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EFFECTS OF CEMENT CONDUCTIVITY ON THE THERMAL PERFORMANCE OF AGS SYSTEMS

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ABSTRACT

Geothermal energy applications have gained significant importance within the renewable energy sector. This growth is caused primarily by supply constraints in fossil-fuel-based energy sources. Recent advancements focus on developing various techniques to extract subsurface heat. Advanced designs and innovative materials are constantly emerging to support these novel applications. This highlights the necessity to carefully analyse all system components. Closed-loop geothermal systems also referred to as Advanced Geothermal Systems (AGS), can be configured in various design methods to extract this energy. This study evaluates the influence of casing cement thermal conductivity on the thermal performance of closed-loop systems. The study compares three cement options using fixed design parameters as low-conductivity (0.8 W/mK) and high-conductivity (2.8 W/mK), and a hybrid model. Also, the surrounding rock formation is modelled with a homogeneous thermal gradient along the wellbore, analysed both for low (35 K/km) and high (75 K/km) thermal gradient scenarios. The results demonstrate that varying cement thermal conductivity impacts the overall thermal output by 8.3 to 12.6%. The hybrid configuration provides a further 1 to 1.5% improvement compared to uniform high conductivity cement, demonstrating the benefit of selecting cement conductivity based on the local direction of heat transfer.

1. INTRODUCTION

In recent years, technological advancements in drilling and materials have resulted in an increased interest in geothermal energy [1]. Also, geothermal energy has emerged as a crucial alternative to fossil-fuel-based systems for space heating and cooling applications [2]. The use of ground-source heating systems is growing rapidly across the world. In these applications, borehole and well designs should be optimised based on the properties of geological formations to maximise thermal efficiency. System configurations vary from shallow to deep well installations depending on their utilisation. In the UK and the EU, shallow well systems are generally installed as ground-source heat pumps (GSHPs) for heating purposes. The European GSHP market expanded by 11.7% in 2023 compared with the previous year, reaching annual sales of more than 150,000 units [3]. Ground-source systems often use high-thermal-conductivity materials to improve heat extraction. In deep wells, cement is applied as part of the casing to stabilise the borehole and prevent collapse. Conventional cement typically exhibits a thermal conductivity of approximately 0.8 W/mK, which is lower than that of most surrounding rock formations [4]. Additionally, closed-loop systems also known as Advanced Geothermal Systems (AGS), alongside open loop systems, can, in a novel application, utilise thermally enhanced cement with conductivities up to 2.8 W/mK. This is achieved through the addition of carbon-based materials as thermal conductivity fillers to maximise heat extraction efficiency [5] [6] [7].

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2. METHODOLOGY

The thermalfluid simulations were conducted using the quasi-steady state method within WellTH, a model developed and validated by J. Kubacka and T.G Karayiannis [8][9]. The closed-loop well design type considered in this study is a co-axial configuration, whereby the inlet fluid travels downwards through the annulus between the casing and central tubing and returns to the surface through the central tubing. The model uses constant initial parameters to evaluate the cement effect in deep well systems. Geometric specifications define the inner and outer diameters of 17.8 and 21.8 mm for the annulus pipe, 10 and 13.97 mm for the Vacuum Insulated Tubing (VIT), and 21.8 and 27.8 mm for the cement layer. Thermal conductivities were set to 55 W/mK for the steel annulus pipe and 0.04 W/mK for the VIT, with respective surface roughness values of 0.015 mm and 0.1 mm. The assessed parameters consisted of an inlet temperature of 25 °C, a mass flow rate of 5 kg/s, and an operational period of 5 years. The soil surface temperature is set to 11 °C, while the rock thermal conductivity, specific heat capacity, and density are defined as 3 W/mK, 950 J/kgK, and 2,500 kg/m³ respectively. The evaluation of the effect of the cement conductivity was evaluated for different depths (H), i.e. 1,500 and 5,500 m and thermal gradients of 35 and 75 K/km. The cement conductivity was taken as 0.8 and 2.8 W/(mK). Furthermore, the surrounding rock formation was assumed to be homogeneous. As illustrated in Fig. 1, high inlet temperatures induce localised heat rejection from the circulating water to the upper subsurface formation due to the well fluid being cooler than the surrounding formation. An equilibrium point (Ep) exists along the borehole depth where the net heat transfer rate transitions from heat loss in well section 1 to heat gain in well section 2.

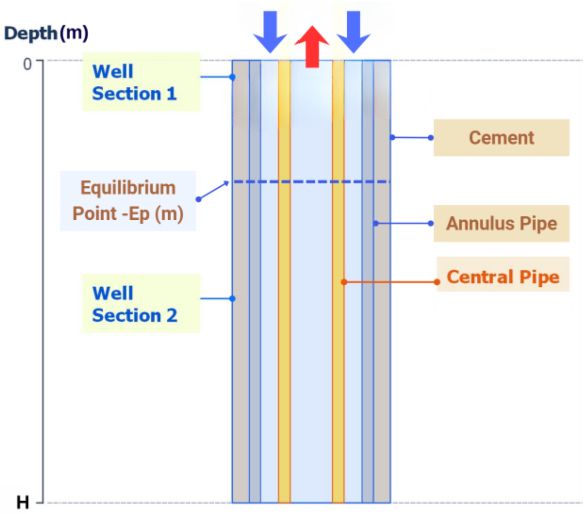

Figure 1. Two stage cement application schematic.

Table 1. Two stage cement application parameters

No	Ep (m)	H (m)	GRAT (K/km)
1	378	1500	35
2	409	5500	35
3	185	1500	75
4	205	5500	75

Identifying this thermal equilibrium provides a strong rationale for a segmented (two-stage) cement application strategy. Accordingly, a comprehensive scenario analysis was conducted comparing (i) uniform low-conductivity cement, (ii) uniform high-conductivity cement all along the depth of the well, and (iii) a two stage (hybrid) configuration. In the hybrid design, low-conductivity cement is placed from the surface down to the thermal equilibrium depth (Ep) to mitigate heat loss, while high-conductivity cement is installed along the deeper section to maximise heat absorption.

3. RESULTS

Results show that cement's conductivity affects the systems thermal performance. For the cases studied here, the thermal output is increased between 8.3 - 12.6% depending on formation specifications. Maximum thermal output increase was obtained for the 35 K/km thermal gradient and 1,500 m depth. The two-stage cement application yields an additional but marginal increase, i.e. 1% to 2% more thermal output for the system. It is clearly seen in Fig. 2. that the maximum thermal output increase of 12.6% is provided by the hybrid cement design at a 35 K/km thermal gradient and 1500 m depth.

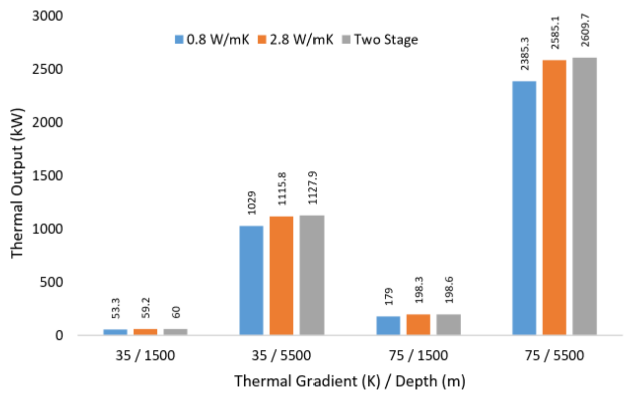

Figure 2. Thermal output for different thermal gradient and depth of the well.

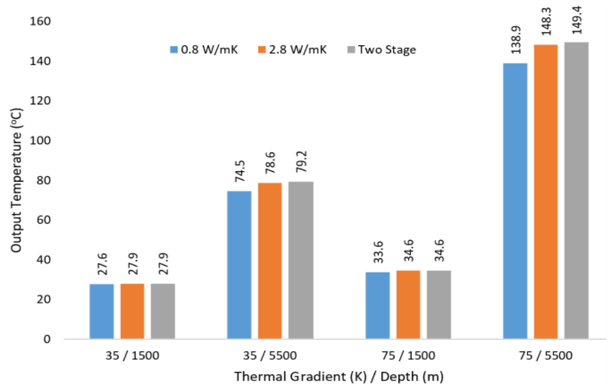

Figure 3. Temperature outlet for different thermal gradient and depth.

The minimum increase is seen as 8.3% at a 75 K/km thermal gradient and 5,500 m depth with the 2.8 W/mK conductivity cement design. At this depth as seen in Fig. 3, the maximum increase in output temperature is 7.5% at a 75 K/km thermal gradient with the hybrid cement application.

4. CONCLUSIONS

High-conductive cement is more expensive than low-conductive cement. However, it can provide additional thermal output and can be considered in the design of closed loop geothermal systems. In the cases examined it use can provide a 12.6% gain with hybrid application and 11% with high-conductive cement usage for the entire well. Shallow applications with lower thermal gradients generate higher thermal outputs with this design. The hybrid application also depends on thermal design, i.e. it can be cheaper than installing high conductivity cement for the entire depth of the well, while providing a marginal increase in the thermal output, i.e. 1% to 1.5% higher thermal output for the cases studied here. Finally, as indicated in this study the application of high-conductive cement results in a measurable increase in the well thermal output. It is recommended that further study take place to evaluate and record the benefits if high conductivity cement in relation to the well thermal output that includes different rage of geometrical and operational parameters plus an assessment of the related economic factors.

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