The Design and Evaluation of an Open Loop Ground Source Heat Pump Operating in an Ochre-Rich Coal Mine Water Environment

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Abstract

Mine water from the abandoned coal mines is considered a good source of low enthalpy energy resource as the temperature of the mine water remains stable throughout the year and is suitable to be used for heating and cooling applications when implemented in conjunction with Ground Source Heat Pump (GSHP). The GSHP is considered to be a low carbon technology and its application for space heating and cooling is being actively investigated and developed by companies and local councils around the world. The open loop GSHP installations, in comparison to closed loop systems, are suitable and economical for large scale heating and cooling demands. This is because there is no time delay for heat transfer when compared with closed loop systems and because they use large volumes of coal mine water at a relatively constant temperatures. A few installations both large and small scale open loop mine water heating and cooling systems have been recently constructed throughout the world. However, coal mine water is associated with relatively poor water quality in some cases, often characterised by high salinity and pyrite oxidation. Despite the fact that mine water temperatures are favourably inclined for an efficient GSHP operations, concerns have been raised over the possibility of damage to the equipment due to poor water quality caused by clogging of the heat exchangers due to pyrite oxidation (ochre) in particular. Not much information is available on the impact of ochre has on the performance of an open loop GSHP when it is operated using the coal mine water rich in pyrite. This paper presents a novel design and implementation of an open loop system of GSHP operating in an ochre rich mine water environment. The results show that open loop systems, when combined with suitable heat pump and the associated design configurations of heat exchangers and maintenance procedures, could provide an efficient and reliable heating system at a lower cost.

Keyword: Sustainability, Green energy, Coal Mines, Open Loop GSHP, Mine water, Heat pump, Iron Ochre, Condition Based Maintenance (CBM).

1. Introduction

The National Coal Mining Museum (NCM) for England, see Figure 1, is on the site of former Caphouse Colliery which is located in Overton, near Wakefield, Yorkshire in the UK at 53.6416 ^{0} N 1.6251^0 W with site elevation of about +147 m asl. As shown in Figure 1, the Caphouse Colliery complex is underlain by Lower Coal Measures in the west and the Middle Coal Measures in the east. The strata consist of cyclical fluvio-deltaic sequences of interbedded sandstone, siltstone, mudstones, coal and associated seatearth, the regional geology dips at an average angle of 3-5^0 in south west direction (INWATCO, 2005a; Burnside et al., 2016). Caphouse Colliery complex was interconnected to other collieries in the area including the Denby Grange Colliery (53.6340^0 N 1.5942^0 W) and Woolley Colliery (53.5961^0 N 1.5338^0 W), see for example INWATCO (2005a) and INWATCO (2005b). The Flockton Thick, Flockton Thin, First Brown Metal, Old Hards, Third Brown Metal, Green Lane, New Hards, Wheatley Lime/Old Man, Blocking and Beeston coal seams have been exploited at the Caphouse Colliery complex (Brown and Goodchild, 1979; Wilcockson, 1950). The coal mines in this region of Yorkshire and Nottinghamshire has an average sulphur content of about 2.13% (Spears and Tewalt, 2009). The Caphouse Colliery was sunk in the year 1780 (Faull, 2011) and the Hope pit was opened in 1830 (Schofield, 2003; Goodchild, 1983). The Colliery complex was closed in 1985 and the museum was opened in 1988 where the underground galleries were opened to public. In order to keep the underground galleries dry and safe, the water was pumped from the pit and discharged into river Calder, the pumping continued till 1993. The pumping of water of the resumed in the year 1996, when the water level started to rise due to a loss of hydraulic connectivity (perhaps due to a collapse of a road way) with neighbouring Woolley shaft (Faull, 2011)

Mine water in abandoned coal mines, such as Caphouse Colliery, can be considered as a good source of low grade geothermal energy, owing to their stable temperature throughout the year and huge volumes of water which are contained in the underground voids and inter-connected roadways stretching long distances. The temperatures of the mine water at a depth of 100 m in UK is circa 13 – 14 ^{o}C (Banks et al., 2004). For air conditioning applications coal mine water could be used directly. However, this level of temperature can be considered too low to be used directly for heating applications. To achieve this, the use of heat pumps enables the temperature to be upgraded for space heating, allowing the temperature to reach low to mid 50 ^{o}C. The heat pump converts the low grade energy into a high grade energy. The majority of the abandoned coal mines lie close to or within former mining towns and villages which are now being developed as industrial buildings or residential housing, creating large heating and cooling needs with the possibility of the implementation of district heating networks. The potential of the coal mine water as a sustainable source of energy for space heating and cooling is enormous, however, till 2013 less than 20 installations were documented (Preene and Younger, 2014).

A detailed theoretical description of the heat pump regarding the working, types and configuration has been mentioned in Athresh et al. (2015), Banks et al. (2004), Omer (2008), Watzlaf and Ackman (2006) and Banks (2012). Al-Habaibeh et al. (2015) have identified the need for technology training and have developed a novel simulator for teaching the technology. The recent advances in the heat pump technology has been described in detail in Chua et al. (2010). The models to estimate the amount of thermal energy that can be recovered of mine water in the underground galleries has been described by several authors including Rodríguez and Díaz (2009), Madiseh et al. (2012), and Andrés et al. (2015). The details of mine water based heating and cooling installations throughout the world has been described by Hall et al. (2011), Ramos et al. (2015) and Preene and Younger (2014). A successful small scale heating system in Markham Vale in the UK has been described by Athresh et al. (2015). A pilot mine water heating and cooling scheme has been successfully implemented in the Dutch town of Herleen and the details of this scheme has been described in Roijen et al. (2007). Following the success of the pilot scheme, the scheme was upgraded to a full scale sustainable energy system and this has been documented in Verhoeven et al. (2014). The scheme at Herleen requires a special mention as it shows how a former mining town facing a social and economic crisis following the closure of the mines has successfully managed to transform itself using the mine water heating and cooling scheme to a sustainable town. Herleen project has shown the way forward to other mining towns around the world still struggling with lack of energy resources and closure of mines.

The open loop based GSHP systems perform much better than closed loop systems when there is a large energy demand requirements, as it eliminates the time needed for heat transfer to take place between the fluid in the closed loop and the external environment. However in open loop systems, the equipment will be exposed directly to the minerals in the mine water and this increases the possibility of a potential damage to the equipment, especially when the system is installed in an ochre rich environment (Banks et al., 2009). Currently limited research has been done in relation to the design and implementation of such systems in ochre rich water systems, particularly the impact of ochre clogging on the equipment and the performance of the system. By means of pilot plant this research work aims to characterise the performance of the system and also find a suitable maintenance regime to overcome this problem.

This paper presents a systems that uses a prophylactic shell and tube heat exchanger to prevent the mine water from coming in direct contact with the heat pump. This is done by transferring the thermal energy from the mine water to an intermediary brine solution in the heat exchanger. A shell and tube heat exchanger is employed instead of the more common plate heat exchanger, as it is easier to clean for maintenance applications. In addition, a novel implementation of alternating use of two heat exchangers and filters, i.e. a second heat exchanger and a filter will always be on standby if maintenance is needed, thereby guaranteeing a continuous operation of the whole system.

2. The Implemented GSHP System Location

Caphouse colliery, where the system has been implemented, is now a part of the National Coal mining museum for England (NCM, 2015), where part of the underground galleries have now been converted into a museum and is open to the public. The underground galleries has to be kept dry and safe for the visiting public and for this reason dewatering pumps are employed to pump out the water. Unfortunately, the energy from this relatively warm water was not utilised efficiently despite the need for significant heating demands for the buildings of the museum. The mine water in that location has an iron content of circa 15 mg/l (Burnside et al., 2016) and is partially oxidised in the pumping shaft. The pumped water is ochre rich and undergoes passive treatment using several settling tanks and reed beds to remove the ochre before discharging it into a water stream. Figure 1 presents a Google satellite image of the water treatment tanks where the orange colour due to ochre is clearly visible.

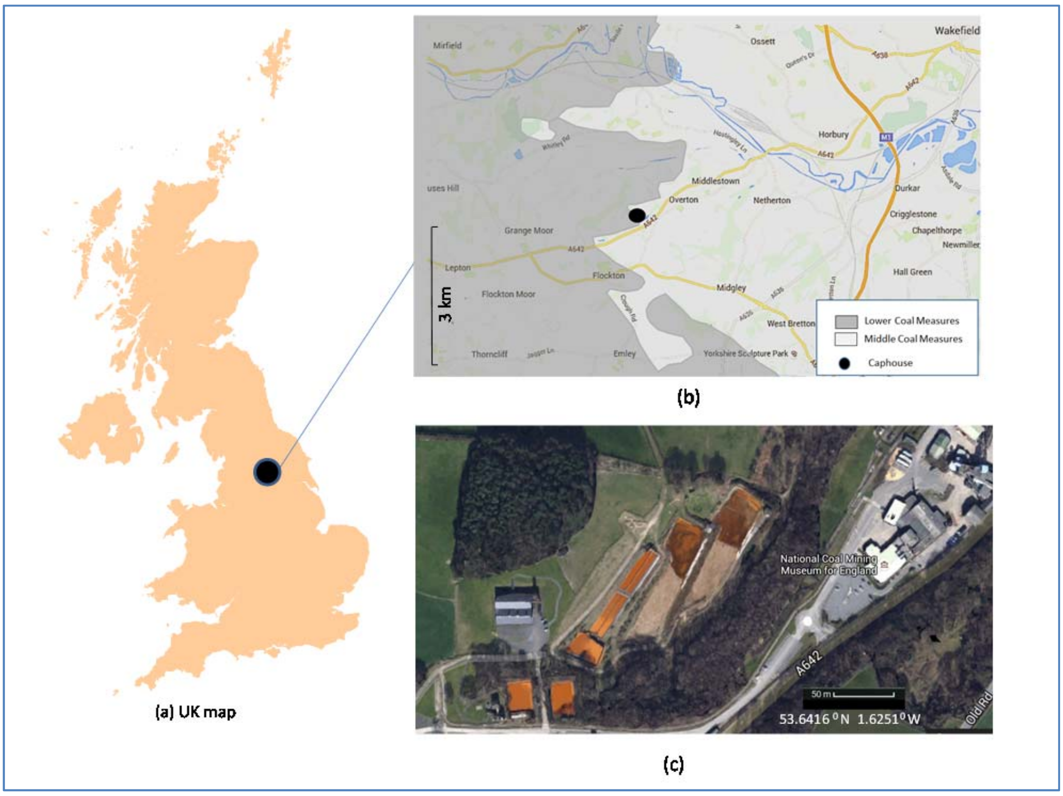

Figure 1: UK map indicating the location of Caphouse Colliery (a), Caphouse Colliery coal measures map completed using BGS bedrock geology (1:625,000) and Google map (b) and a Satellite image where the current mine water treatment lagoons appear in orange colour (Source: Google Earth) (c).

3. Plant description

The implemented GSHP system consists of a single 10.5 kW commercial Vaillant heat pump, two sets of prophylactic shell and tube type heat exchangers. The two heat exchangers are implemented in alternating way during operation to allow for maintenance where one will always be on standby. A mesh filter is also used to provide initial filtration before the heat pump. The filter unit also includes two alternating separate filters to allow easy maintenance similar to the heat exchanges. A 300 litres buffer tank is used to allow stable operation of the heat pump during fluctuation in heating demands. The heat from the system is used for heating the old Inman shaft building which is currently used as an exhibition space at the museum. In order to keep the mining museum galleries dry, water needs to be pumped daily, at a flow rate of circa 30 l/s. During the winter months, water is pumped 24 hours a day and in summer months the water is pumped for circa 15 hours a day. A small amount of mine water is tapped from the main pumping header line and used in the pilot plant and later injected back to the mine water treatment lagoon. Figure 2 presents a satellite image of the location and a schematic diagram of the pilot plant system. Figure 3 presents further details of the components of the system, where Figure 3-a presents the Inman building, Figure 3-b presents the first lagoon where the water from the coal mine is first exhausted to, Figure 3-c presents the location of the container that includes the system and Figure 3-d presents part of the container and the main two header pipes through which the mine water is pumped to the treatment lagoons.

Figure 2: A Google Satellite image of the location with a schematic diagram of the implementation of the system.

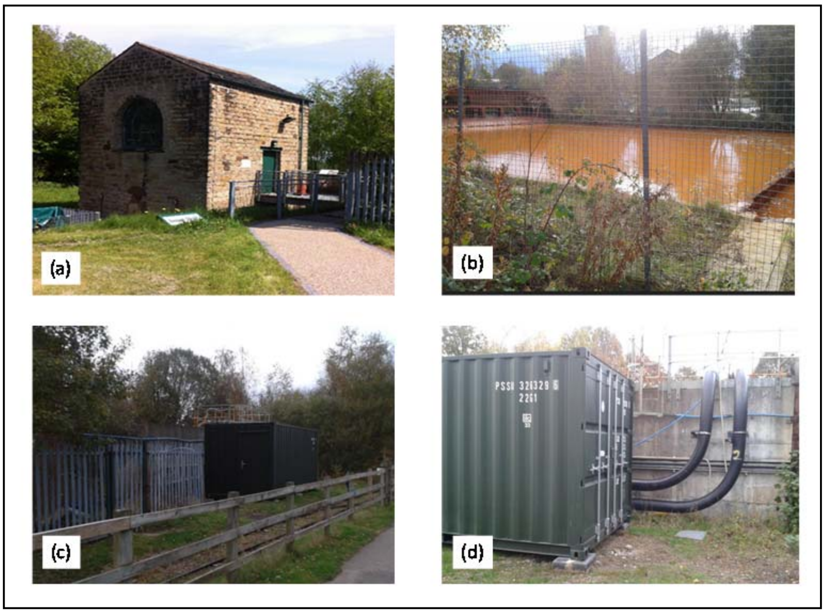

Figure 3: Main components of the system, Inman shaft building heated by the heat pump (a), the lagoon (b), plant housing container (c) and the container with the main two pipes that pump the water from the coal mine (d).

When considering the structure of the system, Figure 4 presents a schematic diagram of the system. As described, the water is pumped from the coal mine to prevent flooding. The water is transferred to lagoons where it is treated by allowing the suspended iron oxide to precipitate, hence cleaning the water for the local water streams. The system tap into the header pipes without the need for an additional pump and the water is circulated via mesh filtering before passing to the heat exchanger and released to the lagoon. A heat pump is used to extract the energy through an isolated system using the heat exchanger and then the extracted heat is used to heat the water in a hot water buffer tank. The rest of the system works as a classical heating system where the hot water in the buffer tank is pumped via an additional standard water pump to the building. Standard radiators are used for the purpose of heating the building.

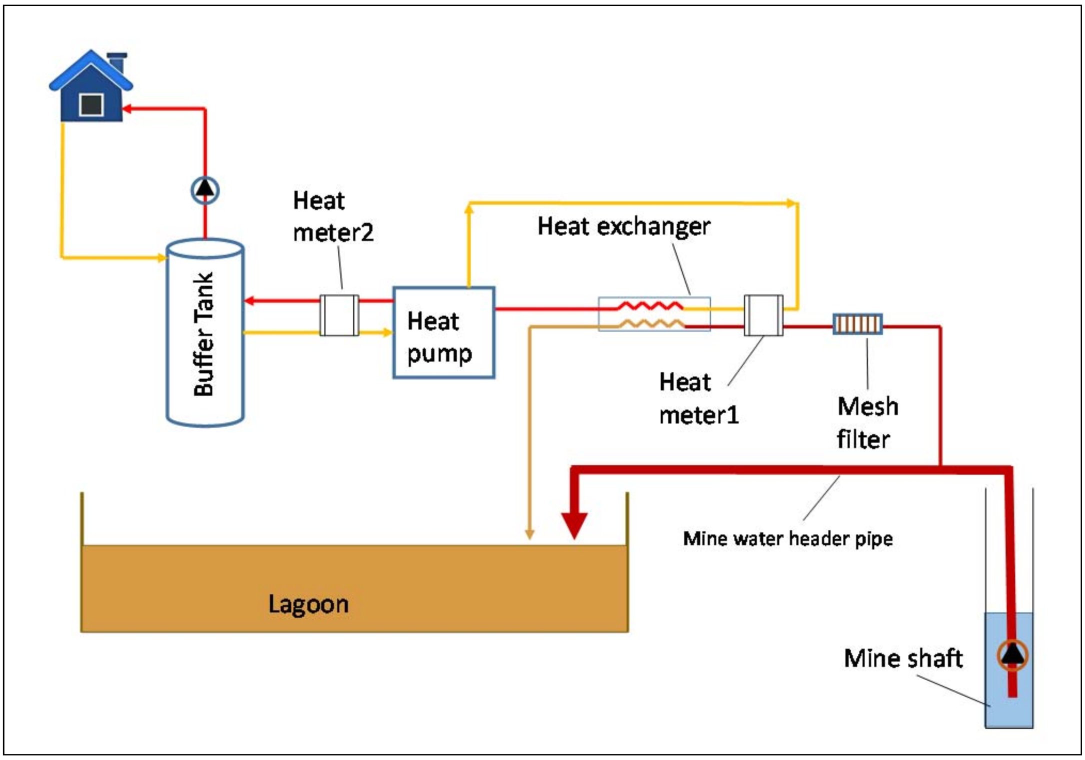

Figure 4: A simplified schematic diagram of the system.

The system for pumping water from the coal mine includes two parallel systems (header pipes) one or both could be operating at any specific time. To allow the extraction of water by either pipe, a novel design (see Figure 5) allows the heating system to circulate water from either pipe based on their pressure, and at the same time preventing the loss of pressure due to water leakage to the low pressure/empty one. If both systems are pressurised, this will create a functional flow based on the lowest pressure assuming both are above the threshold value of the valves.

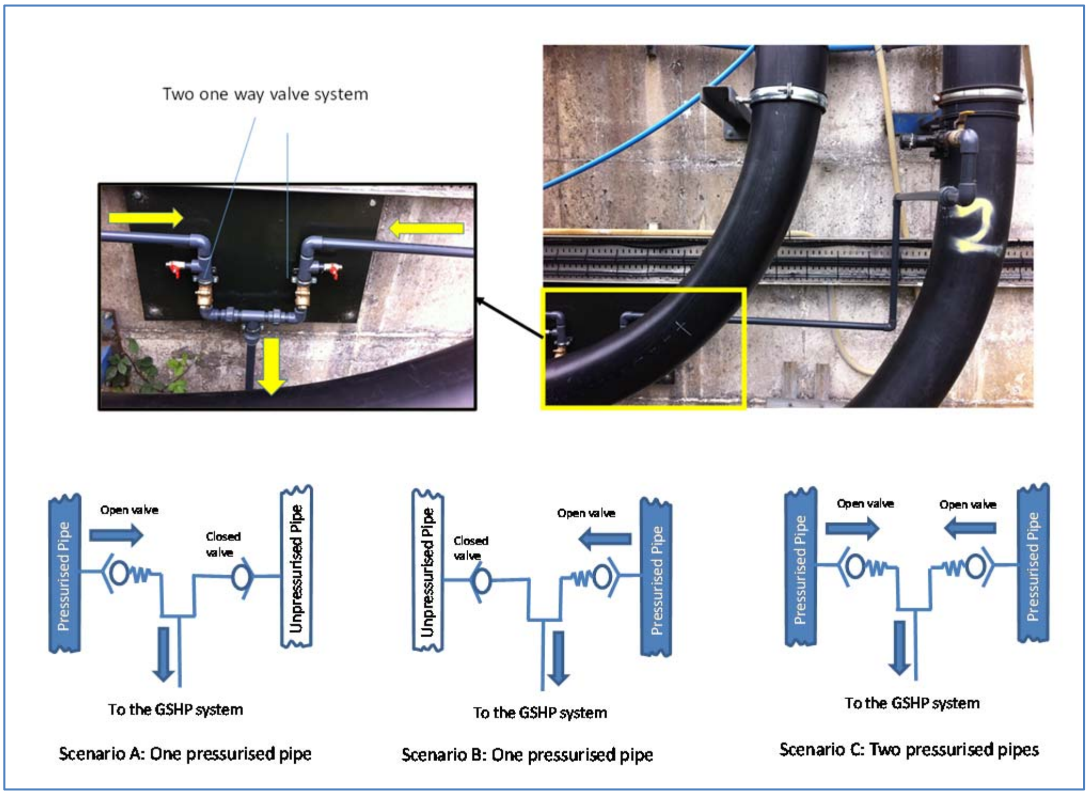

Figure 5: A novel design of one way valve system allows the GSHP to operate effectively from either pipe when pressurised without losing the pressure to the other unpressurised pipe.

4. Data Acquisition and Monitoring of the system.

The main parameters which need to be monitored to determine the performance of the system (see next section) are energy consumption and heat transfer rates between the mine water and the brine. These are determined by measuring the fluid input and output temperatures and instantaneous flow rates. Two Kamstraup heat meters are used to monitor both the mine water and heat pump output parameters. The heat meter measures the flow rate in m^3/h, ΔT of water, instantaneous energy in kWh and cumulative energy in MWh. The Kamstraup heat meter consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is coupled to telemetry and the data is continuously collected. Figure 6 presents images of the main components of the system. The arrows indicate the stages of energy or water flow between components.

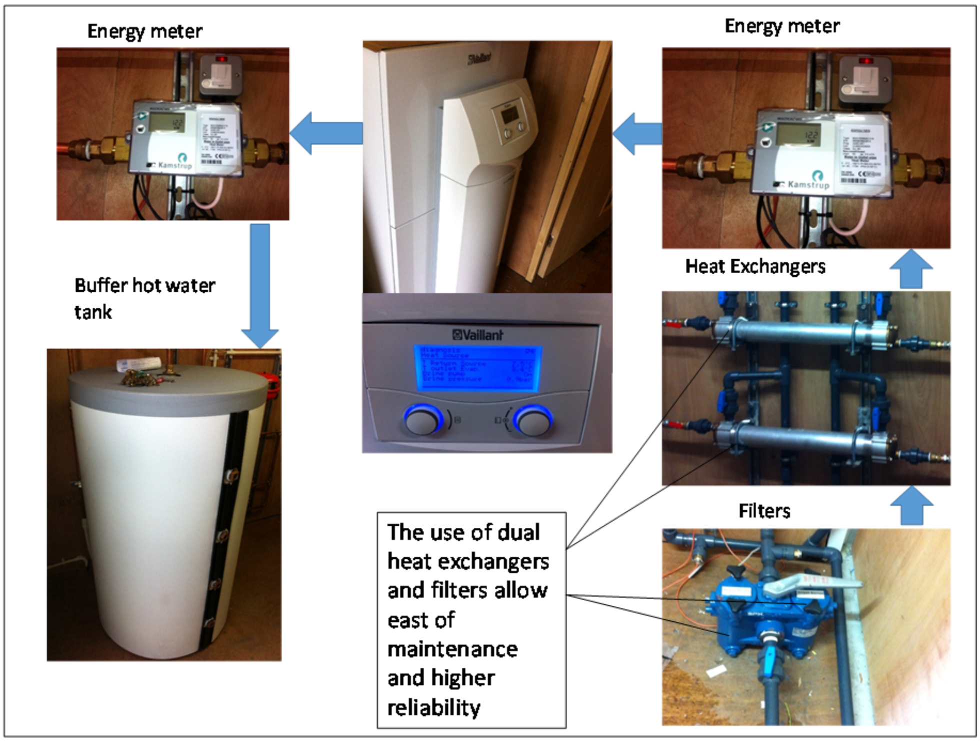

Figure 6: The main components of the GSHP system.

5. Main Performance Indicators

The efficiency of a Heat pump is measured in terms of COP (Coefficient of Performance). It is the main parameter of interest. It is the ratio between the thermal energy output of the heat pump and the electrical energy consumed by the heat pump. The amount of energy produced and consumed by the heat pump mainly depends upon the heat transfers between the mine water and brine, brine and evaporator of the heat pump and between the condenser of the heat pump and building heating fluid. The COP of the system is normally measured by the thermal output of the system relative to the energy consumed by the system. This is, in addition to the heat pump itself, includes the pumping of water from the coal mine and the pumping of water to the end user radiators via the circulation pump. In this application, since the water is pumped as part of the original system and the circulation pump power is negligible when compared with the heat pump, the COP of the heat pump is almost identical to the COP of the system.

In mathematical terms:

$$\mathrm{COP}_{Heat\ pump} = \frac{\text{Thermal Energy produced}}{\text{Electrical Energy consumed}} \tag{1}$$

$$\mathrm{COP}_{system} = \frac{\text{Thermal Energy produced by system}}{\text{Electrical Energy consumed by system}} \tag{2}$$

In this case: $\mathrm{COP}_{heat\ pump} \approx \mathrm{COP}_{system}$ (3)

6. Results and Discussion

6.1 COP and Temperatures

The presented data has been collected during the operation of the heat pump during summer time of 2015. Figure 7 presents the efficiency (COP) of the heat pump which varies between 3.5 and 4.5 depending on the heating demand which is related to the environmental conditions. The efficiency is slightly lower than expected as this data was collected during summer when the demand for heat is the least. When the heat pump operates under part load conditions, the cycling of the compressor (i.e. frequent on and off) of the heat pump takes place and leads to the reduction in efficiency. Figure 8 presents the water temperature from the coal mine and the water exiting the heat exchanger. The mine water seems to be stable at about 14.5 ^{o}C, hence indicating a reliable source of low enthalpy energy.

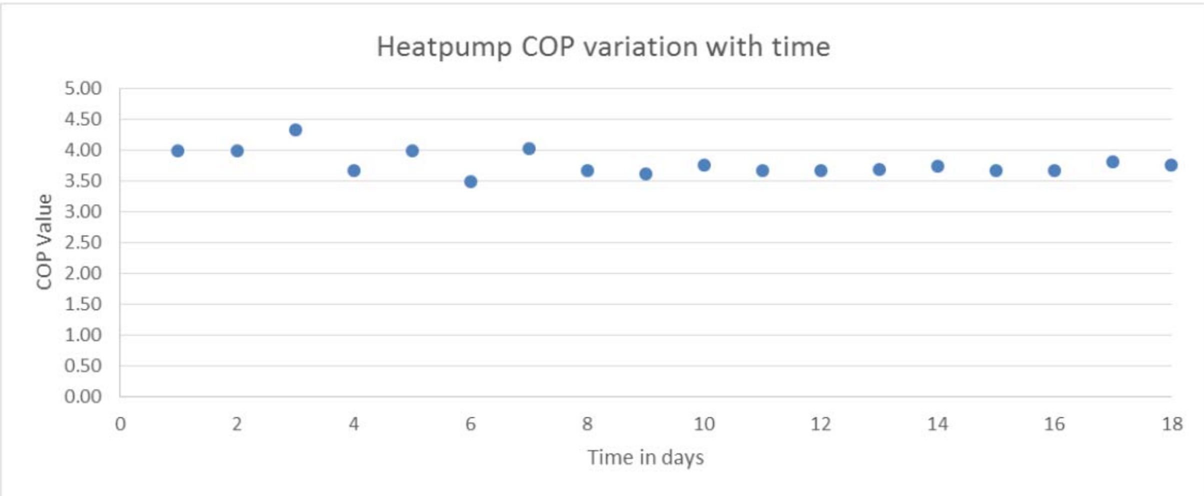

Figure 7: The COP of the system during the testing process for 18 days.

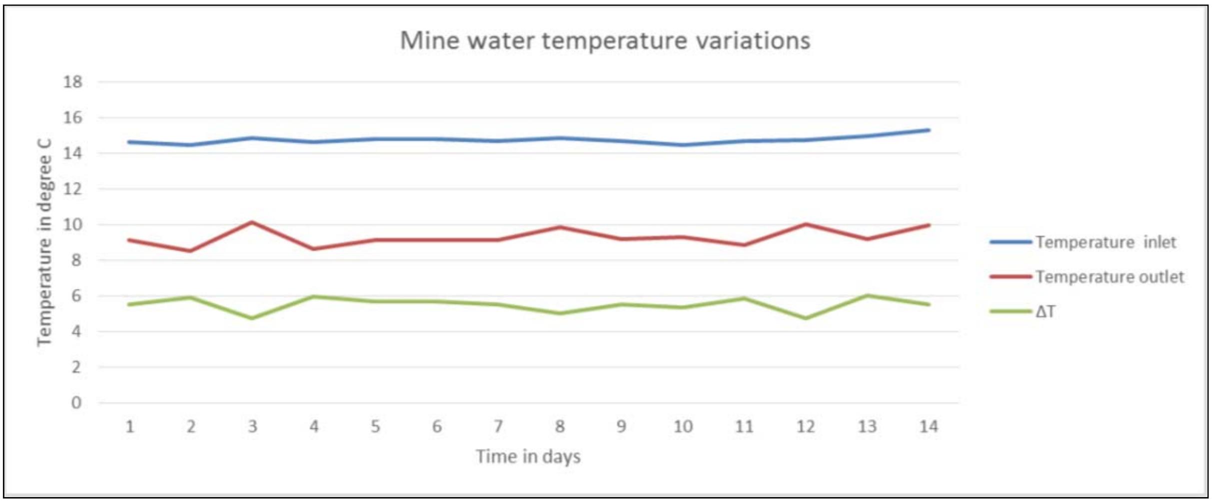

Figure 8: The variation of mine water temperature parameters

6.2 Maintenance and Reliability Issues

In relation to maintenance issues, due to the quality of water, Figure 9 presents the filtering system following several days of operation using the water without any treatment. There is a clear ochre occurrence on the filters that could cause blockages. However, the alternating between the two filters allowed the cleaning process to take place while the system in full operation.

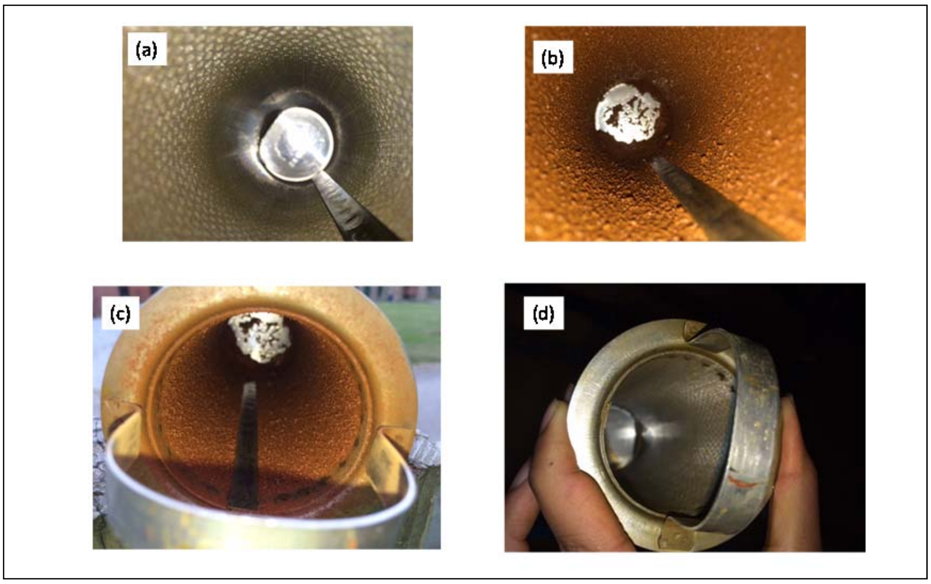

Figure 9: The conditions of the filter as new (a), after several days of operation (b, c) and after cleaning (d).

6.3 Cost and Performance

For a peak thermal output of 10kW, 2000 hours of operation and an annual heating demand of 20MWh, Figures 10 and 11 present the efficiency of the system and the carbon emission respectively. It is clear that the GSHP has a much higher efficiency due to the energy extracted from coal mine water. Also it has much improved carbon emission as a result of that.

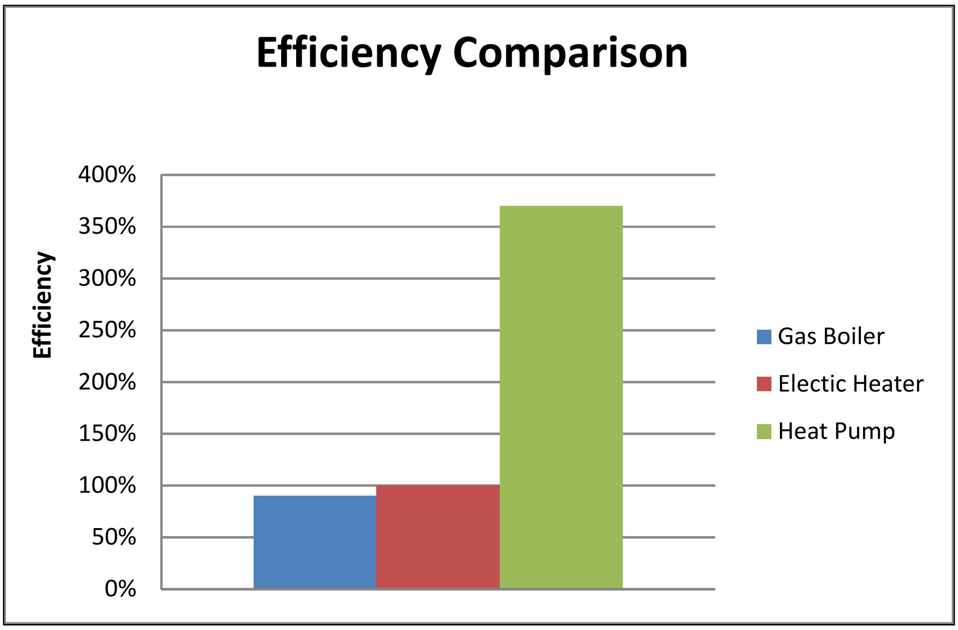

Figure 10: Efficiency comparison using gas, electricity and heat pump heating systems.

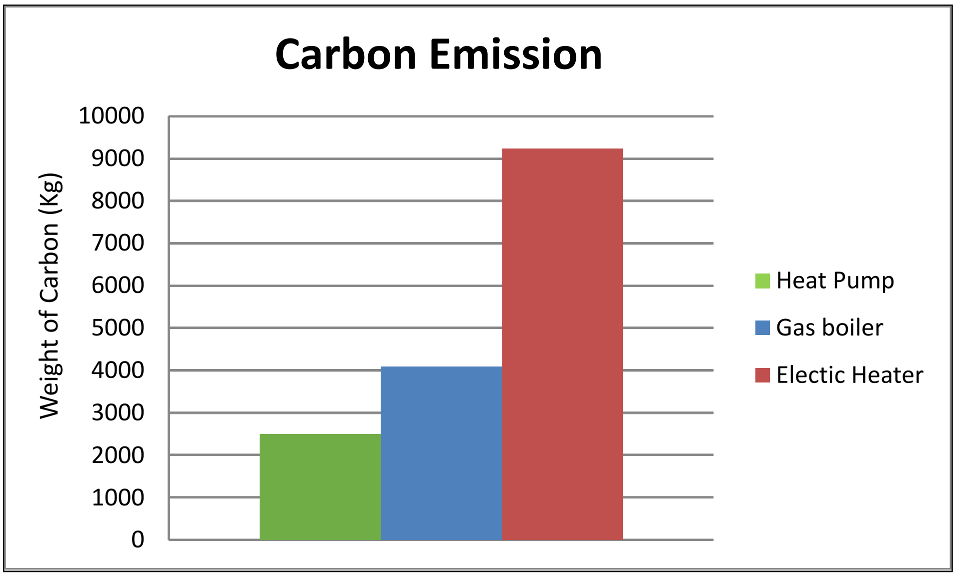

Figure 11: Comparison between carbon emission of the suggested heat pump system in comparison to a gas boiler and an electric heater.

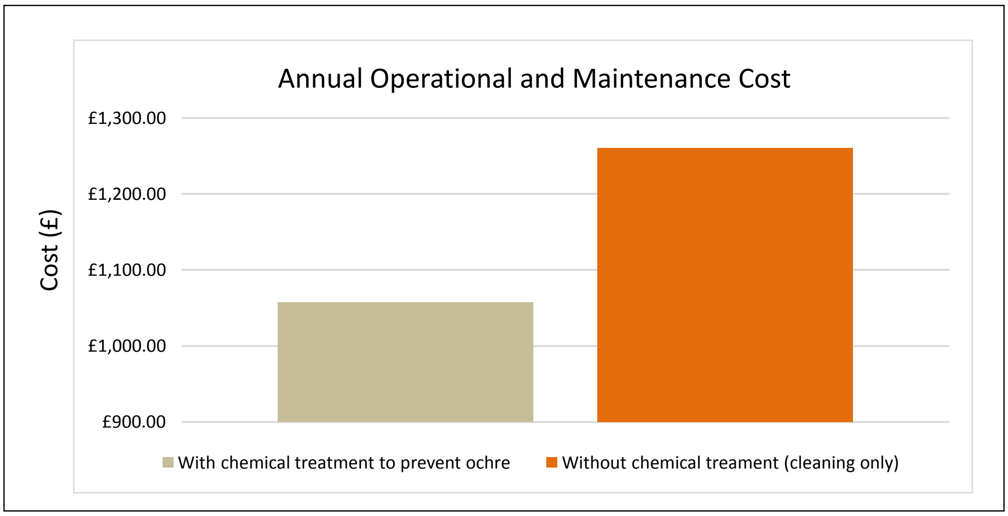

Figure 12: Operational and maintenance cost of the heat pump using two different maintenance schemes.

Figure 12 presents the annual operational and maintenance cost of the heat pump. It is estimated that the electricity consumption cost will be about £540.54 and the maintenance cost will be about £517 per annum for the chemical treatment of water to prevent ochre. The mechanical cleaning process of filters (manual cleaning) will cost about £720 per annum. This is indicating a difference of about £200 between the two schemes. However, the chemical treatment can be automated which might be easier to manage on the long term.

7. Conclusion and Future Work

This paper has presented a novel design and implementation of open loop Ground Source Heat Pump operating in an ochre rich mine water environment. The system has been implemented at the UK's National Coal Mining Museum. Despite the poor quality of water, this system has been implemented successfully using dual filters and dual heat exchanger system which will allow ease of

maintenance and guarantee continuous operation of the system. The advantage of the GSHP in this particular location, in addition to increasing efficiency and reducing carbon emission, is educating the visitors of the museum regarding this technology which will allow public engagement for enhancing the future of this technology within the public domain.
Future work will involve the monitoring of the GSHP system over a two year period for full evaluation. Future work would involve studying the impact ochre deposition has on the overall efficiency of the system, developing a dynamic GSHP system model for optimising the GSHP parameters and creating a condition based maintenance strategy for using a GSHP system in an ochre prone environment.

8. Acknowledgment

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