Influence of Mine Geometry and Working Type on Groundwater Flow and Heat Transport for Geothermal Exploitation

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Abstract

The UK Geoenergy Observatory in Glasgow is a unique at-scale research facility to study mine water geothermal and thermal energy storage. In this work we present results from two heat injection experiments performed at two mine levels characterised by different mine workings. The experiments resulted in different thermal breakthrough times, even under similar test conditions. We compare the results and discuss the influence of the mine geometry and working types on the groundwater flow and heat transport processes with support from numerical modelling. This quantification is important to assess the long-term sustainability and potential of flooded mines for geothermal exploitation.

Keywords: Geothermal, UKGEOS Glasgow, Heat transport, Thermal Breakthrough, Mine workings

Introduction

Flooded disused mines have potential to be used for mine water geothermal and thermal energy storage, contributing to the decarbonisation of heating and cooling. Various installations around the world (Walls et al., 2021) have confirmed the potential of these underground resources in the energy transition. These have not, however, been fully deployed, partly because of the uncertainties relevant to post-closure conditions in the subsurface, drilling success and flow output, flow and heat transport processes and potential risk of thermal breakthrough or long-term sustainability of the resource (NE LEP, 2022, Monaghan et al. 2025). In addition, for mine thermal energy storage, there is uncertainty about the extent of the thermally affected volume in both the mine workings and the rock mass as well as its storage and recovery efficiency.

The UK Geoenergy Observatory, in Glasgow (UK) (www.ukgeos.ac.uk) is an at-scale facility to study mine water geothermal energy and thermal energy storage in mines. The facility consists of 12 boreholes (5 of them screened in two levels of mine workings) and a geothermal centre for flexible experimentation (Fig. 1) (Monaghan et al. 2022). The boreholes are equipped with downhole hydrogeological loggers, and those drilled to the depths of the mine workings have installed fibre optic distributed temperature sensing and electrical resistivity cables. The geothermal infrastructure consists of a heat pump / chiller, three different heat exchangers, submersible pumps in two of the mine boreholes screened at two different mine levels (GGA07, screened in the Glasgow Upper, and GGA05 in the Glasgow Main), and reinjection mains in four of the mine working boreholes (GGA01, GGA05, GGA07 and GGA08).

The Observatory can be used to perform heat abstraction or injection experiments with multiple configurations: abstraction-reinjection in the same mine workings (i.e., GGA01 and GGA07 in the Glasgow Upper, and GGA05 and GGA08 in the Glasgow Main) (Fig. 2), or abstracting from one of the mine workings and reinjecting into the other, both in heating or cooling modes. This allows the possibility of performing experiments based on actual supply conditions (for example with seasonal thermal storage). All in all, the Observatory provides data to measure heat transport mechanisms, estimate the hydraulic and thermal properties at real world scale and de-risk mine related energy installations.

In this work we present the results of two in-seam (i.e. abstraction and reinjection in two boreholes screened at the same mine level) heat injection experiments performed at the Glasgow Observatory, one performed in the Glasgow Upper mine workings in 2023 and the other in the Glasgow Main in 2024.

Methods

Mine water reservoir characterisation

Up to seven coal seams were worked in the area between 1805 and 1928. The mine boreholes of the Observatory targeted two of the shallower mine workings: the Glasgow Upper (approx. 50 m bgl, i.e below ground level) and the Glasgow Main (approx. 85 m bgl). Another level of mine workings, the Glasgow Ell (approx. 74 m bgl) was also intersected by the deeper boreholes but these are not screened at this level (Monaghan et al. 2020a).

The extent and distribution of mine workings was interpreted from the available working and mine abandonment plans from 1880s and 1930s obtained from the Mining Remediation Authority (formerly the Coal Authority). Plans were digitised and georeferenced (with some challenges to accurately georeferencing the plans; see Monaghan et al., 2022 for more details). The analysis included the identification of the coal seams, working methods (pillar and stall, shortwall, followed by total extraction), roadways and shafts.

After analysis, the mine was divided in zones (Fig. 1) that were used as reference for the parameterisation of the numerical models. The working method and post-abandonment conditions (backfilled compaction, collapse, pillar spalling, floor lift) define the current distribution and properties that influence the groundwater flow and heat transport. These conditions were defined with support from other methods, including analysis of legacy records, historical mining narratives, analysis of exposed coal sites, and, more directly with the information from the construction of the Observatory that included the drilling of the boreholes, well logging, borehole camera data and initial hydrogeological testing.

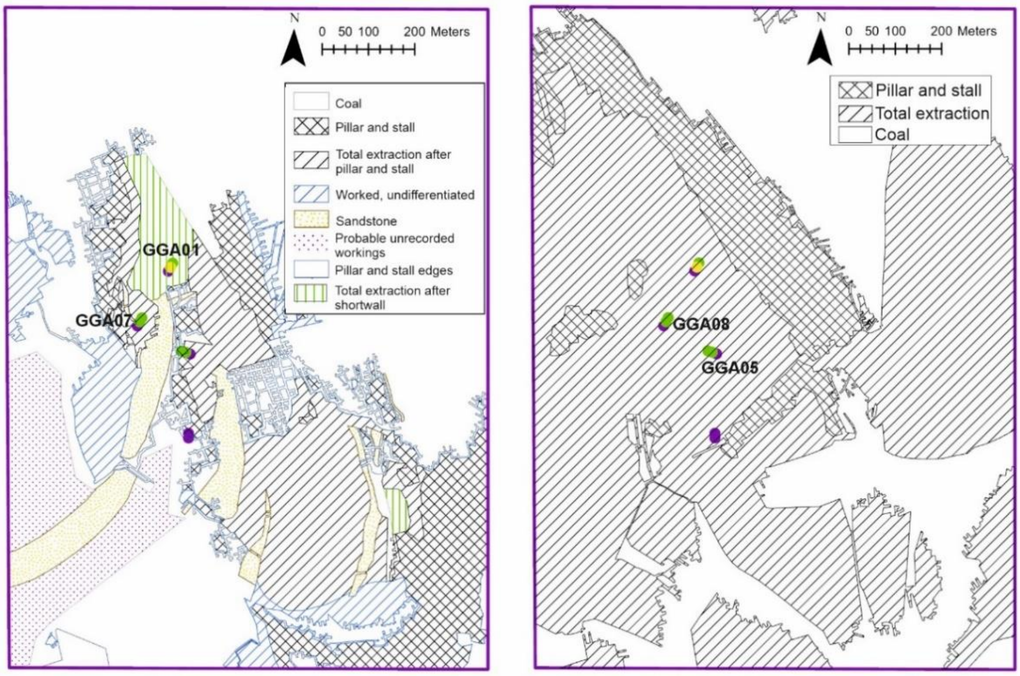

Figure 1 *Zonation of mine workings developed from the mine working plans and the drilling data for the Glasgow Upper (left) and Glasgow Main (right) mine workings. The four sites of Observatory boreholes are shown, with the boreholes used at each heat injection experiment labelled. BGS©UKRI 2025*

At-scale heat injection experiments

Two heat injection experiments in a doublet mode were performed at the Observatory. Two, boreholes GGA07 and GGA05, screened at the Glasgow Upper and Glasgow Main intervals, respectively, and equipped with a submersible pump were used for abstraction, while a different borehole screened across the same mine workings, GGA01 and GGA08, were used for re-injection. The abstracted water was circulated via buried surface pipes and passed through a heat exchanger linked to the heat pump / chiller to increase the water temperature before reinjection (Fig. 2).

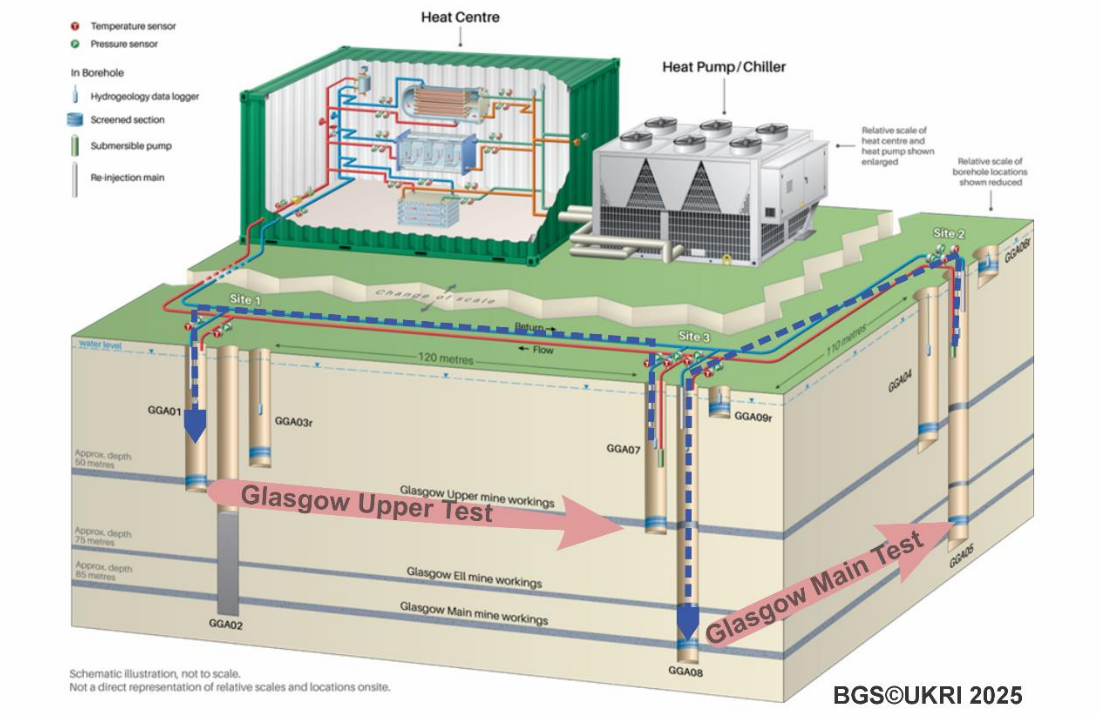

Figure 2 Schematic diagrams of the heat injection tests at the Glasgow Upper and Main mine workings.

The heat injection experiment using the Glasgow Upper mine workings was conducted in September 2023 and had a duration of 17 days (Table 1 for details). The abstraction borehole was GGA07, and the reinjection borehole was GGA01 (Fig. 2), located at about 135 m distance. The average injection temperature was 17.4 °C, although it varied between a maximum of 17.9 °C and a minimum of 16.7 °C, and at two times problems in the heat pump resulted in very short (<5 minutes) cooler injection temperatures that reached 9.6 and 10.1 °C (Fig. 3 - left). Temperatures were measured at the wellhead and the downhole logger located below the reinjection main, both providing near identical readings. The shell and tube heat exchanger was used in this experiment.

Table 1 Experimental conditions in the two tests.

	Glasgow Upper Test	**Glasgow Main Test**
Start date	12/09/2023 11:00	30/08/2024 12:30
Run time	411 h	121 h 48 mins
Abstraction borehole	GGA07	GGA05
Reinjection borehole	GGA01	GGA08
Distance abstraction – reinjection	135 m	119 m
Flow-rate	12 L/s	12 L/s
Initial abstraction T	11.92 °C	12.49 °C
Final abstraction T	12.51 °C	12.93 °C
Average injection T	17.37 °C	16.78 °C
ΔT (initial abstraction T – average reinjection T)	5.45 °C	4.29 °C
Heat exchanger	Shell and Tube	Plate
Thermal breakthrough time (0.1 °C change at abstraction)	116 h (4.8 d)	56 h (2.3 d)

The experiment at the Glasgow Main mine workings started at the end of August 2024 and ran for 5 days. Abstraction was from borehole GGA05, and reinjection at borehole GGA08 (Fig. 2B), located at about 119 m distance. The initial reinjection temperature was 17.2 °C. The average injection temperature was 16.8 °C, but more unstable for the duration of the experiment than in the Glasgow Upper test, with maximum measured T of 17.5 °C and minimum of 15.6 °C. The plate heat exchanger was used in this experiment.

Numerical Modelling

Numerical models of the UKGEOS site were developed using the FEFLOW software. Two different models were used to evaluate each experiment, under the assumption that no connectivity between the Glasgow Upper and Glasgow Main exist (Gonzalez Quiros et al., 2024). The mine working plans and the conceptual hydrogeological model were used to delineate the geometry and implement the boundary conditions. The proposed zonation of mine workings (Fig. 1) was used to delineate zones of parameters for automatic calibration, that was performed using PEST (Doherty, 2018) with the hydraulic heads measured in the Observatory boreholes.

Using this setup, forward heat transport numerical models were simulated with the conditions of the experiment. Thermal properties were assigned to the model using the mine working descriptions. A percentage of materials and voids were assigned based on the zonation, expert knowledge and drilling data. Literature and laboratory values for the lithologies and their percentages were later used to obtain a representative thermal conductivity and volumetric heat capacity at for each zone. The temperature observations at the abstraction boreholes for the duration of the experiment were used as reference.

Results

Experiment Results

Fig. 3 shows the temperature measured at the wellhead sensors of the abstraction and reinjection boreholes during the two experiments. The temperature in the abstraction borehole records the change in temperature related with the arrival of the thermal plume and the timing and character of thermal breakthrough. The temperature change relative to the initial abstraction temperature (ΔT) is shown to facilitate the identification of thermal breakthrough.

In the Glasgow Upper experiment, the initial abstraction temperature at GGA07 was 11.92 °C. The temperature fluctuated in the first 6 h of the experiment (less than 0.1 °C increase), probably because of borehole circulation effects, but stabilised again at 11.92 °C until it started to increase constantly after approximately 3 d (Fig. 3 left). After 4.8 d, the measured temperature increase at the abstraction borehole was more than 0.1 °C and reached a 0.5 °C increase after 14 d, with a maximum of 0.59 °C at the end of the experiment, after 17 days.

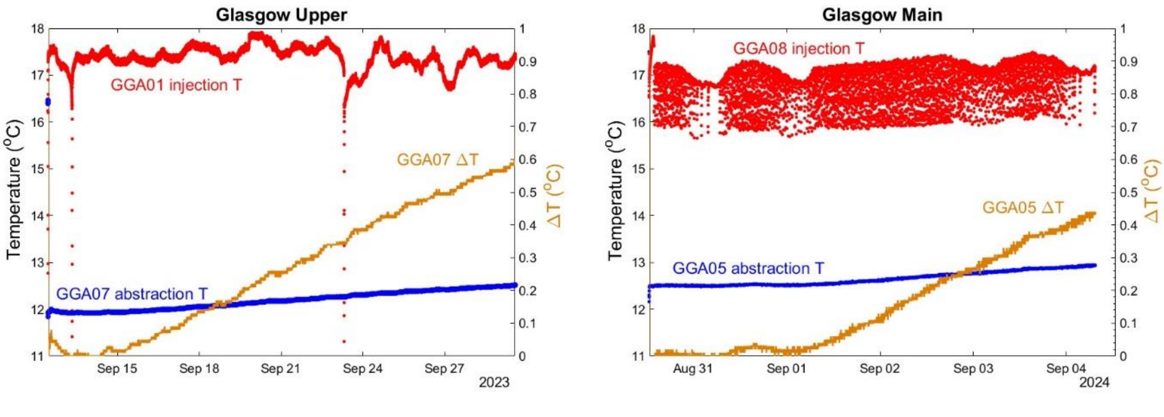

Figure 3 *Abstraction and reinjection temperatures during the Glasgow Upper* ***(left)*** *and Glasgow Main* ***(right)*** *heat injection tests. Experiment duration (x axis) was different. BGS©UKRI 2025*

In the Glasgow Main experiment, the initial abstraction temperature measured at the wellhead was 12.49 °C, suggesting a temperature approximately 0.5 °C higher in the deeper of the Glasgow

Main mine workings compared to the shallower Glasgow Upper mine workings, and reflecting the geothermal gradient in the area. After approximately 2 d the abstraction temperature started to increase, reaching 0.1 °C change after 2.3 d, and a maximum of 0.44 °C at the end of the experiment, after approximately 5 d (Fig. 3 right).

Numerical Modelling

The numerical model was calibrated for the hydraulic properties using the hydraulic heads measured at the boreholes screened in the mine working intervals. The calibration with hydraulic heads from GGA01, GGA04 and GGA07 produced a very good fit (RMSE < 0.03) and resulted in hydraulic conductivity estimates for the areas around the GGA01 and GGA07of $3.2{\times}10^3$ m/d and $3.3{\times}10^3$ m/d, respectively, of similar magnitude to those obtained from the pumping test characterisation (Shorter et al., 2021; Gonzalez Quiros et al., 2024). An example of the distribution of hydraulic conductivities at the Glasgow Upper level is shown in Fig. 4.

Results of the heat transport models resulted in good estimate of the thermal plume arrival times and temperature changes of similar magnitude to those observed in the experiment (an example of results is shown in Fig. 4 right). However, there is still some uncertainty about the combination of parameters to produce the best possible fit. Assigning very high dispersity values resulted in smoother thermal plumes and more attenuated changes, similar to the observations.

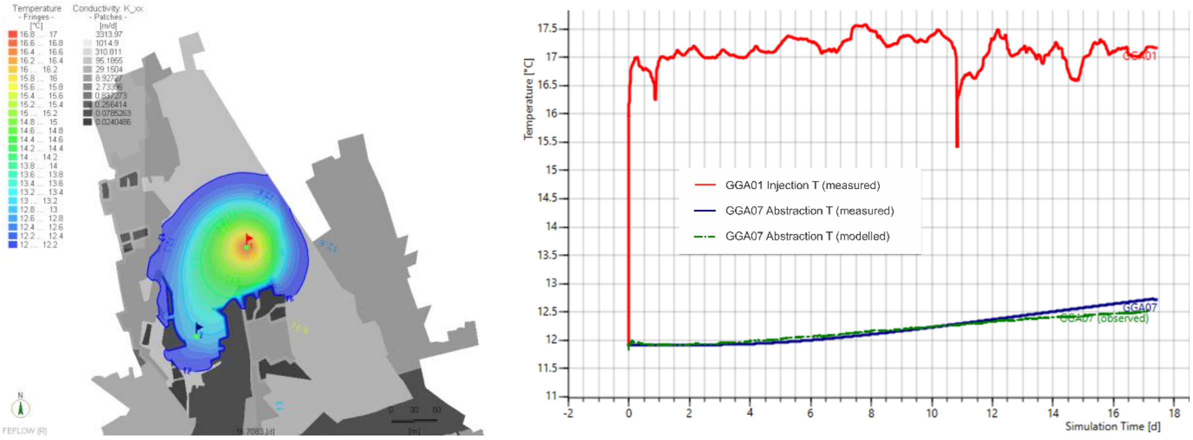

Figure 4 Numerical model results: (left) distribution of temperatures in the Glasgow Upper mine workings at the end of the experiment; and (right) modelled (blue) and observed (green) temperatures in the abstraction borehole. In red injection temperature. BGS©UKRI 2025

Discussion

The time arrival of the thermal breakthrough (considering a temperature change of 0.1 °C) was interpreted in the Glasgow Upper after 4.8 days and in the Glasgow Main after 2.3 days. The longer thermal breakthrough time in the Glasgow Upper mine workings aligns with the interpretation of a greater percentage of backfilled mine workings (Monaghan et al. 2020) and abstraction-injection boreholes located transverse to the direction of former coal pillars, compared to Glasgow Main mine working interpreted to have a greater percentage of open voids. The character of the thermal breakthrough in both cases is small and gradual, as opposed to a single pulse of water that is 5 °C hotter.

The results of the numerical modelling produced good estimates of arrival time of the thermal plume at the abstraction borehole and acceptable temperature variation compared with the observations. This shows that the parameterisation of the mine working heterogeneity is a reasonable approximation and important control on heat processes. However, the differences in modelled temperatures might be a consequence of some processes not being fully represented or not fully representative parameterisation.

Internal heterogeneities (e.g. fractures, open voids, conduits) and the limits of how these can be represented using a zoning and equivalent porous media approach needs to be further investigated. The effect on heat transport (heat loss in the heat injection experiment) of the surrounding rock mass, including the fractured roof, is also uncertain. These and other effects, such as local thermal non equilibrium (LTNE) (Gossler et al., 2020, Heinze, 2024) reported in aquifers at high flow velocities and large grain materials (such conditions are typical of a flooded mine) might result on increasing the effective heat dispersion, while not influencing the advective velocity.

Conclusions

Two heat injection experiments performed at the UK Geoenergy Observatory in Glasgow have revealed the influence of mine working geometry and type in the heat transport processes. Both experiments were conducted under very similar conditions, but thermal breakthrough times were more than twice as long in the mine workings interpreted to have a greater percentage of backfilled mine workings and where boreholes were across the direction of former coal pillars. The results are important to understand the processes of heat transport and assess the long-term sustainability and potential of flooded mines for mine water geothermal and mine thermal energy storage. However, there still remains uncertainty about parameter distribution and magnitude and scale of the thermal processes that requires further research and experimentation.

Acknowledgments

This work has been funded by the EPSRC, United Kingdom grant number EP/V042564/1 Geothermal Energy from Mines and Solar-Geothermal heat (GEMS). An extended version with more detailed results is to be to “Mine Water and the Environment” (IMWA journal).

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