Special Issue Research Article

Numerical and experimental study of transient conjugate heat transfer in helical closed-loop geothermal heat exchangers for application of thermal energy storage in backfilled mine stopes

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Summary

The geothermal potential available from deep underground mines has yet to be utilized. However, stope-coupled heat exchangers (SCHE) are aiming to take advantage of the unused low-grade geothermal energy. Backfilled stopes provide a unique opportunity to install nonlinear heat exchangers, as the geometry is not limited to the shape of a borehole. Helical pipes deliver superior fluid mixing and heat exchange compared to straight pipes, due to the effect of the secondary flow within the helical pipe. The helical closed-loop geothermal heat exchanger enables the backfilled stopes of the mine to be repurposed as thermal energy storage units. This article delves into the experimental results from a unique state-of-the-art laboratory scale helical closed-loop heat exchanger with varying thermophysical parameters. Additionally, a novel conjugate numerical model is developed and its results are validated against the base case of the experimental studies. Additionally, the numerical model is validated in a spatial-temporal sense with thermocouple data from the experimental rig. The numerical model is also applied to a helical SCHE situated within a backfilled stope for the first time. The results of the numerical model suggest that the pumping rate through the SCHE has a significant effect on the heat exchange rate and the overall energy transfer between the SCHE and the backfill. Additionally, the temperature contours from the numerical model suggest that a decreased pitch/helical diameter will increase the storage capacity of the helical SCHE. Overall, an average of 2.5 MW can be stored over the first 4 days of geothermal charging with the investigated full-scale SCHE, boasting a pseudo-steady-state storage rate of 1.7 MW.

Keywords

backfilled stope, closed-loop, geothermal, helical heat exchanger, underground mine

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INTRODUCTION

Deep underground mines offer access to an untapped low-grade geothermal resource that can be used to supplement the heating/cooling demand at the mine site, or for direct uses in the neighboring communities. Backfill is used in open-stopping techniques for underground mining, where an excavation is backfilled with an engineered material to provide adequate ground support. The backfilling of the open stope presents an opportunity to install a heat exchanger, prior to backfilling, with a geometry limited only by the dimensions of the stope. The system can then be used in the same manner as a ground coupled heat exchanger. Helical shaped pipes impart a secondary flow onto the fluid flowing through them because of the centrifugal force imparted to the fluid from the curvature of the helical pipe. The secondary flow increases the convective heat transfer within the pipe, thereby enhancing the heat transfer. Additionally, the presence of the secondary flow will stabilize the fluid flow and increase the critical Reynolds number (ie, higher Reynolds number when entering the transition regime). The helical SCHE (stope-coupled heat exchanger) can be used to develop a seasonal thermal energy storage system that would help deep underground mines with refrigeration.

There is an absence of studies in the current literature that address the heat transfer associated with SCHEs, however there are experiments and numerical models for very similar scenarios such as geothermal helical heat exchangers, helical pile geothermal heat exchangers (PGHE), and straight-pipe SCHEs. There has also been significant research into analytical solutions for helical heat exchangers, however a numerical model is required in the case of an SCHE to take into account the complex geometries as well as for defining individual boundary conditions. Rabin and Korin simulated a series of horizontal rings with a finite difference model, which was then verified/validated against their experimental results from field testing. Park, Lee combined their finite element numerical model and experimental thermal response data to confirm the validity of helical source analytical solutions. Zarrella and De Carli use the capacity resistance model to determine that a short helical heat exchanger has a thermal performance superior to that of u-tube heat exchangers.

Doughty, Nir developed an annular cylindrical model, to approximate a helical heat exchanger, which was run on the integrated finite difference computer code PT. Moch, Palomares used the commercial finite element software COMSOL to determine that the 2D axisymmetric model of the annular cylindrical conduit is easier and faster to run than the model with horizontal rings. However, both models provided acceptable results.

Bezayan, Porkhiai utilize the commercial Gambit/Fluent software to compare configurations of w-tube/u-tube/spiral tube PGHE, and determine that a serial network of helical (ie, spiral) PGHEs delivers the most effective heat transfer rate. Yoon, Lee model helical PGHEs with COMSOL and compare the results to experimental data to determine the thermal conductivity of the ground, thereby improving long-term predictions for PGHEs.

Dehghan, Sisman use COMSOL and experimental results to investigate the effects that pitch length, helix diameter, and distance between helical heat exchangers have on the heat transfer rate. Song, Shi use COMSOL to investigate the effects of helix diameter, helix pitch, spiral coil length, and return pipe placement. The Song et al 3D unsteady state conjugate model is validated against experimental data from a double u-tube setup, however the helical heat exchanger model was not validated with experimental data.

Several studies have investigated experimentally the thermal responses of helical heat exchangers mostly for the application to PGHE. Ghoreishi-Madiseh et al investigated the performance of straight-pipe SCHEs in mineral processing tailings with a small-scale laboratory setup. Ghoreishi-Madiseh et al conclude that conduction is the primary heat exchange mechanism in the backfill, meaning that the thermal conductivity heavily influences the heat exchange.

This study focuses on a unique state-of-the-art lab-scale experimental model of a novel helical SCHE to validate a 3D conjugate heat transfer numerical model, neither of which has been previously achieved. The novel helical geometry, relatively unstudied SCHE technology, and experimental validation of a conjugate heat transfer numerical model serve to fill the research gaps as highlighted in the previous literature review. Furthermore, the experimental model and numerical model were jointly used to investigate the effects of geothermal charging with a helical SCHE. Finally, the numerical model is applied to a full-scale helical SCHE installed within a backfilled stope for the first time, and used to investigate the effects of geothermal charging. Application of the numerical model to a full-scale helical SCHE is important to further the objective of employing a helical SCHE in a mining system.

EXPERIMENTAL SETUP

The experimental setup (c.f. Figure 1) consists of a 20 cm diameter helix along the axis of an aluminum tank (70 cm Ø and height of 155 cm) containing saturated sand. The working fluid is confined to the helical pipe, and is composed of a 50% inhibited ethylene glycol solution. The helical pipe has an outer diameter of 0.635 cm (1/4”), wall thickness of 0.089 cm (0.035”), pitch distance
of 10 cm, and is a total of 141 cm tall. The return pipe running from the bottom of the helix to the top of the tank is situated outside the volume of the helix. LabView is used to control the chiller, piston pump, heating jackets surrounding the tank, and is also used to record the data from flowmeters/thermocouples.

3 | MODEL DEVELOPMENT

The numerical model employed in the experimental geothermal charging study consists of a 3D geometry replicating the geometry of the experimental lab-scale helical heat exchanger. Whereas the numerical model employed in the full-scale SCHE geothermal charging numerical study consists of a 3D geometry composed of helical heat exchanger situated within a backfilled stope. Because of the complex geometry imposed by the helix, the experimental rig and backfilled stope are required to be modeled in three dimensions to accurately represent the reality of the heat transfer. Based on Ghoreishi-Madiseh et al.’s18 conclusion that conduction is the dominant heat transfer mechanism, the ground was not simulated as a porous media. Therefore, the numerical model is designed to be a conjugate model, accounting for the convection within the helical coil as well as the conduction throughout the entire domain.

3.1 | Governing equations

The 3D conjugate numerical model was developed using Fluent 17.2, where the conservation of mass, energy, and momentum equations are solved.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum conservation equation:

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \left( \left[ \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right] - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) I \right)$$

Conservation of energy equation:

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\mathbf{u}(\rho E + p)) = \nabla \cdot (k \nabla T)$$

Where:

$$E = h - \frac{p}{\rho} + \frac{\mathbf{u}^2}{2}$$

3.2 | Boundary and initial conditions

The boundary conditions of the top and bottom of the experimental setup are set as a no flux boundary, based on the fact that these boundaries are well insulated from the environment. The side wall of the experimental rig is set to a constant temperature in order to provide a heat flux that will approach a steady state. The fluid inlet is situated at the top of the experimental rig, where it is set to a constant
volumetric flow rate representative of that achieved within the experimental run. The side wall and fluid inlet temperatures are set to the average of those temperatures measured during the experimental run in question, in order to accurately capture the heat flow within the rig. Additionally, using the average temperature readings reduces the influence of any noise that may be present in the experiment. The boundary of the helical pipe and ground are thermally coupled in order to reduce the numerical work and to increase the model’s accuracy around the helix.

The boundary conditions are identical for the geo-thermal charging study, with the exception of the sidewall being declared as a zero-flux boundary. In reality, the flux coming through the sidewall would be constant; however, with the experimental rig wrapped in insulation, the boundary condition is more appropriately defined as a zero-flux boundary.

The outer boundary conditions for the SCHE are a constant geothermal flux over the entire rock volume surrounding the backfilled stope. The geothermal flux was set to the average global geothermal heat flux of 0.065 W/m².20 The inlet temperature is set to a constant 1°C, as we will assume that the coolth is sourced from a heat exchanger during the winter months. This assumption of a coolth source is most applicable to mines situated at an extreme latitude. The initial temperature of the stope and surrounding rock is set to 20°C. The fluid inlet is represented by a constant volumetric flow rate that is set to the same velocity as the experimental base case.

4 | NUMERICAL METHODOLOGY

A mesh independency analysis was conducted within the commercial finite volume software, Fluent, to determine a suitable mesh size, beyond which there would not be an appreciable increase in accuracy. A mesh size of about 2 300 000 nodes was found to provide a very accurate solution for the 20 cm helix, with the analysis investigating meshes of up to 5 200 000 nodes. No geometry independence was investigated, due to the fact that the numerical model is simulating the insulated lab experiment.

The mesh for the SCHE was densest within the helical pipe, and a mesh size of 18 680 000 nodes was found to provide an accurate solution. No geometry independence was undertaken; instead, the stope was surrounded with a rock volume that maximized the use of available computer memory. Additionally, due to the extreme size of the mesh, the fluid flow profile was solved in a steady state simulation and was assumed to have constant thermophysical properties.

The numerical model is solved using the SIMPLE algorithm, second-order upwind spatial discretization for pressure/momentum/energy/transient formulations, relative residuals below $10^{-6}$, and user-defined-functions to describe the thermophysical properties of the ground and working fluid.

5 | HELICAL SCHE SETUP

The SCHE geometry (c.f. Figure 2) consists of a 15 m diameter helix along the axis of a backfilled stope (20 x 20 m square base, 40 m tall) surrounded by rock (5 m layer on sides, 2.5 m on top and bottom). The working fluid for the helical SCHE is chosen to be water, due to the sheer volume required to fill the SCHE. Ethylene glycol was determined to be cost prohibitive for such a large volume, in addition to the safety liability in the event of a leak as it is a toxic chemical. The helical pipe has an inner diameter of 10 cm, pitch distance of 6 m, and is a total of 40 m tall.

6 | EXPERIMENTAL RESULTS AND NUMERICAL VALIDATION

The numerical model was setup so as to imitate the boundary conditions of the experimental runs. The base case used for the numerical validation has a volumetric flow of 5 mL/s, a constant working fluid inlet temperature of 11°C,
and a constant wall temperature of 20°C. The effect of the working fluid inlet temperature is investigated experimentally by simply changing the inlet temperature and maintaining the other parameter settings from the base case.

Additionally, the geothermal charging is studied by first discharging the 20°C experimental rig with a 6°C inlet temperature at 5 mL/s. This is meant to simulate geothermal extraction, followed by the storage of thermal energy. Subsequently, the heating bands on the sidewalls are deactivated, and the inlet temperature along with the volumetric flow rate values are varied to investigate the effects on the geothermal energy storage.

6.1 | Numerical validation

Figure 3 demonstrates a comparison of the numerical and experimental parametric study's on working fluid inlet temperature. The variations in the inlet temperature settings are based on the physical limits of the experimental rig, which are based on values that could realistically be encountered within an underground mine. The numerical results in Figure 3 (denoted as solid/dashed lines) capture the magnitude and trend of the experimental results very accurately. The very close agreement between the numerical model and the experimental results is enough to validate the numerical conjugate heat transfer model. However, an additional comparison of the experimental and numerical spatial-temporal temperature agreement is useful to further investigate the validation of the numerical model.

Figure 4 lays out the distribution of thermocouples on a support plate within the experimental rig. The experimental rig contains three identical plates aligned along the axis of the helix; the first plate is located 35 cm from the top of the experimental rig, the second plate at 71 cm from the top of

**Figure 3** Parametric study of the working fluid inlet temperature for the numerical model (lines) and the experimental model (markers) that demonstrates numerical validation [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 4** Support plate for the thermocouples within the experimental rig with the associated thermocouple naming convention [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 5** Spatial-temporal validation of the numerical model with experimental results from thermocouple 2 on the first level [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 6** Spatial-temporal validation of the numerical model with experimental results from thermocouple 2 on the second level [Colour figure can be viewed at wileyonlinelibrary.com]
the rig, and the third plate at 123 cm from the top of the rig. Thermocouple 2 (c.f. Figure 4) was chosen for the spatial-temporal validation and will be referred to with the naming convention of level-thermocouple (i.e., 1-2 represents thermocouple 2 on level 1). Furthermore, the spatial-temporal comparison is conducted on the case set with an inlet temperature of 7°C (c.f. Figure 3). It is clear from Figures 5-7 that the numerical model is quite capable of realizing a spatial-temporal temperature distribution that agrees very well with the experimental results. Based on the comparisons (c.f. Figures 5-7), the numerical model is validated in the spatial-temporal sense.

It is clear from Figure 8 that the time required to attain steady state and the delta temperature at steady state are linearly dependent on the inlet temperature. Increasing the inlet temperature leads to a decreased delta temperature at steady state, but a decreased time required to attain steady state. Increasing the inlet temperature will limit the amount of thermal energy that the SCHE is capable of removing from the ground (i.e., lowering the delta temperature), thereby decreasing the time it takes to reach steady state while simultaneously maintaining a higher outlet temperature.

6.2 Experimental geothermal charging study

Figure 9 demonstrates the effect that the volumetric flow rate through the helical SCHE has on the outlet temperature and thermal energy storage within the experimental rig. Figure 9 can be divided into two halves: the initial geothermal discharging period (before 24 hours), and the subsequent geothermal charging period (after 24 hours). It is evident from Figure 9 that a higher flow rate can effectively transfer heat to the ground through the helical SCHE faster than a lower flow rate. Additionally, a lower flow rate is indicative of a longer amount of time.
required to reach the steady state. The 5 mL/s flow rate peaked at 2.35 kW of geothermal charging and averaged 0.74 kW of thermal energy dumping. Whereas the 3.5 and 2.5 mL/s flow rates, respectively, peaked at 1.65 and 1.30 kW of geothermal charging and averaged 0.56 and 0.40 kW of thermal energy dumping.

6.3 | Full-scale SCHE geothermal charging numerical study

A full-scale helical SCHE numerical model was developed to determine the feasibility of geothermal charging in backfilled stopes. Figure 10 demonstrates the effect of discharging and charging the full-scale SCHE on working fluid outlet temperature. The discharging inlet fluid temperature of 1°C reaches a steady state in a week under the imposed conditions, and can absorb an average of 2.5 MW of thermal energy over the 4 days of discharging. In this case, the SCHE achieves a pseudo-steady-state thermal storage rate of 1.7 MW. An array of these SCHEs could effectively provide coolth energy to the condenser of an underground refrigeration plant in order to increase the coefficient of performance, reduce energy consumption, and effectively reduce refrigeration plant size. This type of renewable coolth storage could help mitigate the future air quality issues and energy intensity that will be encountered with ultradepth mining. Additionally, the heat extracted during coolth storage could be used for preheating ventilation air or residential heating, further increasing the productivity of coolth storage.

Figure 11 demonstrates the temperature contour within the stope at three different scales for the discharging phase of the full-scale SCHE (c.f. Figure 10). It is evident that the conduction through the backfill imposes a strong limit on how much energy is transferred from the SCHE to the backfill.

Similar to Figure 11, Figure 12 demonstrates the temperature contour within the stope at three different scales for the charging phase of the full-scale SCHE. Like the discharging phase, the charging phase is clearly limited by the ability of the backfill to conduct heat away from the helical SCHE. The area of influence surrounding the helical pipe (c.f. rightmost inset of Figure 12) is quite small compared to the pitch distance and diameter of the helix. Therefore, a straightforward way to increase the energy transfer from the helical SCHE would be to decrease the pitch and helix diameter. Decreasing the helix diameter could allow an array of multiple helices to be installed within the same stope.

7 | CONCLUSION

A 3D finite volume conjugate heat transfer model was developed and validated against a state-of-the-art lab-scale experiment for the first time ever. Experimental runs were conducted to investigate the effect of working fluid inlet temperature on the working fluid outlet temperature and time required to attain steady state. The thermocouples from within the experimental rig were used to successfully validate the numerical model in a spatial-temporal sense. The parametric experimental runs confirm that the experiment is operating well, and can serve to further validate the numerical model. Increasing the inlet temperature will decrease the time it takes to reach steady state while simultaneously maintaining a higher outlet temperature. The results of the model suggest that pumping rate has a significant effect on
the rate of heat exchanged and the overall amount of thermal energy exchanged between the helical SCHE and the ground.

The validated numerical model was applied to a full-scale SCHE for the first time, to determine the magnitude of energy that an SCHE design could realistically move into/out of a typical sized stope. An average of 2.5 MW can be stored over the first 4 days of geothermal charging, with a pseudo-steady-state storage rate of 1.7 MW. The temperature contours of the full-scale SCHE demonstrate that conduction within the backfill limits the SCHE from effectively using the thermal capacity of the stope. Therefore, the energy storage of the modeled helical SCHE could be increased by decreasing the pitch distance and/or decreasing the diameter of the helix.

Future work will focus on conducting further numerical studies to investigate the effects of geometrical parameters on the performance of the full-scale helical SCHE.

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NOMENCLATURE
\( \rho \) density
\( t \) time
\( u \) fluid velocity
\( T \) temperature
\( p \) pressure
\( \mu \) dynamic viscosity
\( I \) identity matrix
\( k \) thermal conductivity
\( h \) sensible enthalpy
\( E \) total enthalpy

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