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Thermal Power from a Notional 6 km Deep Borehole Heat Exchanger in Glasgow

Isa Kolo*, Christopher S Brown, and Gioia Falcone

James Watt School of Engineering, University of Glasgow, Glasgow, G12 8QQ

*Isa.Kolo@glasgow.ac.uk, Christopher.Brown@glasgow.ac.uk, Gioia.Falcone@glasgow.ac.uk

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ABSTRACT

The UK was the first major economy to legislate for net zero carbon emissions by 2050. In its Climate Plan, Glasgow – the third largest city in the UK – set out its strategy for net zero carbon emissions, healthy biodiversity, and climate resilience by 2030. The city also hosted world leaders in 2021 to deliberate on climate change where the Glasgow Pact was adopted at the United Nations Climate Change Conference. To mitigate greenhouse gas emissions, alternative energy sources must be explored. Unlike intermittent sources (wind, solar), geothermal energy represents a viable candidate for year-round base-load provision. While conventional geothermal electrical power generation systems are increasingly contributing to green power production worldwide, the geological risk inherent in such geothermal developments can be high. An alternative lower risk approach to exploiting geothermal energy is to employ a deep borehole heat exchanger (DBHE), where a supply of natural fluid from a geothermal reservoir is not required. A single well with concentric pipes is constructed so that a heat transfer fluid can flow down the annular section and return extracted heat to the surface via a central pipe. There is no hydraulic interaction with the reservoir and only a single well is required.

In principle, the concept can be applied in any geological setting. While it is mainly used for space heating applications, some studies have suggested the possibility of generating electricity in combination with binary power stations. In this work, Central Glasgow is taken as a case study; a notional 6 km deep borehole heat exchanger is modeled to determine the thermal power that could be extracted. At the assumed depth, the deep borehole heat exchanger is likely to penetrate crystalline basement with a bottom-hole temperature of 225 °C. Results indicate that, with a circulation mass flow rate of 8.33 kg/s, 800 kW of heat could be extracted for 6 months from the DBHE without the fluid inlet temperature going below 36 °C using a power-controlled simulation. With a constant inlet temperature of 10 °C, up to 1096 kW of heat could be extracted using the same mass flow rate within the same period. The outlet fluid temperature from the DBHE goes into the inlet of the binary power plant which typically requires a minimum temperature of 100°C. To maintain a DBHE outlet temperature of 100°C, only a thermal power of 150 kW can be supplied based on the assumptions made in this work. The effects of mass flow rate, varying heat load and varying rock thermal conductivity relevant to the Glasgow area are investigated. Under present economic conditions, it seems unlikely that the significant capital cost of inner-city deep drilling would offer a viable economic return.

1. INTRODUCTION

Geothermal energy is a clean energy source that can help mitigate greenhouse gas emissions. This makes it a viable candidate in pursuing Glasgow's Climate Plan (Glasgow City Council, 2021) which targets net zero carbon emissions by 2030. While conventional exploration of geothermal resources is associated with high risk, a relatively low risk alternative is to use deep borehole heat exchangers (DBHEs) (Agrawal, 2012) – "deep" implying where depths exceed 500 m (Watson *et al.*, 2020). A heat transfer or working fluid is pumped into a DBHE and gains heat through conduction from the surrounding rock (see **Figure 1**); once heated, the output fluid can be used for heating purposes, either directly, or in combination with a heat pump (Sapinska-Sliwa *et al.*, 2016). Moreover, DBHEs require less land use at the surface, which makes them well suited for densely populated areas (Gascuel *et al.*, 2022).

Several studies have looked at using a DBHE for space heating and there are a few projects in existence, such as in Germany (Sapinska-Sliwa *et al.*, 2016) and China (Wang *et al.*, 2017; Huang *et al.*, 2021); see Gascuel *et al.* (2022) for a recent overview. However, most projects and feasibility studies are limited to a depth of 3 km. Studies in the Cheshire Basin of the UK revealed that over 299 kW thermal power could be produced from a 2.8 km well operating for 20 years (Brown *et al.*, 2021), whilst further studies, using the same numerical approach, investigated the impact of 10 design parameters using local and global sensitivity analyses at depths up to 2.5 km (Brown *et al.*, 2023a). Chen *et al.* (2019) analyzed the output from a notional 2.6 km DBHE in which they revealed that, in the short-term, loads in the range of 390 – 520 kW can be imposed on the DBHE. Gascuel *et al.* (2022) studied DBHEs in the depth range of 500 – 3000 m in cold sedimentary basins. Kolo *et al.* (2022) analyzed the potential repurposing of the 1.8 km Newcastle Science Central Deep Geothermal Borehole as a DBHE, showing that ~50 kW could be extracted for space heating from the upper 922 m of the borehole.

Studies reaching a depth of 6 km are few and these have been carried out mainly in the context of geothermal power generation. Cheng *et al.* (2012) studied the possibility of generating power from an abandoned oil well (6 km deep) using isobutane as the working fluid. A DHBE was used in combination with an Organic Rankine Cycle (ORC) to generate power. A maximum net electrical power of 134 kW was reported for isobutane circulating at a flow velocity of 0.18 m/s. The disappointing electricity generation is due to the low heat transfer rate through the rock. Increasing the velocity of the working fluid increases heat extracted but reduces the fluid outlet temperature, which also affects the amount of power generated. Davis and Michaelides (2009) also used isobutane as the working fluid in their study and claimed that when its velocity and the inner pipe diameter are optimized, up to 3 MW of electrical power could be generated from a 3 km deep abandoned oil well typical of the South Texas region. The study used a higher flow rate of 2 m/s for isobutane and there was no mention of the operation/simulation time being considered, which suggests it is likely to be very short. Alimonti and Soldo (2016) studied power generation from a 6 km deep hydrocarbon well coupled to an ORC unit using both water and diathermic oil as heat transfer fluids. The latter is commonly used when the working temperature is above 100 °C as it keeps fluid properties (especially density) unchanged. Results showed that although the diathermic oil reaches higher temperatures, water is more efficient in heat transfer and thermal power generation. For a water flow rate of 15 m^3/hr, a thermal power of 1.5 MW was generated with a net electrical power of 134 kW. Since the output is not comparable to conventional geothermal power plants, the authors suggested that the thermal power would likely be more appropriate for direct heat use via district heating.

The aim of this study is to determine the potential thermal power available from a 6 km deep well located in Glasgow using water as the heat transfer fluid based on its efficiency in comparison to other heat transfer fluids (Alimonti and Soldo, 2016). Glasgow (Figure 1b) is rigorously pursuing a net-zero carbon emissions policy by 2030 through the Glasgow's Climate Plan and other decarbonisation initiatives such as the Low Emission Zone, in which, from June 2023, only cars with certain emission standards would be allowed around the city center (Glasgow City Council, n.d.). A DBHE, with its limited surface footprint, has the potential to supply clean heat and possibly clean power to the city. This study models the impact of different parameters upon the thermal power that could be recovered from the 6 km DBHE, including varying heat load and varying rock thermal conductivity. The effect of mass flow rate on thermal power under different modes of operation (constant inlet temperature vs constant heat load) is also studied. The open-source finite element code OpenGeoSys (OGS) is adopted for simulations in this work, particularly the heat transport borehole heat exchanger module (Chen *et al.*, 2019). A numerical model has been chosen because of the deep nature of the well being considered making it possible to subsequently consider geological heterogeneities as well as three-dimensional heat transfer.

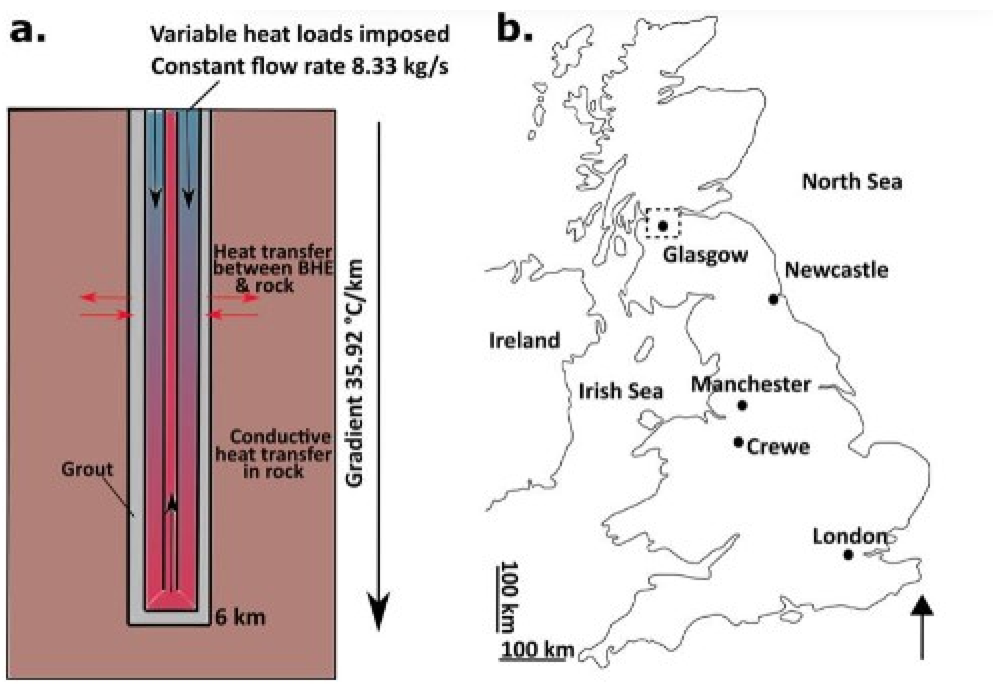

Figure 1: (a) Schematic of a deep borehole heat exchanger DBHE; (b) map of the UK showing the location of Glasgow.

2. METHODS

2.1 Numerical Modelling Approach

The 'dual-continuum' approach for modelling a DBHE is employed in this work using OGS software which adopts finite element discretization. In this approach, the DBHE is modeled and discretized using one-dimensional finite elements. The surrounding rock is considered as a second continuum discretized with three-dimensional prism elements. In **Figure 1**, a simplified representation of the DBHE is assumed with a single casing and single grout layer, in which fluid enters through the annulus and leaves through the central coaxial pipe. The set-up is governed by conduction-dominated heat transfer equations in the surrounding rock and the grout, and advective heat transfer equations for fluid flow in the borehole casing (inlet) and central coaxial pipe (outlet). The four governing equations for the rock formation, grout, inlet, and outlet (in this order) are (Chen *et al.*, 2019; Kolo *et al.*, 2022):

$$\frac{\partial}{\partial t}\left[\phi\rho_f c_f + (1-\phi)\rho_r c_r\right]T_r - \nabla\cdot\left(\Lambda_r\cdot\nabla T_r\right) = H_r \quad (1)$$

$$(1-\phi_g)\rho_g c_g \frac{\partial T_g}{\partial t} - \nabla \cdot \left[(1-\phi_g)\lambda_g \cdot \nabla T_g\right] = H_g \tag{2}$$

$$\rho_f c_f \frac{\partial T_i}{\partial t} + \rho_f c_f \boldsymbol{v}_i \cdot \nabla T_i - \nabla \cdot (\Lambda_f \cdot T_i) = H_i \tag{3}$$

$$\rho_f c_f \frac{\partial T_o}{\partial t} + \rho_f c_f \boldsymbol{v}_o \cdot \nabla T_o - \nabla \cdot (\Lambda_f \cdot T_o) = H_o \tag{4}$$

In the preceding equations, the following subscripts are used: r represents the rock, g represents the grout, i represents the inlet (borehole casing), o represents the outlet (central coaxial pipe) and f represents the heat transfer fluid. ϕ represents the porosity of the formation, ρ is the density, c is the specific heat capacity, T is the temperature, t is the time, H is the source term, λ is the thermal conductivity, Λ is the hydrodynamic thermo-dispersion tensor, and $\mathbf{v}$ is the fluid velocity vector. Thermal resistance exists horizontally for heat flow between the different media which is analyzed like a resistor network. The thermal resistances can be expressed in terms of heat transfer coefficients based on geometrical properties of the borehole diameter, the borehole casing diameter, and the diameter of the central coaxial pipe. This results in the following heat flux (q) boundary conditions for **equations (1) – (4)** respectively,

$$q_{T_r} = -(\Lambda_r \cdot \nabla T_r) \tag{5}$$

$$q_{T_g} = -\Phi_{gr}(T_r - T_g) - \Phi_{ig}(T_i - T_g) \tag{6}$$

$$q_{T_i} = -\Phi_{ig}(T_r - T_i) - \Phi_{io}(T_o - T_i) \tag{7}$$

$$q_{T_o} = -\Phi_{io}(T_i - T_o) \tag{8}$$

where Φ is the heat transfer coefficient with various subscripts – gr implies heat transfer between the surrounding rock and grout, ig implies heat transfer between the inlet (borehole casing) and grout, and io implies heat transfer between the inlet (borehole casing) and outlet (central coaxial pipe) pipes. Details on the relationship between thermal resistance and heat transfer coefficient can be found in Diersch *et al.* (2011). The implementation of the dual-continuum finite element approach in OGS open-source software (Chen *et al*., 2019) is used in this work. The coaxial DBHE model in OGS has been verified extensively against analytical solutions (Brown *et al*., 2023), other numerical solutions (Kolo *et al*., 2022), and using field data (Cai *et al*., 2021).

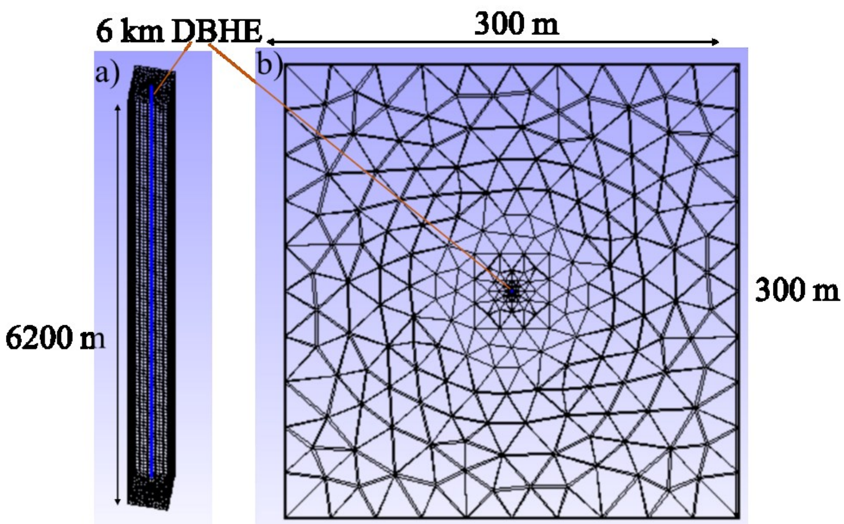

Figure 2: (a) 3D finite element mesh with DBHE and rock domain; (b) magnified plan view of the mesh.

2.2 Model Set-Up, Parameters and Boundary Conditions

The dimensions of the DBHE have been taken from Kolo *et al.* (2022) and Brown *et al.* (2023b). Based on data from the Paisley Coats Meteorological Office Observatory in Glasgow (Met Office, 2023), a ground surface temperature of 10.17 °C is used. While the 6 km well is likely to penetrate crystalline basement, an averaged homogeneous representation of the rock is used in this study with a rock thermal conductivity of 2.5 W/(m·K) (Watson, 2022). A parametric study of higher thermal conductivities in conducted. A detailed geological representation of the well incorporating lithologies to known depths will be considered in future work. A geothermal gradient of 35.92 °C/km has been calculated for Glasgow based on measurements by Browne *et al.* (1987). Hence, under initial conditions, the bedrock is assumed to have a temperature increasing linearly with depth. Two boundary conditions have been used for simulations – a constant heat load boundary condition has been used predominantly, but when studying mass flow rates, a constant fluid inlet temperature has also been used. For the constant heat load simulations, the rock, fluid, and grout are assumed to be initially in thermal equilibrium. A domain size of 300 × 300 × 6200 m (x, y, z) has been used to ensure that there is no thermal interference with the boundaries. For top, bottom, and lateral sides, zero heat flux (Neumann) boundary conditions have been used, as no noticeable difference was reported between Dirichlet and Neumann boundary conditions for the inlet and outlet fluid temperatures, provided the domain boundaries are far enough from the DBHE (Kolo *et al.*, 2022). A flow rate of 8.33 kg/s is taken as the reference flow rate with water as the heat transfer fluid but a parametric study is conducted (Kolo *et al.*, 2022); other parameters are summarised in **Table 1**. The meshed domain showing the DBHE is presented in **Figure 2**.

Table 1: Thermo-physical parameters of the DBHE model (Kolo *et al.*, 2022; Brown *et al.*, 2023b)

PARAMETER	VALUE	UNITS
Borehole Depth	6000	m
Borehole Diameter	0.21600	m
Outer Diameter of Inner Pipe	0.100500	m
Thickness of Inner Pipe	0.00688	m
Thickness of Outer Pipe	0.008100	m
Thickness of Grout	0.019050	m
Thermal Conductivity of Inner Pipe	0.45	W/(m·K)
Thermal Conductivity of Outer Pipe	52.70	W/(m·K)
Density of Rock	2480	kg/m^3
Thermal Conductivity of Rock	2.5	W/(m·K)
Specific Heat Capacity of Rock	950	J/(kg·K)
Volumetric heat capacity of rock	2.356	$MJ/(m^{3}\cdot K)$
Density of Grout	995	kg/m^3
Thermal Conductivity of Grout	1.05	W/(m·K)
Specific Heat Capacity of Grout	1200	J/(kg·K)
Density of Fluid	998	kg/m^3
Thermal Conductivity of Fluid	0.59	W/(m·K)
Specific Heat Capacity of Fluid	4179	J/(kg·K)
Surface Temperature	10.17	°C
Geothermal Gradient	35.92	°C/km
Volumetric Flow Rate	0.00833	m^3/s
Heat Load (Base Case)	800	kW

3. NUMERICAL RESULTS AND ANALYSIS

3.1 Temporal Evolution

A load of 800 kW is imposed with a flow rate of 8.33 kg/s. In the initial 24 hours, the fluid temperatures increase rapidly as shown in **Figure 3a** due to the high temperature fluid at the base of the DBHE being brought to the surface. Continuous extraction of heat will lead to the surrounding rock cooling in proximity to the DBHE which causes a reduction in the extracted fluid temperature over time (see

Figure 3c). From an outlet fluid temperature (Tout) of 77°C at 0.7 hours, the temperature rapidly falls to 73 °C after 100 hours and continues to decline, reaching 59.9 °C after 6 months. The fluid reaches a very high temperature at the base of the 6 km deep borehole (125.9°C at 6 months), as shown in **Figure 3b**. However, when flowing upwards, it loses heat to the relatively cooler surroundings. It is observed from **Figure 3b** that in the initial 24 hours (0.7 and 8.6 hours), the cooler temperature close to the surface has a strong cooling effect on the fluid within 1000 m depth. With time, the inlet fluid tends towards the linear geothermal gradient (6 months). **Figure 3c** shows that the surrounding rock in the immediate vicinity of the DBHE has cooled significantly within 6 months. While for 3 km – 6 km, the DBHE has extracted heat from the rock, at 1 km, the DBHE appears to be heating the shallower part of the borehole which reduces the overall extraction efficiency. Hence, for very deep DBHEs, the use of insulating material in the top region of the borehole will improve efficiency. The radius of thermal influence increases with depth (measured to a difference of 1 °C in contrast to static conditions); the thermal field propagates to a maximum of: 1) 4 m from the DBHE at 1 km depth, 2) 8 m at 3 km depth, 3) 12 m at 5 km depth and 4) 13 m for 6 km depth. At 1 km, the temperature profile within the rocks is concaving downwards around the DBHE, whilst for the other depths the heat flow concaves upwards (cf. **Figure 3c**). The symmetry observed in the thermal field in **Figure 3c** is a result of assuming fully homogeneous and isotropic geology.

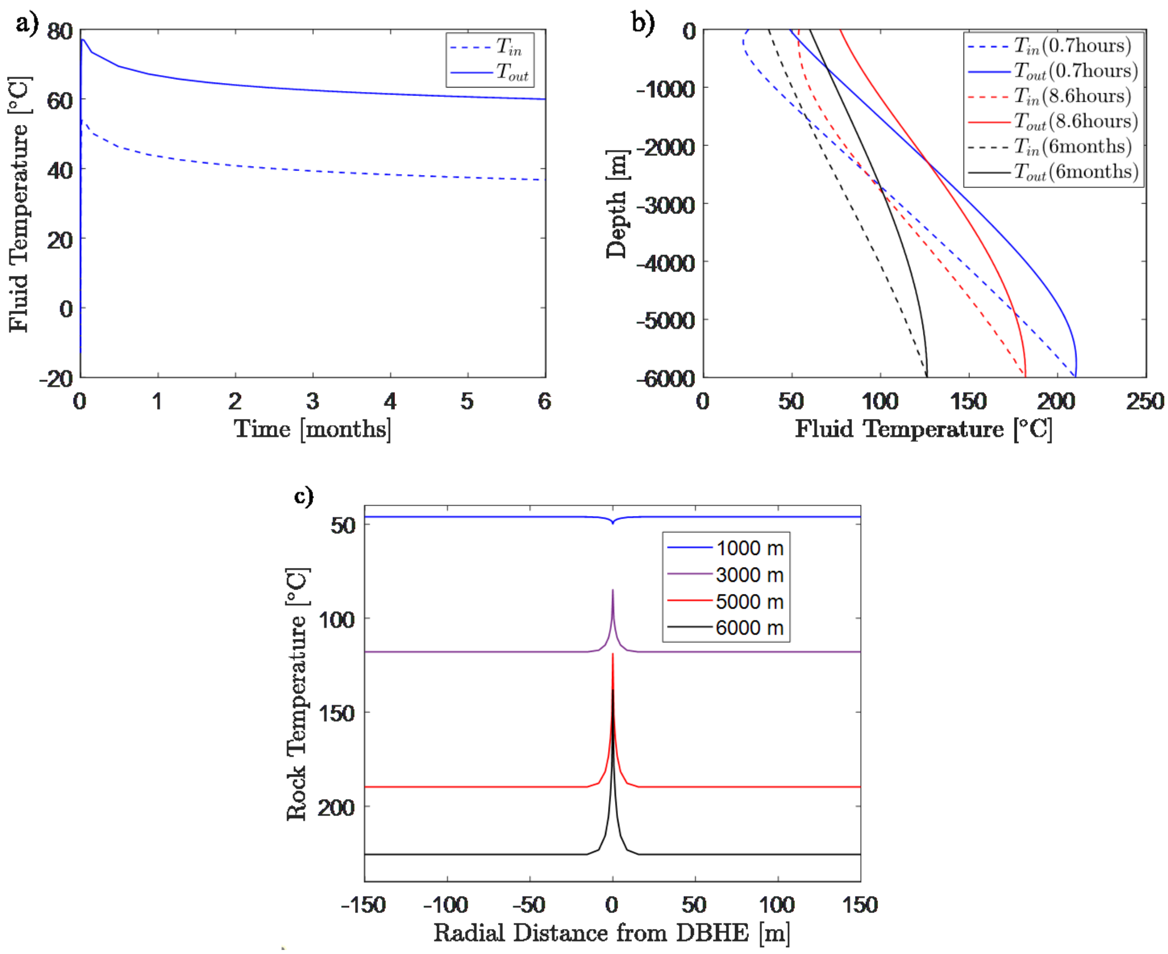

Figure 3: 800kW constant power load – (a) Inlet and outlet fluid temperature over one heating season; (b) Fluid inlet and outlet temperature with depth at 6 months; (c) Rock temperature on the mid-plane cross-section at different depths (DBHE at 0 m). Mass flow rate is 8.33 kg/s.

3.2 Variation of Heat Load

The heat load is varied between 150 kW and 1200 kW to test the likely operational loads that could be sustained by the DBHE. Results for the inlet and outlet temperatures are shown in **Figures 4a and 4b**, respectively (and **Table 2**). Rapid cooling in fluid inlet and outlet temperature within the first three months of operation is observed for heat loads ≥ 700 kW with temperature drop ≥ 16 °C in 6 months.

- For 500 kW, the temperature drop is only 8 °C, while for ≤ 200 kW, the temperature is still increasing within the first 6 months. This is because in the latter case, the extracted heat load is significantly small compared to the available load and hence no thermal drawdown is visible.
- Heat loads in the range of 700 kW to 800 kW with inlet temperatures in the region of 46 °C to 37 °C, respectively, after 6 months are likely to be sustainable in the long-term.

- A heat load of 1000 kW can be supplied for 6 months without the inlet temperature going below 18 °C. However, based on the logarithmic decline rate, 1000 kW is unlikely to be sustainable in the long term (≥ 20 years).
- For a heat load of 1200 kW, the inlet temperature approaches 0°C after 6 months implying that only one heating period can be sustained assuming water as the heat transfer fluid.

The mode of operation, either using intermittent or constant heat load, also impacts the sustainability of the system (Brown *et al.*, 2023b). When using a DBHE with a heat pump for space heating, a minimum inlet temperature of 4°C should be used (Chen *et al.*, 2019). In the case of electricity generation, a minimum outlet temperature of 100 °C is a reasonable threshold to work with (Atkins, 2013). This implies that in 6 months, only 150 kW thermal power can be generated without the fluid inlet temperature falling below 100 °C. This output is not comparable to conventional geothermal power plants which typically have an installed capacity of ≥ 1 MW of electricity equivalent to 10 MW thermal power (assuming 10 % efficiency) (EGEC, 2022; Sigfússon and Uihlein, 2015), especially considering the cost of drilling a well to a depth of 6 km. Hence, it appears that it is not economically competitive to consider electricity generation using a conventional DBHE.

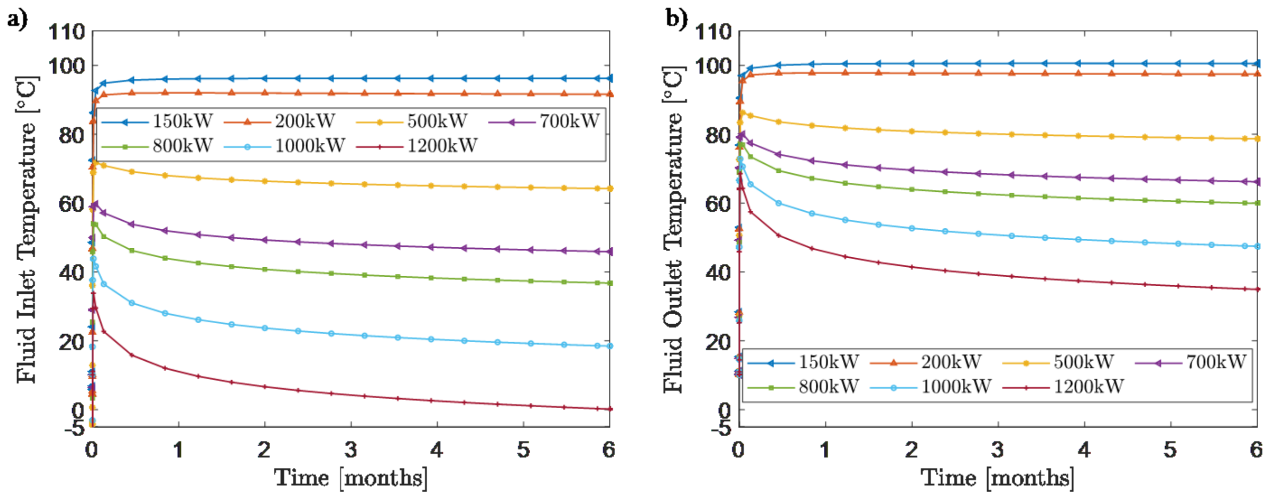

Figure 4: Inlet (left) and outlet (right) fluid temperatures for different heat loads at the top of the DBHE. Mass flow rate is 8.33 kg/s.

Table 2: Inlet and Outlet Temperatures for different heat loads at 6 months.

Heat Load [kW]	150	200	500	700	800	1000	1200
Inlet Temp. [°C]	96.20	91.63	64.20	45.91	36.77	18.48	0.19
Outlet Temp. [°C]	100.55	97.43	78.69	66.19	59.95	47.45	34.96

3.3 Variation of Rock Thermal Conductivity

The thermal conductivity of the rock has a significant effect on the fluid outlet temperature as seen in **Figure 5a**. The base case with a thermal conductivity of 2.5 W/(m·K) gives an outlet temperature of 59.95°C after 6 months. When the rock thermal conductivity increases to 3.5 W/(m·K) and 4.5 W/(m·K), the outlet temperatures rise significantly to 67°C and 71°C, respectively. It can be inferred from **Figure 5a** that with each increase in thermal conductivity, the successive temperature change decreases. **Figure 5b** indicates that a higher thermal conductivity is associated with higher rock temperature since heat moves more rapidly from hotter surroundings to the rock in the immediate vicinity of the DBHE to replenish the extracted heat.

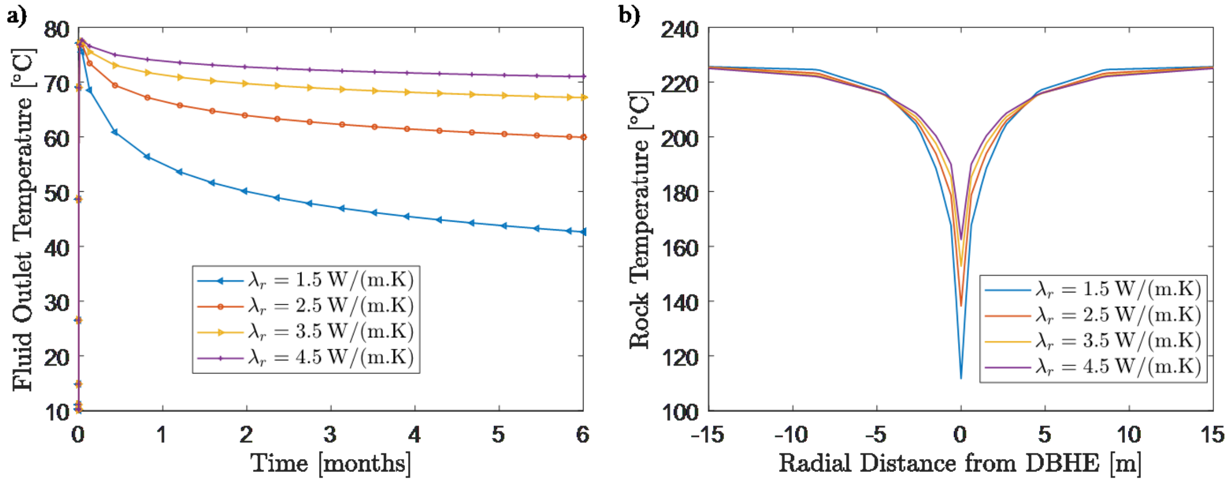

Figure 5: Outlet fluid temperatures (a) and rock temperature at 6 months (b) for different rock thermal conductivities. 800 kW heat load is imposed with a mass flow rate of 8.33 kg/s.

3.4 Variation of Flow Rates

Flow rate is an important variable in the operation of a DBHE. Observing **Figure 6a** at 6 months, the outlet temperatures for 5 kg/s, 8.33 kg/s, 10 kg/s and 12 kg/s are 19.2 °C, 59.9 °C, 68.7 °C and 74.7 °C, respectively. A high flow rate ensures turbulent flow which increases forced convection within the DBHE thereby enhancing heat extraction. With a higher flow rate, the fluid has less time to heat up within the annular space, but also loses less heat in the central outlet pipe from thermal interactions with the fluid in the annular space. This is demonstrated in **Figures 7a and 7b**, where the fluid with the lowest flow rate of 5 kg/s stays longest within the DBHE and hence reaches the highest temperature at the DBHE bottom. However, it loses heat significantly before reaching the outlet due to heat exchange between downward flowing and upward flowing fluid, known as thermal short-circuiting. It is noteworthy that the inlet temperature for a mass flow rate of 5 kg/s is −19 °C (well below 0 °C) after 6 months of operation, due to higher temperature change imposed as the boundary condition because of lower mass flow rate; hence, 800 kW cannot be supported by a mass flow rate of 5 kg/s because water will freeze at such low temperatures. This leaves operational flow rates at ≥8.33 kg/s based on the values considered. The higher outlet temperature from higher mass flow rates suggests that variable mass flow rates in the operation of a DBHE can be used to optimize operation (Beaudry *et al.*, 2022). For example, when considering a variable load in a building, a higher mass flow rate can be used during periods of peak load which is then reduced when the load is back to normal levels.

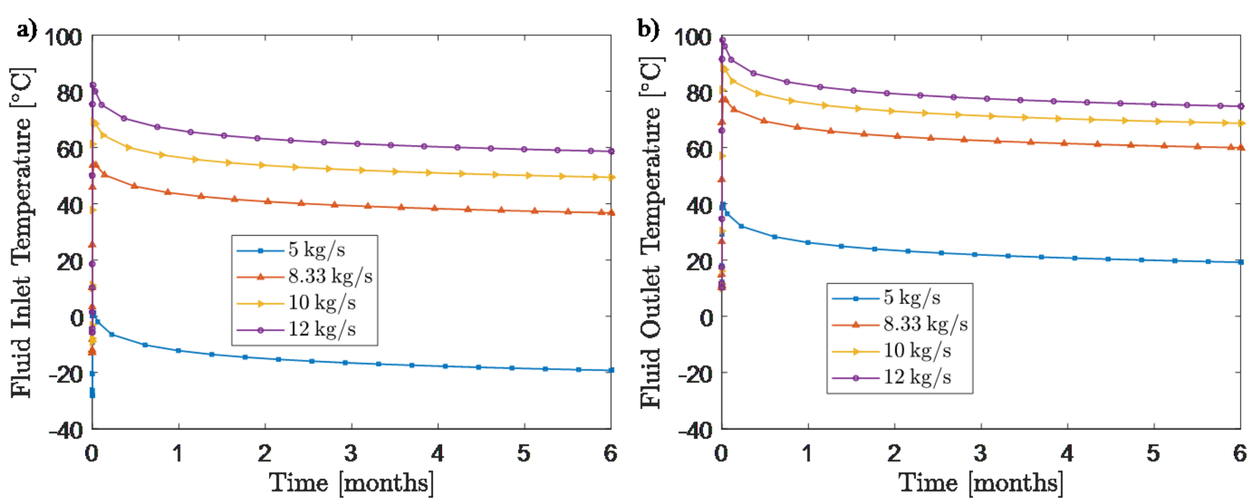

Figure 6: Outlet fluid temperatures (a) and inlet fluid temperatures (b) with varying mass flow rates. Heat load is 800kW.

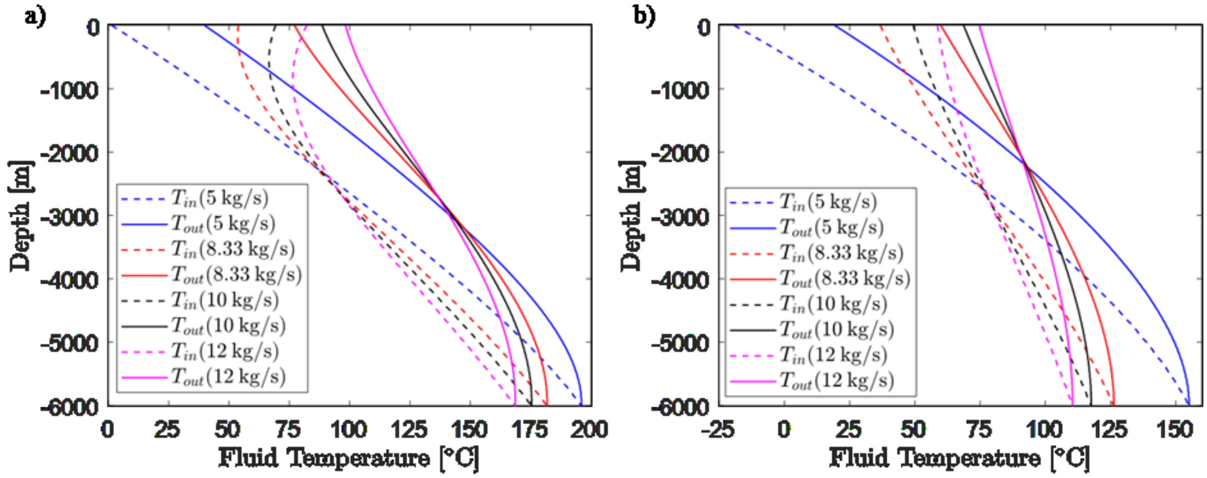

Figure 7: Fluid inlet and outlet temperature with depth at 8 hours (a) and 6 months (b). Heat load is 800 kW.

3.5 Temperature-Controlled Simulations and Variation of Flow Rates.

A temperature-controlled simulation is next where the fluid inlet temperature is used as input. Different inlet temperatures have been considered herein between 10 °C and 25 °C, with increments of 5 °C. **Figure 8a** shows the evolution of outlet temperature with time for different inlet temperatures. The relationship is linear since a 5 °C increase in the inlet temperature results in 3.42 °C increase in the outlet temperature. The linear relationship at 6 months is shown on **Figure 8b**. Despite the increase in fluid outlet temperature, the temperature change (difference in outlet temperature and inlet temperature) decreases relative to the rock temperature and hence there is less heat extraction. The heat extracted after 6 months varies from 1096 kW for 10 °C inlet temperature to 932 kW for 25 °C inlet temperature.

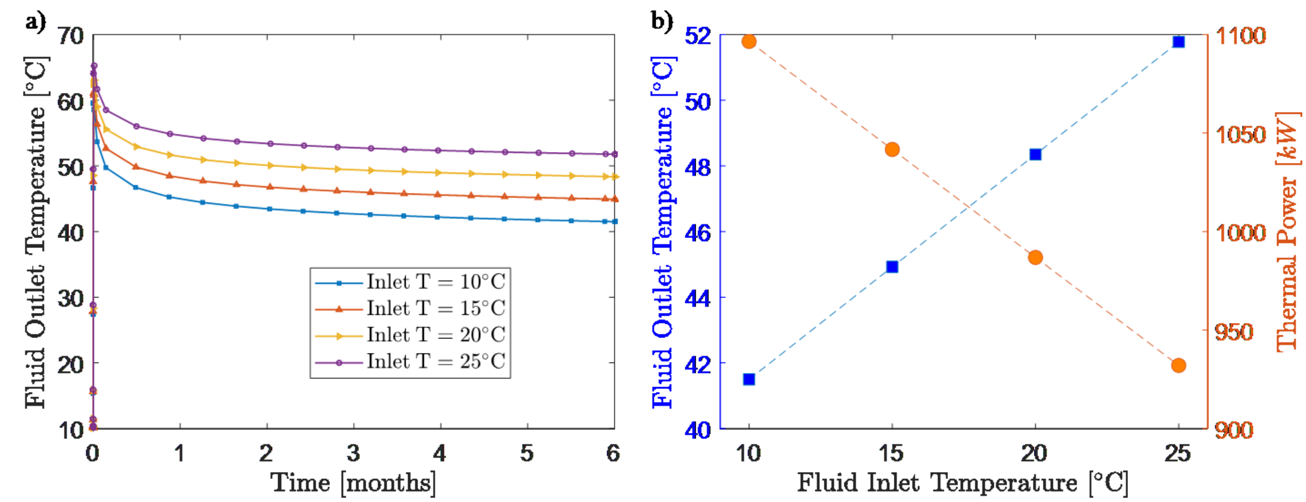

Figure 8: (a) Fluid outlet temperatures for different inlet temperatures; (b) Fluid outlet temperatures and corresponding thermal power for different inlet temperatures at 6 months. Mass flow rate is 8.33 kg/s.

When the flow rate is varied for a constant inlet temperature simulation, the outlet temperature develops as shown in **Figure 9a**. Quasi-steady state is reached quickly (~38.5 °C at 6 months) with a flow rate of 5 kg/s. When the flow rate increases to 8.33 kg/s, the outlet temperature increases to 41.5 °C, cf. **Figure 9b**. However, a further increase in flow rate causes a reduction in the outlet temperature indicating that 8.33 kg/s is the optimum value. Beyond this point, there is still an increase in the thermal power (1475 kW at 12 kg/s) because the reduction in temperature is compensated by higher volume of heated fluid (Brown *et al.*, 2021).

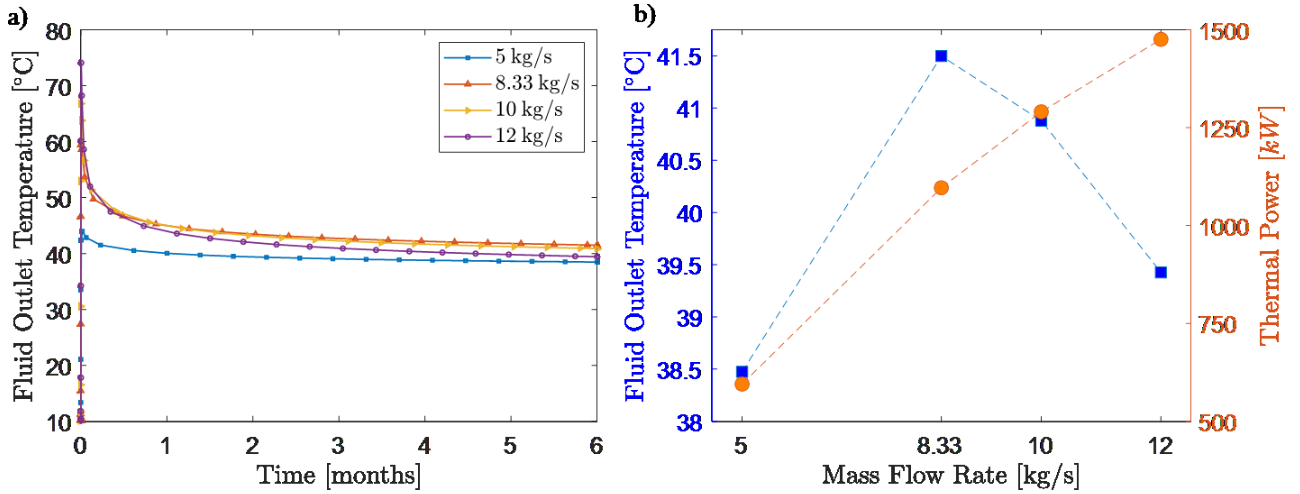

Figure 9: (a) Fluid outlet temperatures for varying mass flow rates; (b) Fluid outlet temperatures and corresponding thermal power for varying mass flow rates at 6 months. The inlet temperature is 10°C.

4. DISCUSSION AND CONCLUSIONS

A notional 6 km DBHE has been modelled in the city of Glasgow using the dual-continuum finite element approach implemented in OpenGeoSys. Only one heating season with a duration of 6 months has been considered. Results indicate a thermal power output of ~800 kW with a mass flow rate of 8.33 kg/s without the fluid inlet temperature going below 36.77 °C and ~1000 kW without the fluid inlet temperature going below 18 °C. For geothermal power production, a DBHE outlet temperature of 100 °C is typically required, and hence, only 150 kW of thermal power output will be available to meet this requirement. The very low thermal output from such a system suggests that it would not be commercially viable to couple a conventional DBHE to an ORC unit to generate electricity. This corroborates earlier studies (Alimonti and Soldo, 2016; Cheng *et al.*, 2013). For a very deep DBHE, the upper region (< 1000 m) of the system tends to start warming up with time, making it valuable to consider insulating the upper part of the borehole which cuts across this region. Identifying a place with higher rock thermal conductivity (such as the Kipperoch area, see Watson (2022)) will significantly increase outlet temperature by up to 10 °C, as inferred from the analysis of rock thermal conductivity. It is noted that a flow rate of 5 kg/s cannot provide the 800 kW output since the inlet temperature declines to −19 °C in 6 months. In a variable load operation scenario, it would be worthwhile to consider operation of the DBHE with a variable mass flow rate such that with higher load demand, a higher flow rate is used to optimize operation.

A different boundary condition using the inlet fluid temperature was also considered. Results showed that up to 1096 kW of thermal power can be supplied with a constant inlet temperature of 10 °C and a mass flow rate of 8.33 kg/s. Varying the mass flow rate revealed the optimum value to be 8.33 kg/s after which the outlet temperature starts to decline. It is noted that this is a short-term analysis, and a heat pump has not been assumed for the operation of the DBHE. While only water has been considered as heat transfer fluid, isobutane which has been used in other studies should also be considered. Incorporating a non-homogeneous lithology is also likely to impact results since the lithology will significantly vary across 6 km. Economic analysis of pumping at different flow rates is important but has not been considered in this study. Nevertheless, the cost of drilling a well to a depth of 6 km is prohibitively high making such a DBHE uneconomic; the technology is best suited for repurposing already existing wells which offsets the drilling cost.

5. ACKNOWLEDGEMENTS

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