LOw Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure enviromental risks

LOCAL

Research Fund for Coal & Steel

LoCAL Deliverable D4.1

D4.1: Report on benefit/cost and energy efficiency by the use of mixing process studied under task 1.2, WP1

WP number	WP.4
Partner responsible	Alkane Energy

Alkane

HARNESSING RENEWABLE ENERGY

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LoCAL background

This report forms part of the output from the LoCAL (*Low Carbon AfterLife: Sustainable Use of Flooded Coal Mine Voids as a Thermal Energy Source- a Baseline Activity for Minimising Post-Closure Environmental Risks*) project, funded by the European Commission Research Fund for Coal and Steel, grant number RFCR-CT-2014-00001.

The fundamental objective of LoCAL is to provide a number of technical, economic and management tools, aimed at overcoming barriers to the uptake of mine water in abandoned flooded coal mines as a source for heating and cooling (passively, or via the use of heat pumps). The project is divided into five Work Packages (WP) and a number of Tasks.

WP	Task		UoG	Alkane	NTU	UoO	HUNOSA	GIG	Armada
1	1.1	A new tool for heat transfer modelling in flooded mine workings							
	1.2	Quantifying important mixing processes at the system scale							
	1.3	Demonstration of new tools on a system in development							
2	2.1	Preventative strategies for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters							
	2.2	Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment systems.							
3	3.1	Technical, legal and management STEEP/ cost-benefit analysis of various types of decentralised heat pump system, versus centralised plant room system							
	3.2	Pathways to market							
	3.3	Models for incorporating cooling into a delivery system							
	3.4	Ownership, management and financial models							
	3.5	Toolbox assuring multiplication of the project results							
4	4.1	Pilot implementation at Markham site (UK)							
	4.2	Pilot implementation at pilot site in Asturias (ES)							
	4.3	Pilot implementation at pilot site in Bytom (PL)							
5	5.1	Project management							
	5.2	Reporting							
	5.3	Dissemination							

UoG = University of Glasgow (UK), Alkane = Alkane Energy Ltd. (UK), NTU = Nottingham Trent University (UK), a subcontractor to Alkane; UoO = University of Oviedo (Spain), GIG = Central Mining Institute (Poland). Black boxes indicate Task Manager, grey indicate Task Participant.

The LoCAL Project aims at providing bespoke tools for investigating flow and heat transfer in flooded mine workings. New tools for quantifying and modelling heat transfer in networks of flooded mine workings are under development Another aim of the LoCAL project is to overcome the hydrochemical barriers to effective heat transfer from raw and treated mine waters. Ochre clogging is a well-known phenomenon which affects many mine water heating and cooling systems. The LoCAL project covers technical and engineering issues, and provides economic, legal and management models for efficient energy extraction and distribution of various types of decentralised and centralised heat pump.

Project activities are being undertaken in mining areas of the UK by research organizations in partnership with industrial enterprises (University of Glasgow in partnership with Alkane Energy Ltd.), Spain (University of Oviedo, with HUNOSA as the industrial partner) as well as in Poland (Central Mining Institute, in partnership with Armada Development).

This report aims to throw more light on the benefit/cost and energy efficiency from the mixing process. This task links to the Task 1.2 of the WP1.

Main objectives of WP 4:

- To find out how the COP of a system differs with a water level at different heights below the ground surface attending to a flooding process.
- To quantify the mixing process and the effect on the efficiency (COP) in a system with the reinjection of used mine water,
- To find out how the COP of large-scale system differs by the use of different heat exchanger and the economic impact of the WP2, advanced methods for preventing corrosion and incrustation affecting heat transfer.
- To support with real data models for efficiency of energy extraction and distribution analysed on WP3.

The objective of this Report is to fulfil the requirements of Deliverable 4.1 of LoCAL – Report on benefit/cost and energy efficiency by the use of mixing process studied under task 1.2, WP1".

Initially it was proposed to study the mixing process at two sites:

- Markham: where the water is pumped and injected back into the same shaft but at different levels
- Manvers: where the water is pumped and discharged at different levels, but from different seams that were suspected to be hydrologically separate.

Results are available only for Markham site and not from Manvers site, as the permission to drill a borehole at the Manvers site could not be obtained. There has been some of the lessons learnt about the challenges to the implementation, which will be documented in detail as part of Task 3.2 (Pathways to Commercialisation). Following permits were obtained for the Manvers site to drill a borehole:

- Blanket Agreement from the Coal Authority to get exclusive rights to exploit mine water for heating purpose.
- Permit from the local council. For this, the Ecological study report had to be done and submitted along with the application. This pushed the time further.
- Section 32 permit from the Environmental Agency to conduct pump tests. Additional Water Features survey had to be conducted and the report had to be submitted along with application. Again causing further delay
- Supplemental Agreement could not be obtained from the Coal Authority; as a condition was placed on Alkane Energy to surrender the current Coal Mine Methane(CMM) extraction license for the site. This is commercially not feasible, as Alkane Energy's core business is extracting CMM and generating electricity.

However, the entire process has been worthwhile and has provided valuable lessons for future development of Mine Water based Energy System.

Some aspects of the deliverables and related technologies have been covered in Caphouse case study within the National Coal Mining Museum which covers the cost benefits of using an existing mine water pumping station and will be covered in the final report.

For Markham, energy recovered from the CHP engine was mixed with hot water from GSHP to study the cost benefits. More work was done to study the stratification due to mixing of hot water from other sources with the energy from the GSHP. A test rig which was built for other project was utilised to simulate if stratification in a borehole where water is pumped and injected back in the same bore hole can be achieved experimentally. If this is the case, then the technology could be enhanced for the future. For this project a technology developed from a separate project which was designed for Thermal Energy Store using the 'water-snake' technology developed by Gannet Ltd. The market for Gannet Ltd technology is heating and cooling of buildings, but this test provides evidence that the technology could have wider applications. The test rig was an opportunity to simulate and test water mixing in the same tank. The temperature range was intentionally varied to see the stratification in temperature.

Summary of the deliverable

The hydro-chemical tests were carried out on the mine water samples taken at different levels of the water column. It was found that the pumping had not broken down the stratification. The performance of the system was evaluated to check if there is any variation due the stratification in the borehole at Markham, where the water is being pumped and reinjected back into the same shaft at different level. At Mavers the plan was to pump water and discharge it from different seams which are hydrologically separate. This involved drilling a borehole to one of the seams, but the permit to drill was time consuming and could not be obtained. Hence this part of the deliverable could not be completed.

Details of the deliverable

Markham Colliery History and Configuration

Markham Colliery, located just north of Bolsover, Derbyshire, UK, comprises four main shafts. The site (1.3285°W 53.2424°N) ('Burnside, et al., 2016). Three of those shafts were filled and capped. Two shafts (shafts No. 2 and 3) is now on the land occupied Alkane Energy. Since 1904, Markham colliery worked coal from several seams of the Westphalian Lower and Middle Coal Measures strata (Sheppard, 2005). Markham No. 3 shaft is the only one of the shafts that has not been backfilled, following abandonment in 1993. The shaft was brick-lined at 15 feet (4.6 m) diameter and was reportedly c. 490 m deep (HealeyHero, 2016). Shaft no. 1 and 4, with which shaft no. 3 interconnected, reached the Blackshale coal at c. 630 m deep ('Burnside, et al., 2016). Markham colliery is part of a wider network of hydraulically interlinked abandoned collieries, including those at Arkwright (53.2296°N 1.3633°W), Bolsover (53.2350°N 1.3116°W), Duckmanton (53.2447°N 1.3521°W) and Ireland, Staveley (53.2626°N 1.3456°W). Markham No 3 Shaft was left largely open, following abandonment, with a hydraulically open plug at the level of the Ell seam (-357 m asl), to allow venting of mine gas, see Figure 1

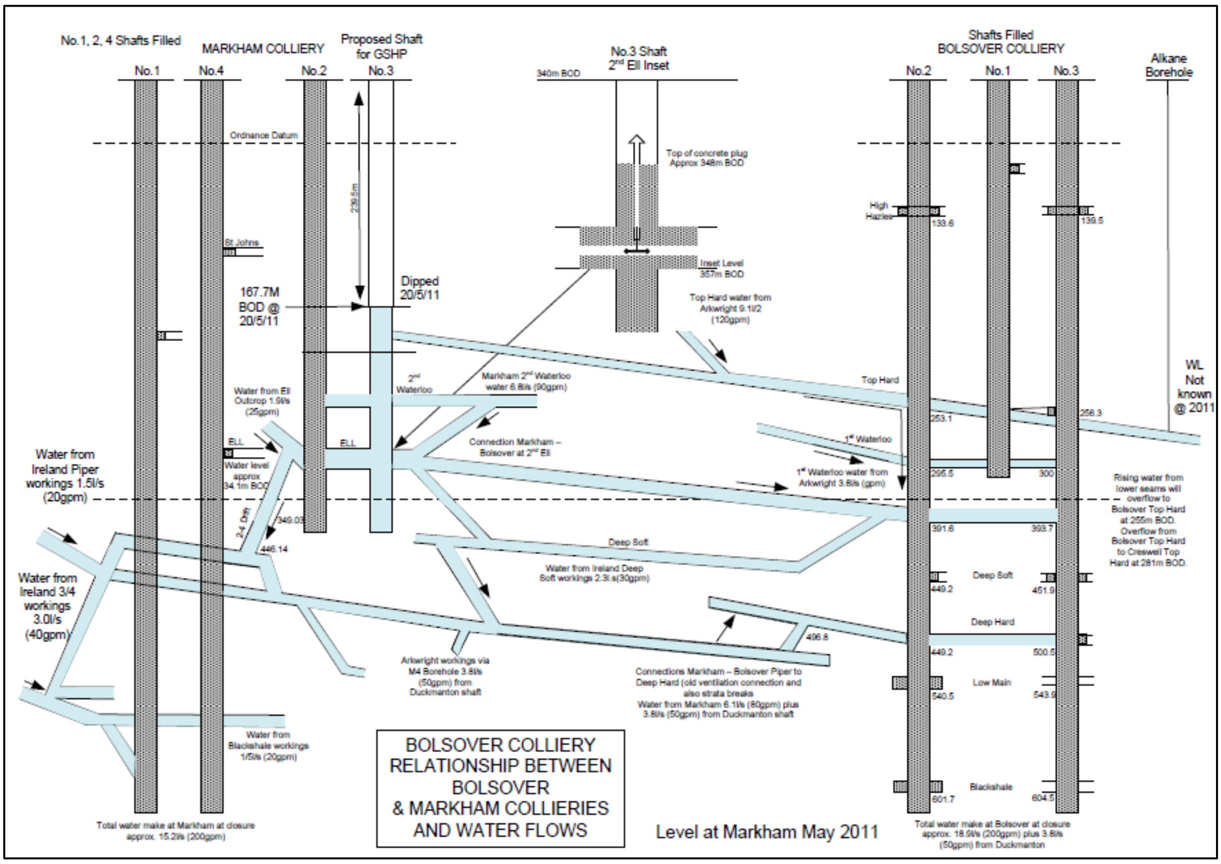


Figure 1: Schematic of the Markham colliery complex

Mine water pumping regime from shaft number 3.

From 2012, water was pumped from 235 m below ground level (bgl) in the shaft at c. 15°C and 2-3 L/s, through shell and tube heat exchangers coupled to a 20 kW heat pump, to supply space heating to Alkane's commercial offices. The thermally spent (cool) water was returned to the same shaft at c. 250 m bgl at around 12°C. In January 2015, taking advantage of rising water levels, the pump was repositioned at 170 m bgl, and the reinjection diffuser at 153 m bgl. See Figure 2

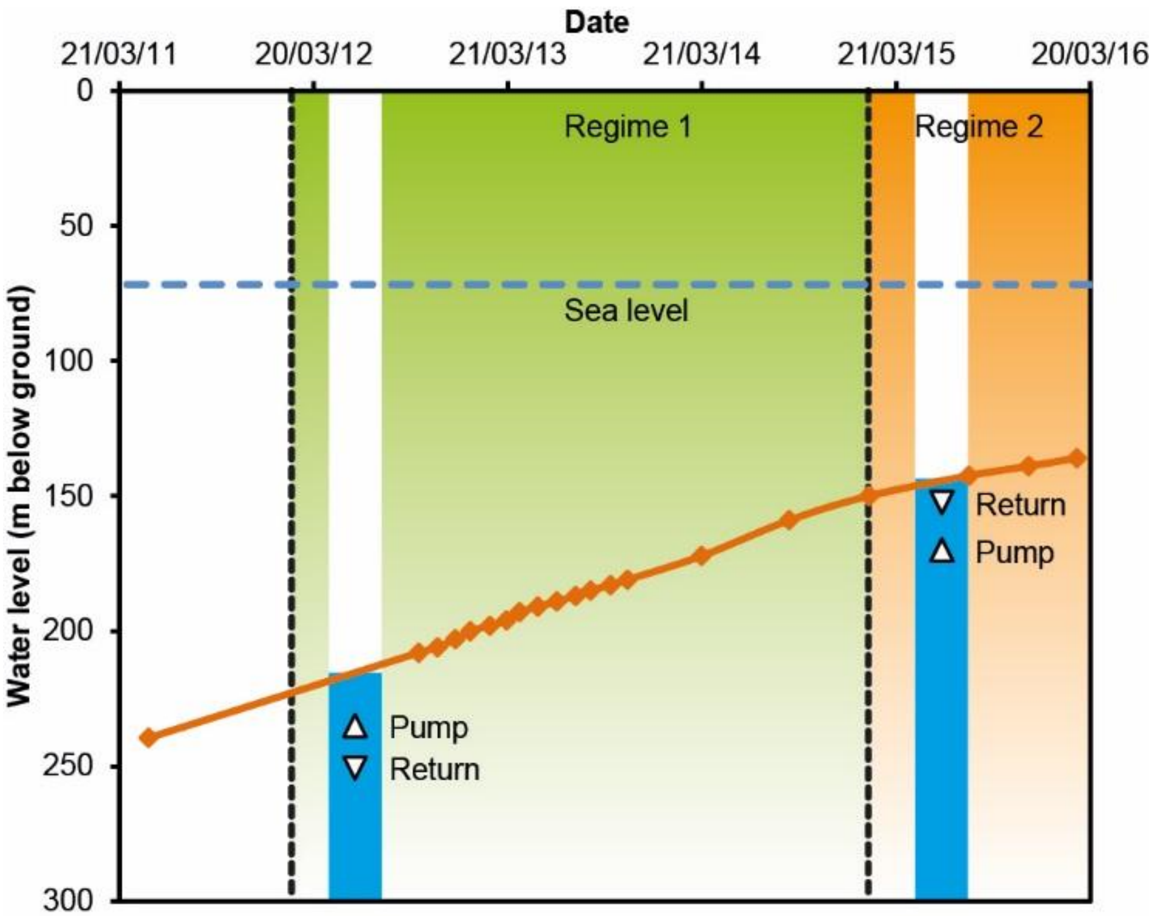


Figure 2: Schematic of the Markham No. 3 Shaft 'standing column' heat extraction arrangement, with rise in water level plotted ('Burnside, et al., 2016)

GSHP pilot plant

A pilot plant of size 20 kW thermal output is installed at Alkane Energy site at Markham. The GSHP is used to heat the control centre and the maintenance depot of Alkane Energy and the site requires heating 24×7. The system is designed to extract warm water from the abandoned mine shaft and inject a slightly colder spent water back into the same shaft, and the heat pump is used to upgrade the low grade heat of mine water into a higher grade heat and utilise this high grade heat to heat the office buildings of the Alkane Energy at Markham. Recently the GSHP was extended to pre-warm one of the standby gas engine as well. The satellite image of the site is as shown in Figure 3.

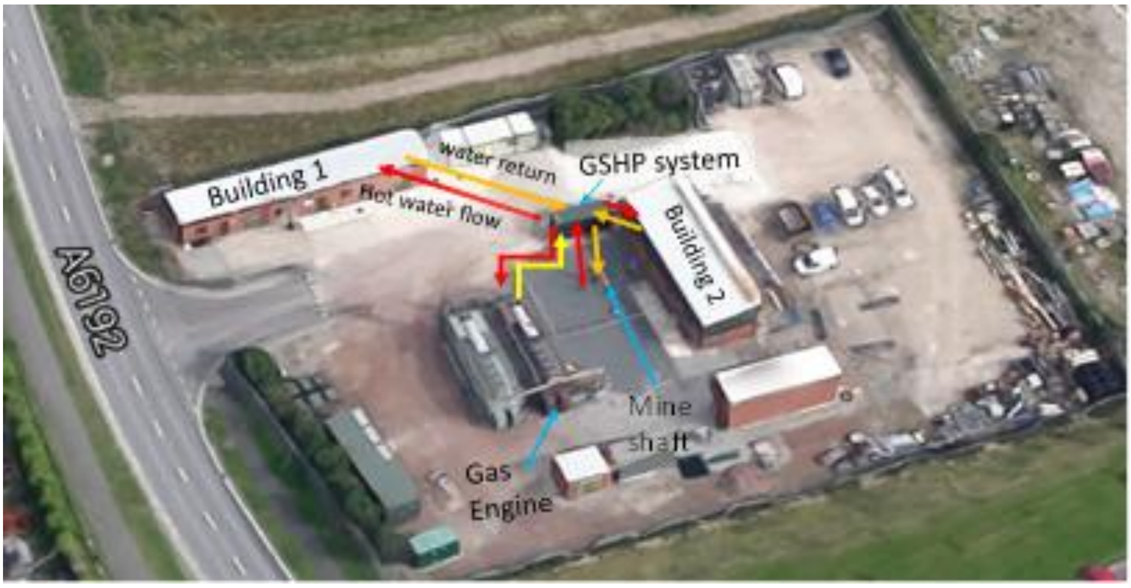


Figure 3: Aerial view of site from google maps.

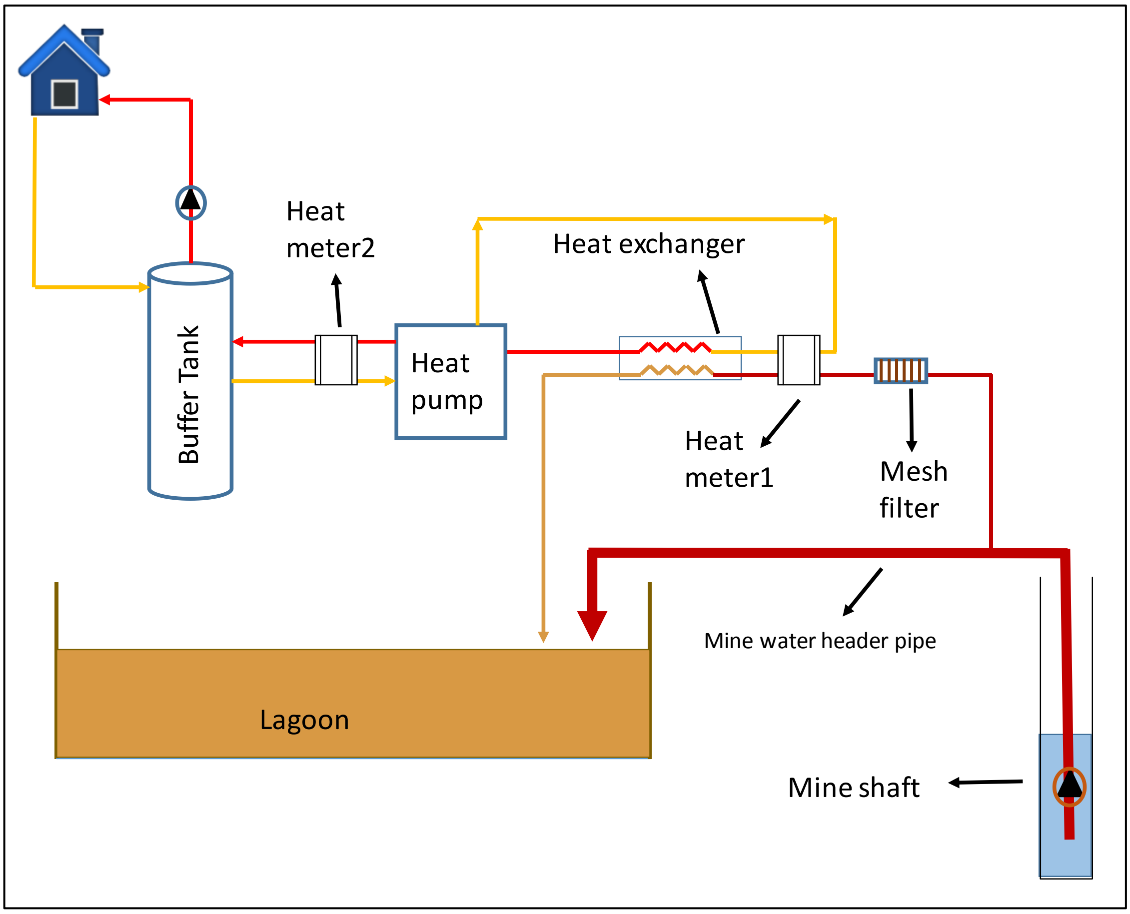


Figure 4: Schematic of the Markham system

Description of the system components

The schematic of the pilot plant is as shown in Figure 4. It consists of a commercial 20 kWth Danfoss heat pump (see Figure 8), two counter flow shell and tube type heat exchangers of 12.5 kW capacity each (see Figure 7), a 300 litre buffer tank (see Figure 8), mesh filter and pipes connecting all the units are fitted in a 20 feet modified container. The container also houses the control panel for the borehole pump. A 11 kW borehole pump, see Figure 9, is installed at a depth of 170m and return diffuser at a depth of 153m below the ground level. Initially the borehole pump was installed at a depth of 235m below the ground level and the diffuser was at a 250m depth. As a safety mechanism, the methane in the mineshaft is monitored and would trip the system if the methane level crosses 1.75 %.. The office building uses three different kinds of emitter systems to heat the buildings, they include wet radiator units, fan coil units and under floor heating systems, see Figure 10.

Figure 5: Mine water flow and return pipe.

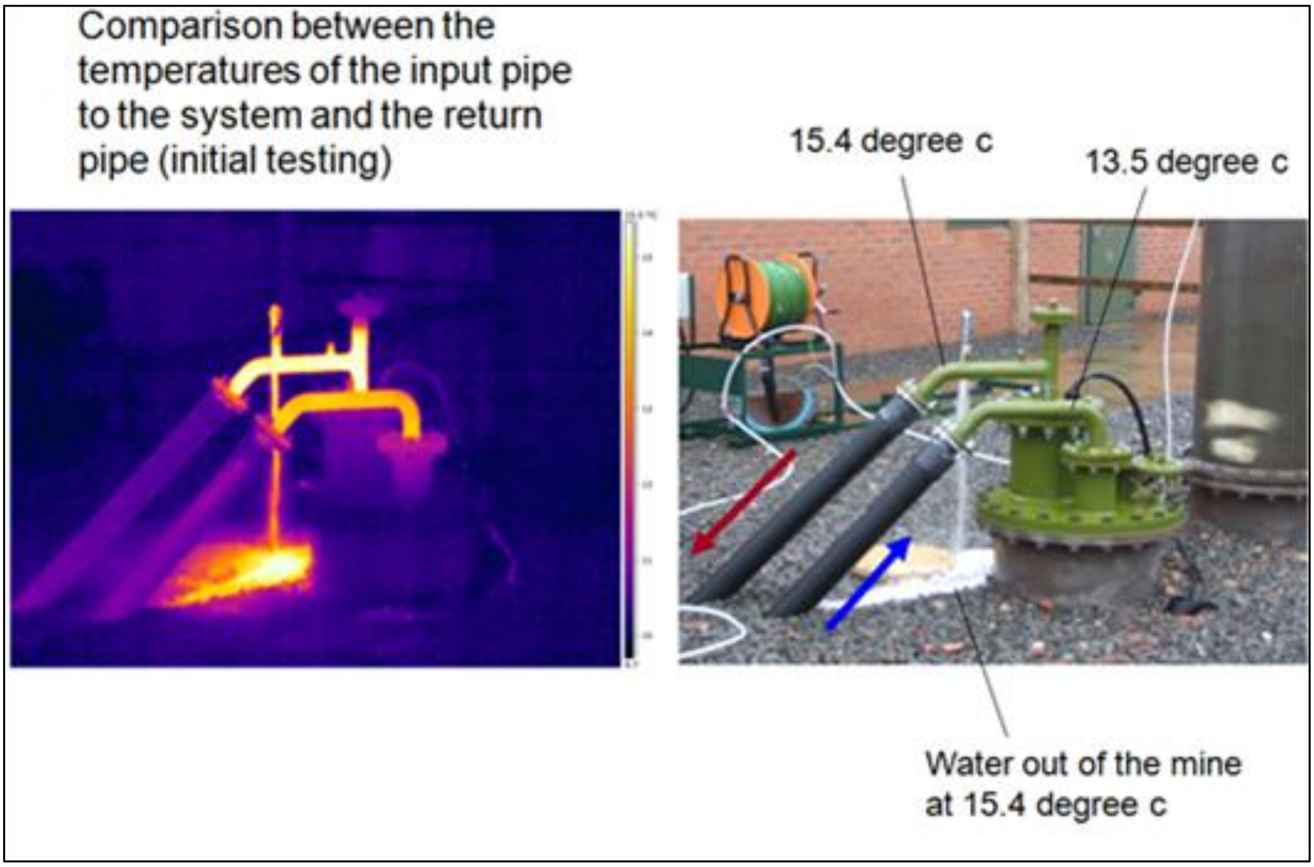


Figure 6: Thermographic image of mine water flow and return.

Figure 7: (a) Filter. (b) Heat exchanger.

Figure 8: (a) Heat pump. (b) Buffer tank.

Figure 9: Borehole pump

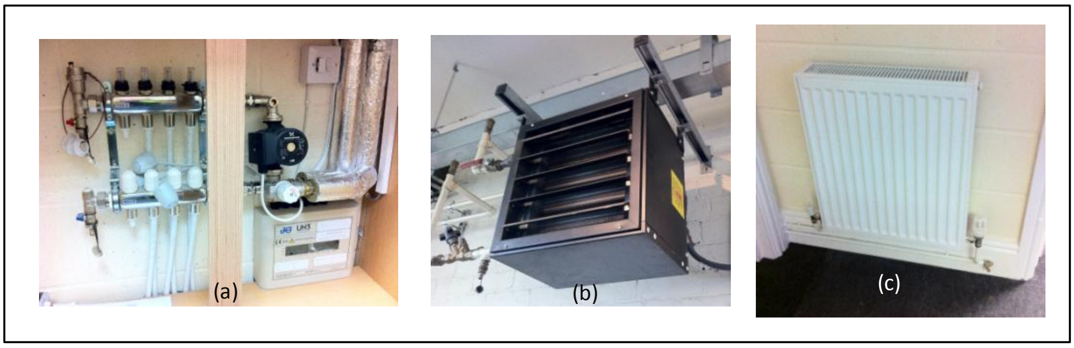


Figure 10: The Emitter systems used to dissipate the heat

Results

Hydrological mixing

As part of monitoring activities, suites of chemical samples had been collected from the pumped water supply. These results allow for comparison with the samples collected throughout the LoCAL project and provide useful insight into variations in water chemistry as shaft water levels have continued to rise and as the pump location has changed.

The water analysis obtained from Markham fall into three broad categories (Figure 10):

- Type A. Samples obtained during the investigative phase in 2011, prior to the installation of the heat pump system, from 250 and 340 m depth.
- Type B. Samples obtained from 2012 up to 28th January 2015, during the trialing and operation of the 'standing column' arrangement at 235-250 m depth (Regime 1 -Figure 2).
- Type C. Samples obtained following 28th January 2015, during the trialing and operation of the 'standing column' arrangement at 153-170 m depth (Regime 2 -Figure 2)..

A clear difference is found between samples from

- Types A & B, which typically represent very saline, ammonium-, methane- and iron-rich water.
- Type C, which represents much less saline, methane- and iron-poor water.

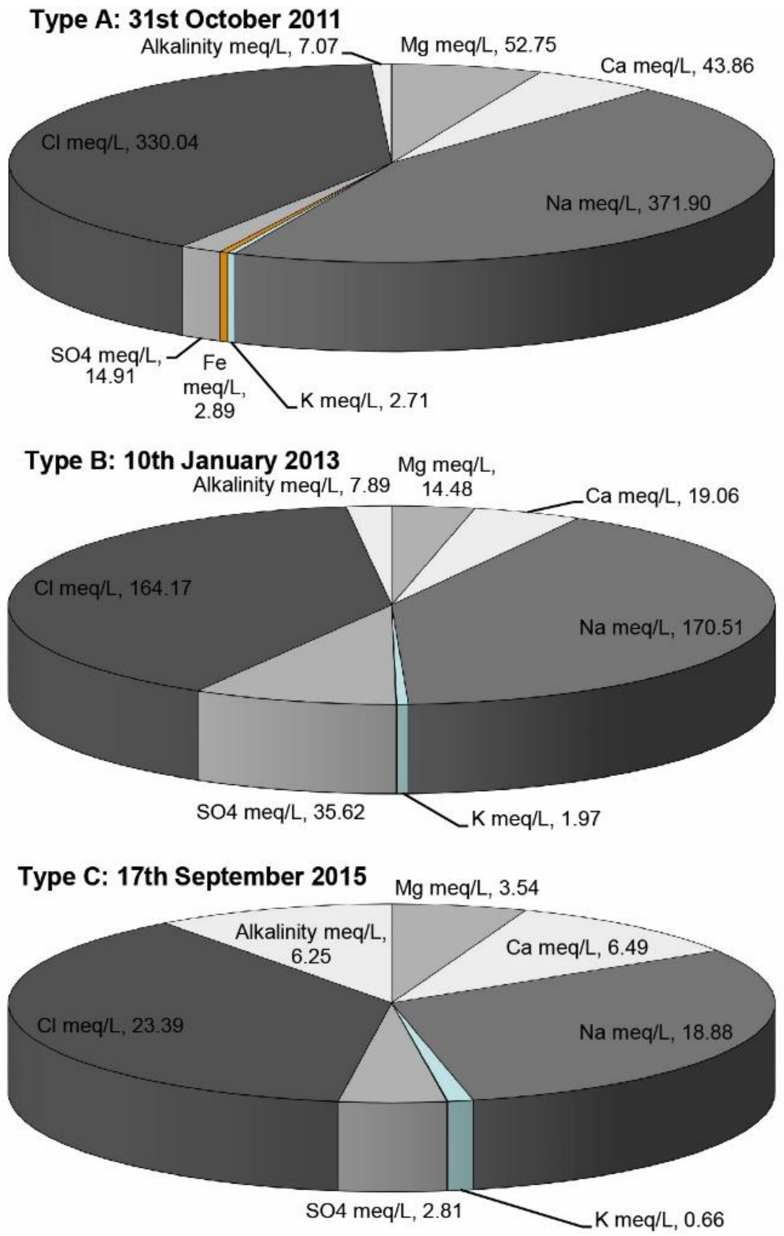


Figure 11: Pie diagrams comparing the major ion (meq/L) composition of the Markham No. 3 Shaft mine water in October 2011 (Type A), January 2013 (Type B) and September 2015 (Type C) (Burnside et al. 2016).

In the case of Markham, water salinity is clearly distinct across each of the three recorded pumping depths (Figure 3), and so represents an important tracer for determination of stratification and flow boundaries within the shaft's water column. Any increase in salinity in during the present LoCAL sampling regime would indicate breakdown of stratification within the water column and upwelling of deeper, saline waters. As this has not been observed we can conclude that the current pumping set-up does not encourage any breakdown of stratification. This observation is supported by stability in water chemistry composition throughout the LoCAL sampling regime at Markham (Figure 13).

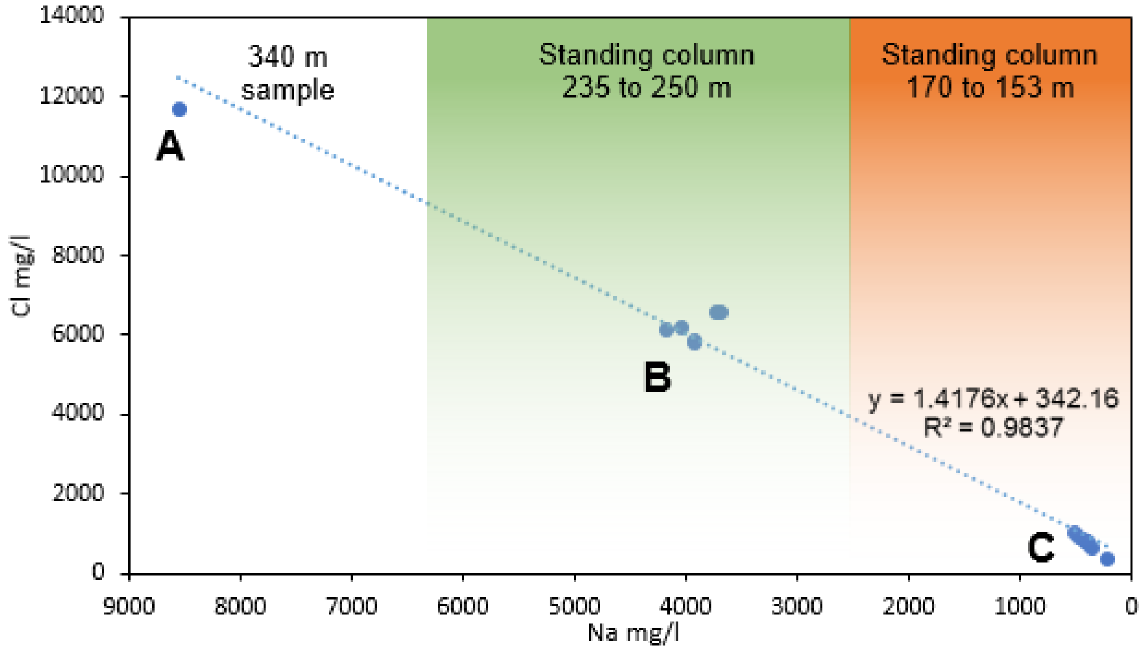


Figure 12: Plot of salinity (Na vs. Cl) evolution throughout alteration of pump depth. Water types labelled as in Figure 11

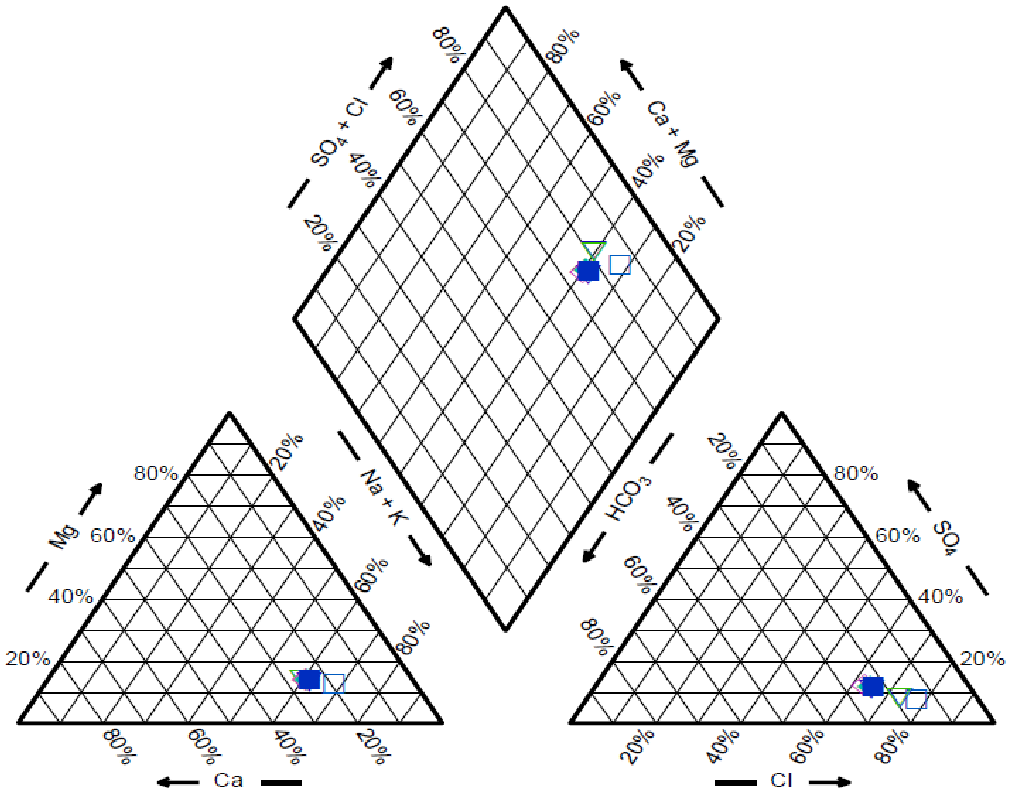


Figure 13: Piper diagram representation of cation and anion sample distribution for Type C waters

The consistency in temperature, 14.1 ± 0.7°C, of pumped waters (170 mbgl) further suggests that the thermally spent cool water (153 mbgl) has minimal influence on extracted waters and may indicate further stratification boundary, or boundaries, between the extraction pump and reinjection diffusor.

Performance of the system due to the rise in water level

At Markham, the water is being extracted and discharged back into the same shaft. The main advantage of this setup, it requires smaller land area and lesser capital cost (almost half) instead of having two boreholes to pump from one and discharge into the other. From Figure 14, the overall COP is rising as the water level rises and since the water is predicted to rise further, the overall COP is expected to get better than the current value.

Coal Authority UK, are responsible for operating the mine water pumping stations in UK to prevent the mine water from discharging into surface water bodies like lakes and rivers and contaminating them. In order minimise the pumping cost, the pumps are supposed to achieve an ideal pumping efficiency of 5 kW/Ml/m (The energy required in kWh to lift a mega litre of water from a depth of 5 meters).

The pumping efficiency at Markham is on a higher side, see Figure 15, even though the power consumption is steadily reducing with the rise in mine water levels. This is because the borehole pump being used is oversized for the current heat load (flow rate).

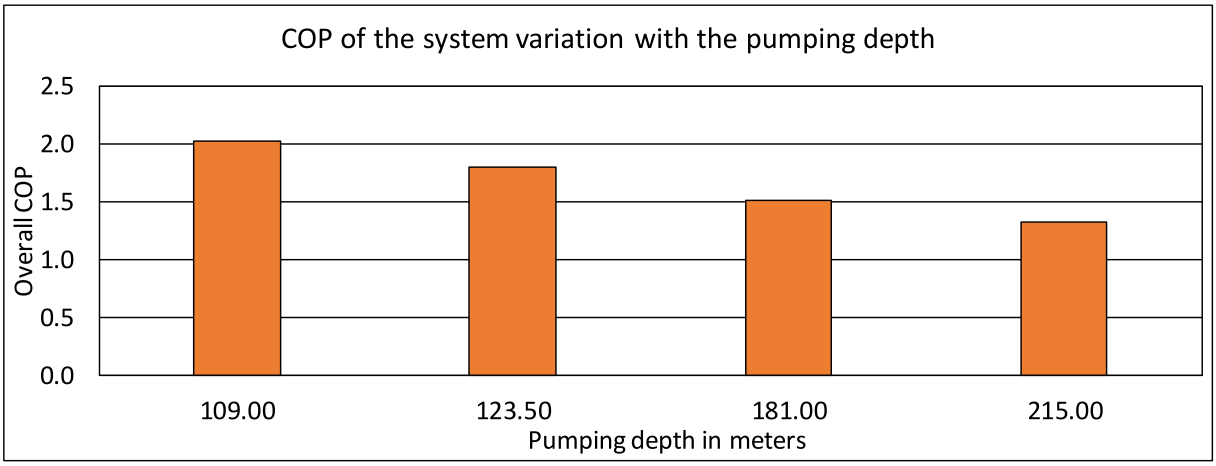


Figure 14: Improvement in the overall COP due to the rising mine water levels

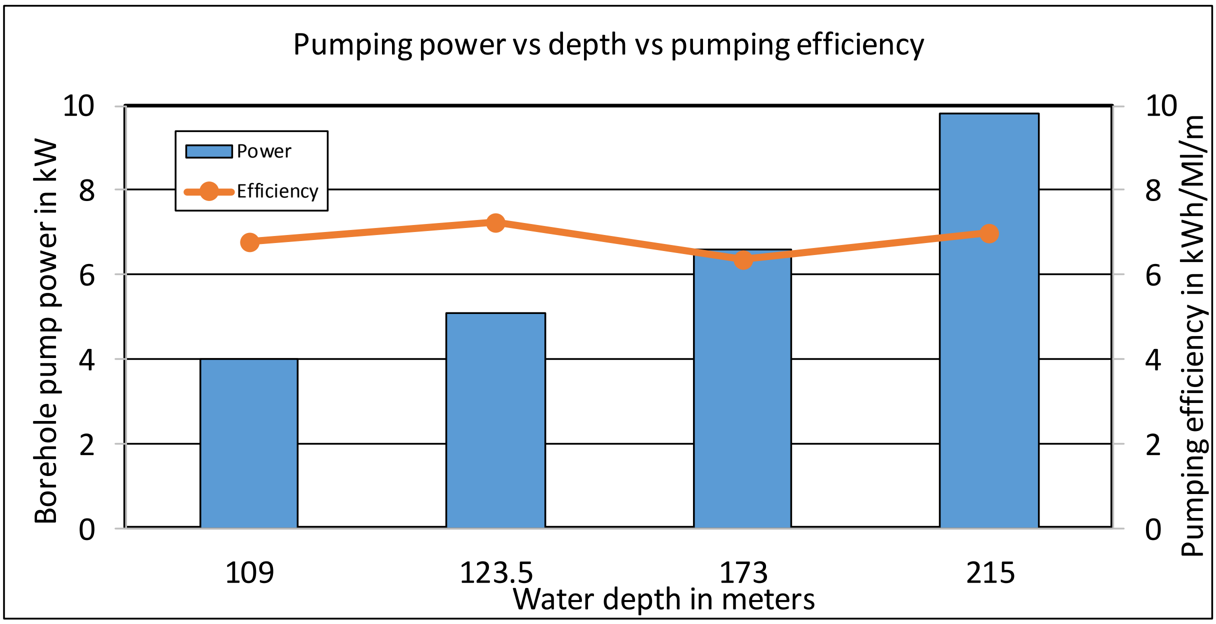


Figure 15: Pumping efficiency graph

Mixing of hot water recovered from CHP

Description of the CHP integration with GSHP is presented below

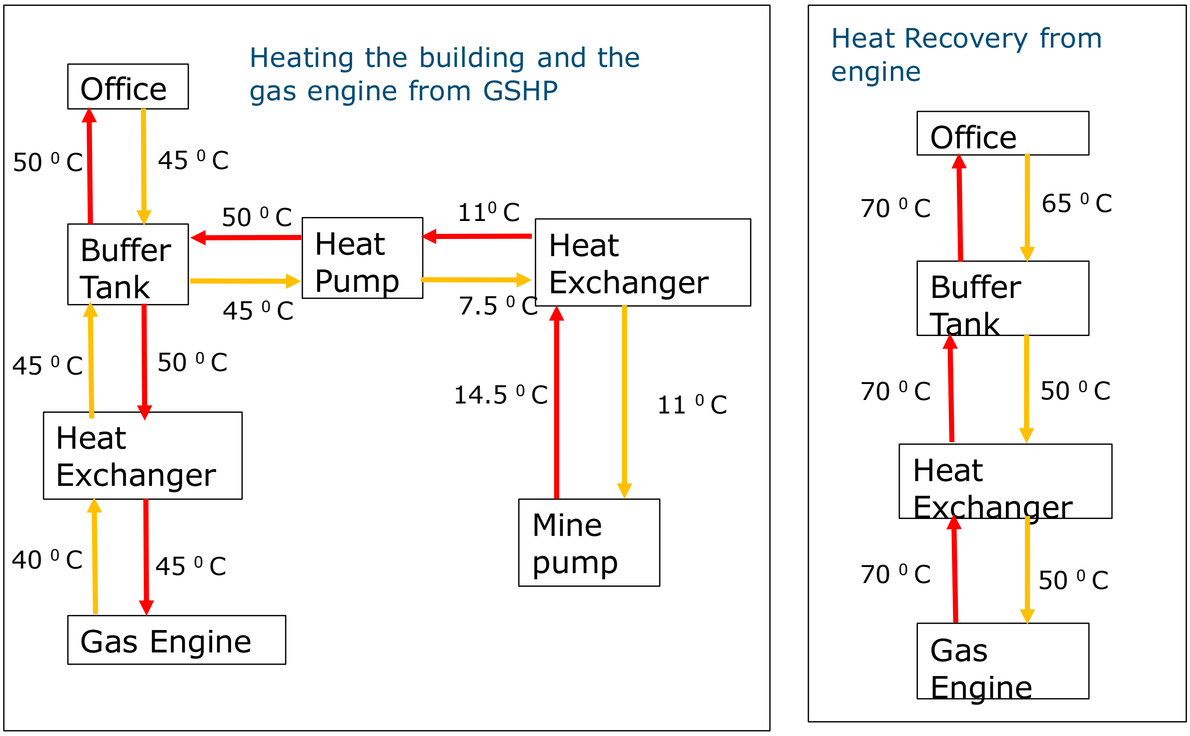


Figure 16: Schematic of the GSHP engine heating.

There are two natural gas engine generators at Markham that are used to generate electricity, as when there is a demand for electricity from National Grid, UK. This kind of generation is known as STOR (Short Term Operating Reserve) (National Grid, 2016). The engines can be pressed into service within a short space of time, in order to do that, the engines are pre warmed in the standby mode. An Electric heater was providing the heating. Recently the GSHP has been extended to provide heating for one of the engine as well. The other benefit is that when the engine is running, the heat from the engine is recovered and stored in the buffer tank and used for space heating, negating the use of GSHP. Using the GSHP by coupling it with a conventional system, increases the overall efficiency. This coupling of GSHP with the engine was not a part of the initial research work and was added later and no experimental work has been carried out, as the engine is run mainly in the evenings of the winter months of November to February, when the demand for the energy is the greatest and there is less day light hours and very little energy is generated by solar.

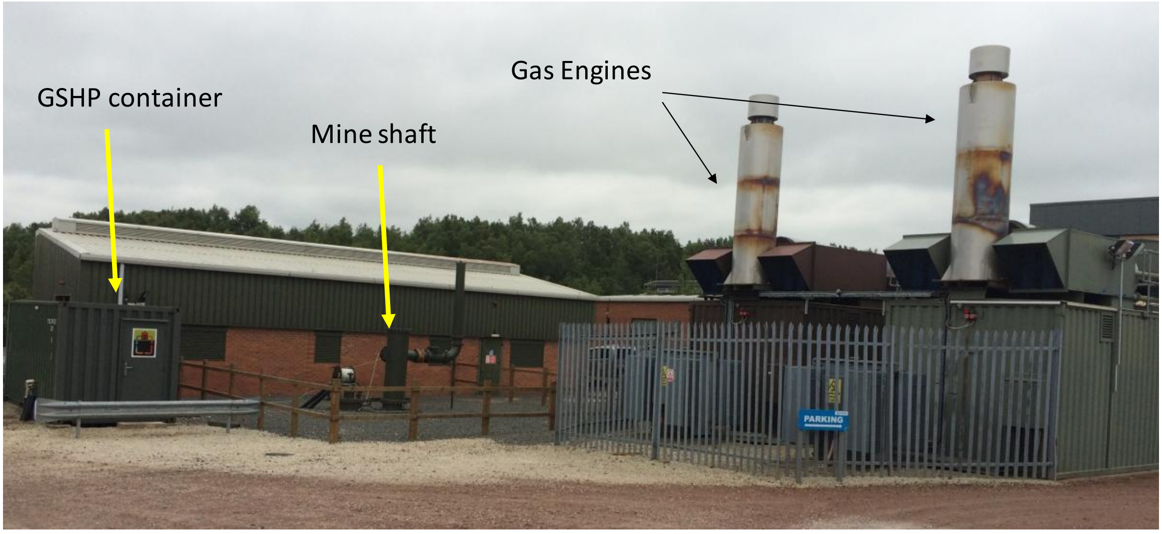
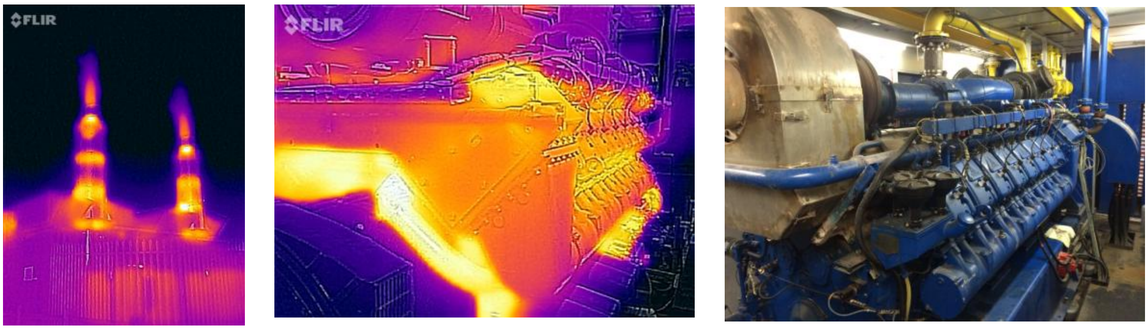


Figure 17: The standby gas generators at Alkane Energy, Markham.



(a) (b) (c)

Figure 18: (a) The thermal image of the engine in operation mode. (b) The thermal image of the engine in standby mode. (c) Normal image of the engine.

The Figure 17 shows the location of the engine, GSHP plant and the mineshaft. Figure 18 shows the thermographic image of the engine in standby mode and the amount of heated that is being chucked out through the engine exhaust when the engines are in operation.

$$COP_{system} = \frac{Q_{HP}}{W_{HP\ electrical} + W_{MP\ electrical}} \qquad (1)$$

The efficiency (COP) of the GSHP system is given by the Equation 1, where Q_{HP} is the thermal energy output given by the heat pump in kJ, $Q_{HP\ electrical}$ and $W_{MP\ electrical}$ are the electrical energy consumed by the heat pump and the borehole pump respectively.

When the engines are in operation, a part of the thermal energy from the engine coolant is recovered and is stored in the buffer tank as hot water and this hot water is circulated around the office blocks to keep them warm. Thus, negating the need to switch on the GSHP.

$$COP_{modified}=\frac{Q_{HP}+Q_{recovered}}{W_{HP\ electrical}+W_{MP\ electrical}} \qquad (2)$$

Equation 2, gives the relation to calculate the improved COP, where $Q_{recovered}$ is the thermal energy recovered from the engine coolant and stored in the buffer tank. $COP_{modified}$ is the improved COP.

$$COP_{modified}>COP_{system} \qquad (3)$$

The details of performance of and possible improvement in the overall COP due to the recovery of heat from the engine coolant will be reported in the final report.

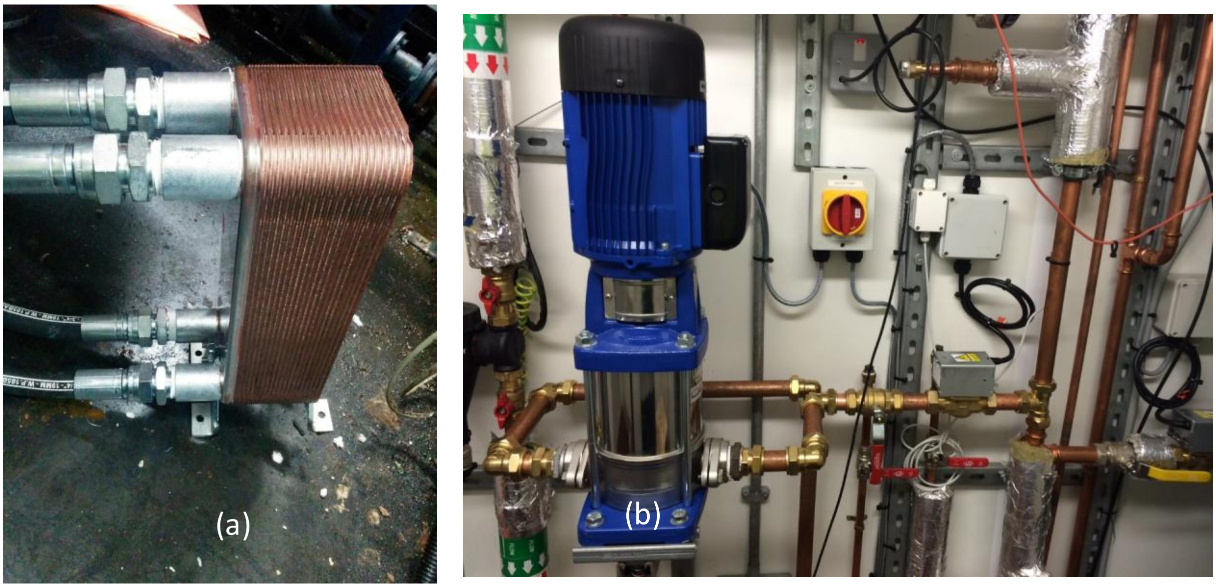


Figure 19: (a) Plate heat exchanger on the engine side to transfer and recovery heat. (b) Circulation pump to circulate heat to the engine.

Figure 20: Pipes being laid to convey hot water from (a) GSHP container (b) Engine

Testing the stratification in a custom built test rig using a Water Snake concept

A Water Snake is used to test stratification in a tank. It is a highly flexible thin walled tube which is fixed and sealed to the feeding line into the vessel. The open end is free to float within the vessel such that it will rise or drop to a position of neutral buoyancy. Thus, the end of the snake will move to the right temperature level equal to the temperature of water flowing in the snake hence reducing any mixing between different temperature levels (Fanshawe, Al-Habaibeh and Shakmak, 2015). Figure 21, outlines the basic principle of the water snake movement inside a thermal tank. The water snake will move to the proper layer of water that its temperature and density identical to the temperature and the density of the supplied water. The water snake is connected to the inlet pipe with its other end left open and free to float within the vessel such that it will rise or drop to a position of neutral buoyancy.

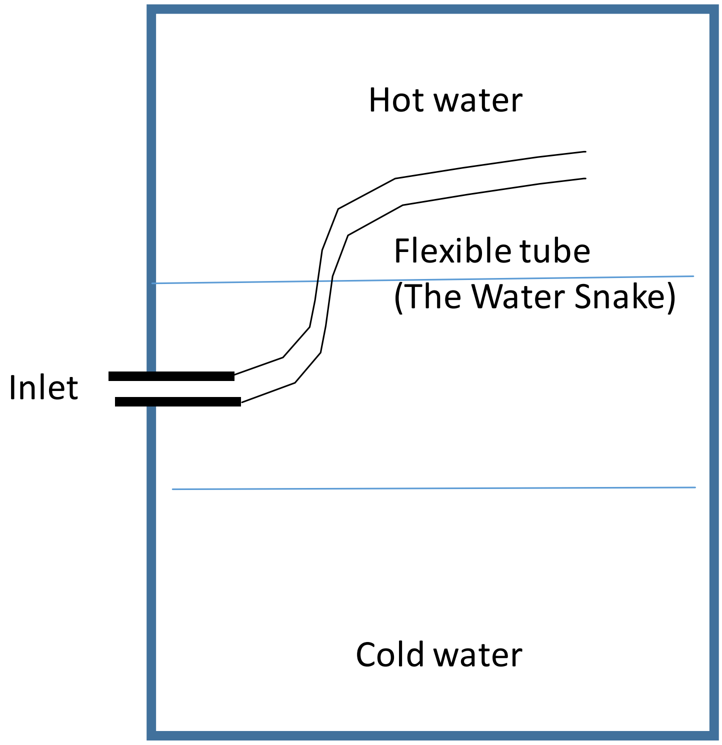


Figure 21: A schematic diagram that shows the movement of the water snake to the proper water layer that match the inlet water temperature.

Figure 22 presents a schematic diagram of the automated experimental test rig developed to evaluate the new technology (Water Snake) for stratified hot water.

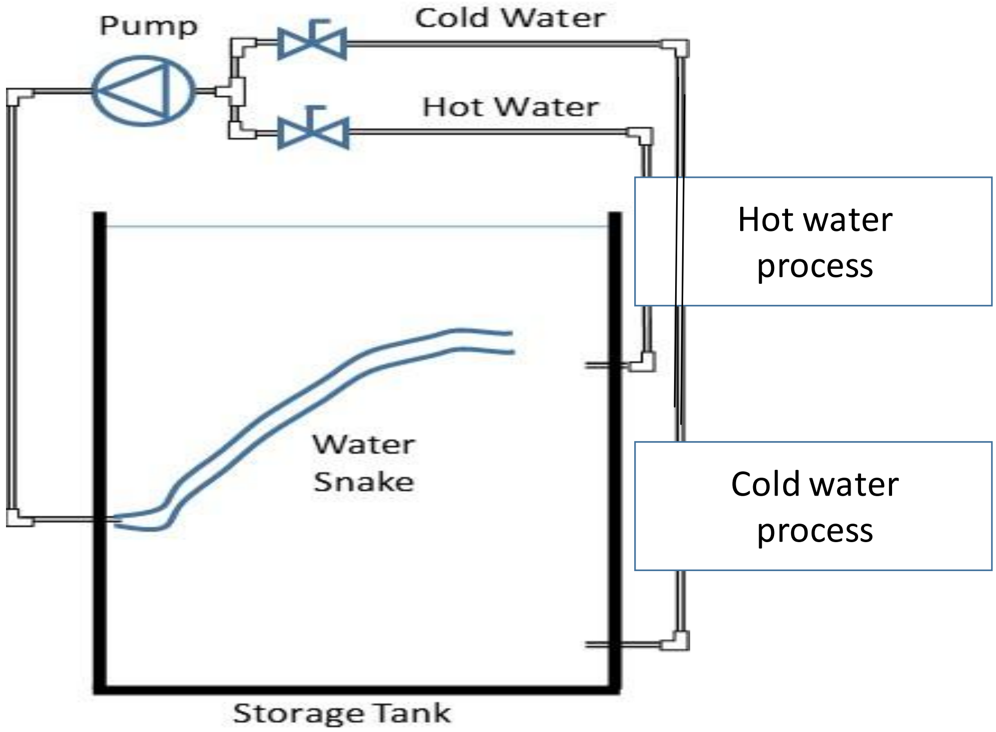


Figure 22: A schematic diagram of the automated experimental test rig.

Evaluation of the stratification process inside the tank is carried out using either density approach or temperature approach. In this paper, for the evaluation of the stratification the temperature approach is used.

Results

Thermal images of the front side of the tank have been taken using FLIR B200 thermal camera. The images showed a clear stratification of the tank after using the water sank. Figure 17 presents one of multiple images taken throughout the experiment. It shows how the tank is fully stratified.

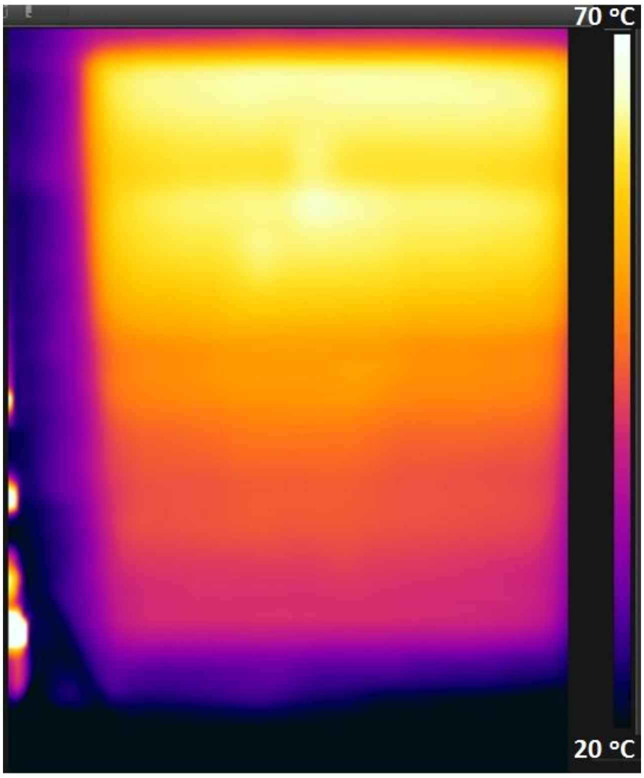


Figure 23: : Infrared thermal image of the fully stratified tank taken after using the water snake.

Conclusions

It is clear from the hydro-chemical analysis of water samples at Markham, that there is no increase in the salinity due to the change in pumping levels. This infers that the pumping of water does not cause any breakdown in stratification levels. Since there is no breakdown of stratification; there is no mixing or any variation in temperature of the mine water, the performance of the system remains unaffected.

By mixing hot water from different technologies; a significant cost benefits can be obtained due to an increase in the overall efficiency of the system. This shows the way forward for alternate energy sources to replace the conventional energy sources without significantly affecting the reliability or stability. The lab based testing also confirm that when there is pumping and discharge at different levels within the same shaft; no breakdown in stratification is observed.

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- Banks D, Athresh A, Al-Habaibeh A and Burnside N (in prep) Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. Provisionally accepted for publication in *Journal of Sustainable Water Resources Management.*

Accepted papers

- Athresh A.P., Al-Habaibeh A. and Parker, K., An innovative and integrated approach for using energy from the flooded coal mines for pre-warming of a gas engine in standby mode using GSHP. Energy Procedia.
- Al-Habaibeh A., Athresh A.P. and Parker, K Performance analysis of using mine water from an abandoned coal mine for heating of buildings using an open loop based single shaft GSHP system. Applied Energy

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List of figures