (40), and non-compliance with the defined criteria (61), the remaining 29 studies were combined with the 9 records acquired from previous studies, resulting in the 38 publications included in this review.

2.2. Data Analysis

The 38 selected articles were separated based on their research objectives and carefully analyzed. Any data that were associated with closed-loop EGSs were identified and tabulated in an Excel spreadsheet, organized in terms of CLGS design, key parameters, and

modeling methods. The heat transfer parameters used in each study were then analyzed and summarized; these included fluid temperature profiles, outlet temperatures, heat extraction rate, pressure drop, thermal power, and pumping power.

3. Results

3.1. General Findings

Research trends were analyzed by plotting the number of publications over four different time periods (Figure 2). It was found that there was a significant increase in published articles between 2016–2021. Specifically, the number of articles published in this period increased by 414% compared to the previous period (2011–2015). This reflects the importance of new renewable energy sources as the world transitions to clean energy and suggests that researchers have started to consider the potential of closed-loop EGSs.

Figure 2. Number of EGS-related publications over time.

The number of publications in each journal was also quantitatively analyzed. The 38 reviewed papers were retrieved from nine research journals (Table 2). A total of 13 articles were published in the Journal of Renewable Energy, while five articles were published in Geothermics, Energy, and Applied Thermal Engineering. Applied Energy and Heat and Mass Transfer published two articles each. Only a single paper was published in both Fuel and the Journal of Petroleum Science and Engineering. This analysis suggests that Renewable Energy is the main journal that publishes research associated with closed-loop geothermal systems. This topic has also received significant attention from journals such as Geothermics, Energy, and Applied Thermal Engineering.

Table 2. Distribution of articles in each journal.

Journal Name	Number of Articles
Renewable Energy	13
Geothermics	5
Energy	5
Applied Thermal Engineering	5
Energy Conversion and Management	4
Applied Energy	2
Heat and Mass Transfer	2
Fuel	1
Journal of Petroleum Science and Engineering	1

Table 3 describes the country in which the studies were conducted. Half of the selected studies were conducted in China. These results also highlight that while publications in China began in 2012, there has been a significant increase in publications between 2018 and the present day. In contrast, countries with the largest potential geothermal reserves, such as the USA, Turkey, Italy, Iceland, and Japan, published fewer papers. For example, the USA accounts for 10.5% of publications to date, while Canada and Iran only contributed 7.8% and 5.2%, respectively. Furthermore, Turkey, Japan, and Iceland had the smallest percentage of publications (2.6%)—the same as countries with smaller geothermal reserves (e.g., Poland, Hungary, South Africa, Qatar, and France). In conclusion, with the exception of China, very few papers associated with closed-loop EGS technologies are published in other countries. This should motivate other countries to evaluate the potential of EGS in their countries because EGS is applicable in almost all environments, regardless of the permeability of the reservoir.

Table 3. Articles categorized by country and year of publication.

Country Name	Publication Number	Publication Year
China	19	2012, 2018, 2019, 2020, 2021
USA	4	2005, 2015, 2017, 2021
Canada	3	2019, 2020, 2021
Italy	2	2013, 2016
Iran	2	2015, 2016
Turkey	1	2019
Hungary	1	2020
Qatar	1	2014
France	1	2015
South Africa	1	2013
Iceland	1	2019
Japan	1	2021
Poland	1	2006

3.2. The Design, Modeling, and Heat Transfer Performance of CLGSs

3.2.1. Design and Methods of Modeling of CLGSs

In CLGS, the working fluids do not come into direct contact with the reservoir. The main mode of heat transfer is the conduction between the reservoir and working fluid across well casings and cement. A secondary mode of heat transfer is convection through the working fluid. There are two types of CLGS: (1) coaxial CLGS (CCLGS) and (2) U-shape CLGS (UCLGS).

Design of Closed-Loop Geothermal Systems (CLGS)

The CCLGS is composed of two sections: the injection and the production wellbore. The injection and production sections are separated by thermal insulation to minimize heat loss. The design of a traditional CCLGS is shown in Figure 3, while a horizontal CCLGS, which exhibits enhanced heat transfer performance due to the enlargement of its heating surface, is presented in Figure 4.

A UCLGS consists of a descending injection well, a horizontal or lateral wellbore, and a production or ascending wellbore (Figure 5). The injection and production wellbores are equipped with well casings, cement, and insulation; in contrast, the lateral wellbore only has cement. A summary of the key parameters of the various CLGS designs evaluated in this systematic review, such as their inner tubing, wellbore depth, and length of horizontal wellbore, is presented in Table 4.

Figure 3. Schematic concept of a CCLGS [25].

Figure 4. Schematic concept of a horizontal CCLGS [26].

Figure 5. Schematic concept of a UCLGS [27].

Based on the design parameters presented in Table 4, we find that vertical CCLGSs are the dominant design, accounting for 65.8% of the CLGS in the literature. Horizontal CCLGSs and UCLGSs make up 15.8% and 18.4% of the CLGS designs, respectively. The diameter of the wellbores is in the range of 76.2 to 80 mm, while the horizontal length of the CCLGSs and UCLGSs is between 3000–5000 m. The depth of the wellbores is generally greater than 2500 m, which is categorized as deep geothermal depth. These results suggest that there are very few studies that have explored horizontal CLGSs and UCLGSs; hence, improvements to their design for EGS applications should be further investigated.

CLGSs Models

This section presents the mathematical models used in the selected publications to describe the process by which heat is exchanged between the reservoir and the wellbore. The heat exchange model used to assess the heat flow within a CLGS is critical. An unsteady or transient state heat transfer model allows for simulations of the temperature profile around the wellbore as well as the overall productivity of the system. The fundamental energy conservation model based on Fourier's Law expresses the profiles of ground temperature during heat extraction via a closed-loop wellbore system. The following formulas describe the governing equations for a system with cylindrical geometry and in a uniform medium. As the coaxial pipe and U-type closed-loop systems are buried in layered media, conduction occurs between the rock layers and the wellbore [27], and the energy equation can be written as follows:

$$\frac{1}{a} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \quad (1)$$

where a denotes the coefficient of thermal diffusion of the rock; r and z represent radial and vertical coordinate systems, respectively; t denotes time, and T denotes temperature. Due to the high-temperature gradient at the center and the low-temperature gradient at the radial edges, a new variable that utilizes an irregular difference in step size is added in the radial direction:

$$\sigma = \ln \left(\frac{r}{r_0} \right) \quad (2)$$

where r_0 is the radius of the borehole; thus, Equation (1) can be rewritten as Equation (3).

$$\frac{1}{a} \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial^2 T}{\partial \sigma} + \frac{\partial^2 T}{\partial z^2} \quad (3)$$

If the σ coordinate is incremented by a standard step of $\Delta\sigma$, the r coordinate will change geometrically as described in the equation below:

$$\frac{r_{i+1}}{r_i} = \frac{r_1}{r_0} = \exp(\Delta\sigma) = \beta \quad (4)$$

The governing equation (Equation (3)) can be solved numerically with suitable initial and boundary conditions (BC). Table 5 summarizes numerical simulations conducted in the literature. All publications included in this review employed numerical techniques to solve the governing equations, with the finite difference method (FDM) being the most commonly used technique, accounting for 31.6% of the methods used, while finite element methods (FEM) accounted for 28.9%. These were followed by finite volume methods (FVM) with 18.4%, while the remaining 21.1% of the studies did not report the methods used.

Table 4. CLGS designs in the literature.

Reference	CLGS Type	d _i (mm)	D _i (mm)	Depth (m)	Horizontal Length (m)
Song et al. [27]	UCLGS	142.9	216.8	3500	-
Nalla et al. [28]	CCLGS	76.2	311	5593	-
Kujawa et al. [29]	CCLGS	60.3	244.5	3950	-
Bu et al. [30]	CCLGS	34	244.5	4000	-
Focaccia and Tinti [31]	CCLGS	40	-	-	-
Yekoladio et al. [32]	CCLGS	50–300	-	-	-
Templeton et al. [33]	CCLGS	40/80	150/196	-	-
Wight and Bennett [34]	CCLGS	-	244.5	4200	-
Le Lous et al. [35]	CCLGS	114	235	5000	-
Noorollahi et al. [36]	CCLGS	60.3	146.05	4200	-
Alimonti and Soldo [37]	CCLGS	77.9/88.9	150.4/177.8	6100	-
Mokhtari et al. [38]	CCLGS	-	-	1015.4	-
Caulk and Tomak [39]	CCLGS	120	180	1500	-
Sun et al. [40]	CCLGS-H	152	250	1500	-
Song et al. [25]	CCLGS	200	384	5000	-
Shi et al. [41]	CCLGS	150	340	-	-
Renaud et al. [42]	CCLGS	75	219	2070	-
Ghoreishi-Madiseh et al. [43]	CCLGS	50	384	100	-
Zhang et al. [44]	CCLGS	62	114.3	1800	-
Sun et al. [45]	CCLGS-H	76	219	3800	3000
Wang et al. [46]	CCLGS-H	76	158	2000	2000
Yu et al. [47]	CCLGS	62	125	5000	-
Yildirim et al. [48]	CCLGS	127	203	2500	-
Dai et al. [49]	CCLGS	110	-	2070	-
Hu et al. [50]	CCLGS	76.2	188	3500	-
Wang et al. [51]	CCLGS-H	76	224.5	4350	1850
Hu et al. [52]	CCLGS	120	200	2000	-
Kalmár et al. [53]	CCLGS	73	114.3	-	-
He et al. [54]	CCLGS	62	139	2800	1900
Wang et al. [26]	CCLGS-H	76	224.5	2900	1900
Wang et al. [55]	CCLGS-H	76	224.5	2355	2300
Pokhrel et al. [56]	CCLGS	103.8	161.7	-	-
Sun et al. [57]	UCLGS	142.9	216.8	5000	5000
Sun et al. [58]	UCLGS	76	89	3800	3000
Yuan et al. [59]	UCLGS	156	-	4000	4000
Ghavidel et al. [60]	UCLGS	200–400	-	-	2000
Fallah et al. [61]	UCLGS	311.15	317.88	7000/10,000	7000/5000
Zhang et al. [62]	UCLGS	147	189	2000	2000

Note: d_i—Inner diameter of the tube; D_i—Inner diameter of the well; H—Horizontal.

Table 5. Methods used to model CLGSs.

Reference	CLGS Type	Numerical Method	Software
Song et al. [27]	UCLGS	FDM	-
Nalla et al. [28]	CCLGS	-	-
Kujawa et al. [29]	CCLGS	-	-
Bu et al. [30]	CCLGS	FVM	-
Focaccia and Tinti [31]	CCLGS	-	-
Yekoladio et al. [32]	CCLGS	-	-
Templeton et al. [33]	CCLGS	FEM	FlexPDE
Wight and Bennett [34]	CCLGS	-	-
Le Lous et al. [35]	CCLGS	FEM	FFEFLOW
Noorollahi et al. [36]	CCLGS	FVM	Ansys
Alimonti and Soldo [37]	CCLGS	-	-
Mokhtari et al. [38]	CCLGS	-	-
Caulk and Tomak [39]	CCLGS	FEM	Comsol
Sun et al. [40]	CCLGS-H	FDM	-
Song et al. [25]	CCLGS	FDM	-
Shi et al. [41]	CCLGS	FEM	Comsol
Renaud et al. [42]	CCLGS	FVM	Ansys
Ghoreishi-Madiseh et al. [43]	CCLGS	FVM	Ansys
Zhang et al. [44]	CCLGS	FEM	Comsol
Sun et al. [45]	CCLGS-H	FDM	-
Wang et al. [46]	CCLGS-H	FDM	-
Yu et al. [47]	CCLGS	FDM	-
Yildirim et al. [48]	CCLGS	FEM	Comsol
Dai et al. [49]	CCLGS	FVM	-
Hu et al. [50]	CCLGS	FEM	Comsol
Wang et al. [51]	CCLGS-H	FEM	Comsol
Hu et al. [52]	CCLGS	FVM	T2Well
Kalmár et al. [53]	CCLGS	FDM	-
He et al. [54]	CCLGS	-	-
Wang et al. [26]	CCLGS-H	FEM	Comsol
Wang et al. [55]	CCLGS-H	FEM	Comsol
Pokhrel et al. [56]	CCLGS	FVM	Ansys
Sun et al. [57]	UCLGS	FDM	-
Sun et al. [58]	UCLGS	FDM	-
Yuan et al. [59]	UCLGS	FDM	-
Ghavidel et al. [60]	UCLGS	FEM	Comsol
Fallah et al. [61]	UCLGS	FDM	-
Zhang et al. [62]	UCLGS	FDM	-

Note: CCLGS-H—Horizontal CCLGS.

3.2.2. Heat Transfer Performance of CLGSs

This section discusses the heat transfer performance and sensitivity parameters of CLGSs studied in the selected literature. Five key parameters determine the heat transfer performance of a CLGS: temperature distribution, heat extraction rate, pressure or pressure drop, thermal power, and pumping power. Most publications conducted a sensitivity analysis to investigate the impact of certain variables on the heat transfer parameters, including wellbore depth, production time, flow rate, reservoir gradient temperature, the thermal conductivity of the insulation, inlet pressure, inlet temperature, wellbore diameter, fluid type, horizontal length, reservoir thermal conductivity, and wellbore spacing for multi-lateral CLGSs (Table 6).

Table 6. Heat transfer performance parameters and sensitivity variables investigated by each publication.

Reference	Heat Transfer Parameter Sensitivity Analysis Variable															
	T	Qr	DP/P	Pth	H	q	t	Tgrd	Kins	Pin	Tin	d	Fluid	Lhor	Kres	Ws
Song et al. [27]	✓			✓	✓	✓	✓				✓					
Nalla et al. [28]	✓				✓											
Kujawa et al. [29]	✓				✓	✓			✓							
Bu et al. [30]	✓	✓	✓		✓											
Focaccia and Tinti [31]	✓				✓	✓						✓				
Yekoladio et al. [32]	✓				✓											
Templeton et al. [33]	✓				✓		✓	✓			✓					
Wight and Bennett [34]	✓				✓	✓										
Le Lous et al. [35]	✓					✓		✓	✓							
Noorollahi et al. [36]	✓			✓		✓										
Alimonti and Soldo [37]	✓			✓	✓	✓							✓			
Mokhtari et al. [38]	✓			✓	✓							✓				
Caulk and Tomak [39]	✓				✓	✓		✓								
Sun et al. [40]	✓	✓	✓			✓				✓	✓					
Song et al. [25]	✓				✓	✓	✓		✓							
Shi et al. [41]	✓	✓	✓	✓			✓									
Renaud et al. [42]	✓	✓				✓	✓									
Ghoreishi-Madiseh et al. [43]	✓				✓		✓									
Zhang et al. [44]	✓			✓		✓	✓		✓				✓			
Sun et al. [45]	✓		✓			✓	✓		✓						✓	
Wang et al. [46]	✓	✓				✓	✓					✓	✓	✓		
Yu et al. [47]	✓	✓	✓		✓	✓				✓						
Yildirim et al. [48]	✓			✓	✓	✓		✓								
Dai et al. [49]	✓	✓			✓		✓									
Hu et al. [50]	✓	✓		✓		✓										
Wang et al. [51]	✓				✓		✓									
Hu et al. [52]	✓		✓				✓			✓	✓					
Kalmár et al. [53]	✓			✓	✓	✓			✓							
He et al. [54]	✓		✓								✓		✓			
Wang et al. [26]	✓				✓		✓				✓					
Wang et al. [55]	✓			✓	✓		✓									✓
Pokhrel et al. [56]	✓			✓	✓				✓							
Sun et al. [57]	✓	✓	✓		✓	✓				✓						
Sun et al. [58]	✓	✓	✓		✓	✓		✓	✓	✓			✓	✓		
Yuan et al. [59]	✓			✓			✓				✓				✓	✓
Ghavidel et al. [60]	✓				✓		✓									
Fallah et al. [61]	✓		✓	✓	✓		✓									
Zhang et al. [62]	✓	✓				✓	✓							✓	✓	

Note: T—Temperature; Qr—Heat rate; DP/P—Pressure drop/Pressure; Pth—Thermal power; H—wellbore depth; q—flowrate; t—time; Tgrd = reservoir gradient temperature; Kins = Conductivity Coefficient of the insulation; Pin—Inlet Pressure; Tin—inlet temperature; d = wellbore diameter; Fluid—fluid type; Lhor—Horizontal length; Kres—Conductivity coefficient of the reservoir; Ws = wellbore spacing (multi-lateral type CLGSs only).

Heat Transfer Performance of CCLGSs

The distribution of fluid temperature in wellbores is a key performance parameter that influences the efficiency of power generation. Every paper in the selected literature utilized simulations to investigate temperature profiles over the length of the wellbore distance and over time. A typical temperature profile along a CCLGS wellbore is shown in Figure 6 [25]. The fluid temperature increases in the down-flow direction as heat exchange with the reservoir occurs due to the temperature gradient. Once the fluid has sunk to the bottom, it returns in the up-flow direction, and its temperature decreases depending on the insulation treatment described in Figure 6. A total of 21% of the studies in the literature conducted this sensitivity analysis to observe the effect of the thermal conductivity of the insulation on the up-flow temperatures.

Figure 6. The temperature profile of the working fluid in the wellbore [25].

The change in temperature over time was investigated by 47% of the studies, while 66% of the studies explored the temperature profile across the length of the wellbore. Figure 7 shows the typical variations in temperature against production time. The fluid temperature decreases as the reservoir temperature decreases over time due to the cooling effect of the fluid. The temperature that was influenced by flow rate was concluded by 55% studies; the higher the flow rate is, the greater the temperature decrease. This is because higher fluid flow rates reduce the time available for heat exchange.

Figure 7. Outlet temperature and thermal power as a function of production time [25].

The thermal power generated by the heat exchange between the wellbore and the geothermal reservoir was investigated by 29% of the studies. Similar to temperature, thermal power decreases over time; however, the higher flow rates result in increased thermal power, as illustrated by Figure 7.

The difference in temperature profiles between H₂O and CO₂ working fluids was compared 13% of the references. Figure 8 demonstrates that, when flow rates are held constant, CO₂ has a higher heat extraction rate than H₂O [45]. This is because CO₂ has a lower specific heat capacity than H₂O.

Figure 8. Variation in wellbore temperature at different flow rates and working fluids [45].

The pressure profile along the wellbore as well as the pressure difference between the injection and production wellbores were investigated by 26% of the studies. Figure 9 illustrates the pressure distribution along injection and production wellbore with changing flow rates. It suggests that the pressure differences increase as the flow rate increases.

Figure 9. Wellbore pressure at different flow rates [47].

Heat Transfer Performance of UCLGSs

The temperature distribution of UCLGSs is similar to CCLGSs along the descending section. Initially, the temperature of the working fluid increases gradually along the

descending section. It then continues to increase at the same rate as it flows through the horizontal section due to constant heating. The temperature of the fluid begins to decrease when it reaches the topmost parts of the ascending section (Figure 10).

Figure 10. Temperature distribution in UCLGS wellbores [57].

The effect of inlet pressure on temperature was only studied by 18% of selected publications. Based on the results of [58], it was found that when the inlet pressure increases, the temperature of CO₂ in the geothermal wellbore increases until a certain point before decreasing (Figure 11). This suggests that there is an optimal inlet pressure at which the maximum outlet fluid temperature is achieved. For example, the optimum inlet pressure is 28 MPa in this case (Figure 11).

Figure 11. Pressure distribution across the wellbore at different flow rates [58].

Comparison of CCLGS and UCLGS

Sun et al. [58] compared the heat transfer performance of UCLGS and CCLGS when CO₂ was used as the working fluid (Figure 12). The output temperature of the UCLGS was found to be higher than the CCLGS. The fluid was also continuously heated in the lateral section. In addition, the heat lost in the descending and ascending sections was less than CCLGS.

Figure 12. Comparison of the temperature distribution across the wellbore for CO₂ working fluids in different CLGSs [58].

A comparison of the heat transfer performance of CCLGSs and UCLGSs is also presented in Figures 13 and 14. It is clear that UCLGSs are superior to CCLGS with regards to higher heat extraction and outlet temperature.

Figure 13. Comparison of heat extraction with varying circulating fluid flow rates for CBHE or CCLGS and UBHE or UCLGS [62].

Figure 14. Comparison of temperature profiles over time and against different fluids for CBHE or CCLGS and UBHE or UCLGS [62].

4. Discussion

One of the main objectives of this paper was to evaluate how CLGSs had been modeled and simulated. Our findings suggest that conventional FDMs are appropriate for the simulation of wellbore heat transfers. In addition, they are least computationally expensive due to the simplicity of their algorithms compared to FVMs and FEMs. As the fluid model inside the wellbore pipes does not necessarily have to be complex, rectangular meshes or simple discretization can be applied using FDMs instead of the more complex fluid models provided by FEM and FVM. However, FEM and FVM approaches can still be used due to the availability of ready-to-use software such as Ansys, COMSOL, Open Foam, among others.

Research on the development of UCLGS has increased significantly since 2018 as it offers several advantages compared to CCLGS. These include higher heat mining rates and flowrate capacities, which allow for greater energy generation. The only limitation of UCLGSs is the higher cost associated with the directional drilling of the horizontal wellbore sections. In addition, CCLGS has smaller footprint requirements for system installation as the injection and production lines use the same wellbore piping. However, this system is more suitable for direct applications such as district heating due to the limitations regarding flowrate capacity and heat extraction rate. Hence, further research on how to address the limitations of both UCLGSs and CCLGSs is important. For example: how can wellbore layout be optimized such that the heat transfer area is increased, enhancing the heat transfer performance of the system. In addition, further research on improving the thermal resistance of the insulation is also key to enhancing the heat mining performance of both types of CLGSs. Additionally, a comprehensive techno-economic study and life-cycle assessment (LCA) analysis should be considered for further study to evaluate the feasibility of the entire geothermal facility. More attention should be given to obtaining accurate reservoir data and field testing, especially regarding the temperature gradient of the surrounding rock formation, as this will impact the accuracy of simulations that assess the performance of the geothermal system.

Sensitivity studies have been conducted to investigate the effect of important variables on the heat transfer performance of CLGSs, such as flow rate, type of working fluid, production time, horizontal length, temperature and pressure of the inlet, and insulation conductivity. However, the effect of different types of working fluid on the size of equipment such as the pumps, turbines, heat exchangers, and piping is not well understood. Therefore, it is important to investigate how the different properties of the working fluid, especially CO₂, affect the equipment sizing and cost of the geothermal plant.

Many studies found that CO₂ was a superior working fluid to H₂O, which is the traditional working fluid used in geothermal applications. Further study on applications

of CO₂ would be promising. For example, more research could be conducted on the integration of CCSU technologies in CLGSs.

5. Conclusions

This review on the design, modeling methods, and heat transfer performance of CLGSs provides a fundamental understanding of the various types of CLGS available, the four key performance parameters, and the 12 sensitivity analysis variables that are important in EGSs. The four main parameters that characterize key heat extraction in geothermal applications are temperature, heat extraction rate, pressure differentials, and thermal power.

Further studies on how to improve the heat transfer performance of CLGS are important. This includes research on the optimization of the wellbore layout to enhance the heat extraction rate and to reduce pressure drops. Other research that will provide important contributions to geothermal development includes techno-economic and life-cycle assessment (LCA) analyses, which can help with reducing the capital cost of the entire geothermal plant system. In addition, the findings suggest that UCLGSs that utilize CO₂ as the working fluid represent a promising combination of technologies. Additional research on the integration of UCLGSs with CCSU technologies should be carried out. These studies will positively contribute to addressing the challenges associated with the energy transition to meet green energy demand while simultaneously decreasing the CO₂ emission from fossil-based fuels.

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