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Abstract

The following report addresses the problem of heating input water during the process of solution mining for potash. With an ever-increasing pressure to reduce reliance on fossil fuels, being able to warm inlet water with underground heat would be an advantage for any solution mining company. The report examines the problem in general to discover whether a temperature of 328K can be reached at the bottom of the mine.

A finite difference method was used to simulate the heat transfer within a Microsoft Excel spreadsheet, with validation provided by SolidWorks Flow Simulation Software. Varying atmospheric temperature, flow rate and type of blanket fluid were all simulated, however at optimum design the simulation resulted in a temperature of 305.95 K.

Although the results suggest that the underground heat source will not be sufficient, the lack of modelling of the heat transfer in the sump of the mine and the lack of data available for the properties of brine means that the results are just the first stage in the analysis of the problem. Further recommendations of how to approach the problem next have been made.

Nomenclature

Symbol	Definition
$\dot{m}$	Mass Flow Rate
$\dot{Q}$	Heat Transfer
a	Width of Nodes
b	Height of Nodes
c	Depth of Nodes for a 1 Degree Slice
C_p	Specific Heat Capacity
D_i	Hydraulic Diameter of Pipe or Annulus
h	Heat Transfer Coefficient
Nu	Nusselt Number
Pipe 1	Section of Mine Carrying Water
Pipe 2	Section of Mine Carrying Blanket Fluid
Pipe 3	Section of Mine Carrying Brine
Pr	Prandtl Number
Re	Reynolds Number
T_1	Temperature at Node 1
T_2	Temperature at Node 2
T_3	Temperature at Node 3
T_4	Temperature at Node 4
T_b	Temperature of Bottom Node in Fluid
T_t	Temperature of Top Node in Fluid
u	Velocity of Fluid
V	Volume of Node
ΔH	Change in Enthalpy
ΔT	Change in Temperature
ΔT_{SL}	Change in Temperature from Solid to Liquid
ΔT_{tb}	Change in Temperature from Bottom node to Top node
Δz	Change in Height of Node
λ	Thermal Conductivity of Solid
λ_f	Thermal Conductivity of Fluid
ρ	Density

Introduction

Potash is used predominately in the agricultural industry, with 95% of production being used as a fertilizer or as plant food (Wishart, 2004). The rest of the potash production goes towards the manufacturing of glass and ceramic products, explosives and alkaline batteries and even sodium chloride, or table salt, substitutes for human consumption (Kogel, 2006).

The potash referred to through the following document will be Muriate of potash; its main constituent being potassium chloride (International Plant Institute, n.d). This potash is usually mined from 'underground bedded salt deposits' (Wishart, 2004); one technique used is solution mining.

There are a number of advantages and disadvantages of this process. For

example, the process has less of an environmental impact than conventional mining that can cause sinkholes, water contamination and soil contamination (Bell and Donnelly, 2006), and lower operating costs. Additionally there are increased ore resources with solution mining (Gupta and Mukherjee, 1990). However, there is still the chance of some groundwater contamination using the solution mining method, and the complex technology also required may be the reason that the process is still not as popular as conventional mining techniques (Gupta and Mukherjee, 1990).

As the solubility of potash increases with temperature, it is necessary to have the water used in the process to be as warm as is required for the specific downstream purification plant, whilst providing the highest potassium yield as possible. Too cold and the potash yield will not be sufficiently high, and too warm can affect the cation collectors used in the processing of the salt solution and render the potash water repellent (Titkov, 2003, and Hartman, 1992).

Aims

The aim of this report is to analyse a solution mining process in order to discover whether the heat from the underground rocks around the mining apparatus is sufficient to heat the water during the process, or whether an outside source of heat is required.

Objectives

The objectives of this report are as follows:

- Create a model to predict the effects of initial water temperature, water flow rate and mining location from first principles and previously published academic work.
- Assess the reliability of the model using Computational Fluid Dynamics software.
- Produce quantitative predictions of the effect of initial water temperature and water flow rate on the temperature reached in the sump of the mine.

Objectives that have been considered to be unrealistic for the time frame of the project are:

- Create a model to predict the effects of initial water temperature, water flow rate and mining location on the flow in the mining sump. This process is much more complex than the flow in the pipes and so previous academic work providing models will be used for quantitative predictions.

Deliverables

The deliverables of this project are theoretical models of the heat and mass transfer using theory and computational methods, along with a range of quantitative predictions for varying inlet temperatures and flow rates. The computational method will be a SolidWorks flow simulation, and the theoretical will be the analysis of the mining problem using finite difference methods.

Literature Review

Mining Process

The mining process used for the production of potassium chloride, a common variety of potash, has been described in a range of publications; with the same principles presented in each. The method follows the steps of drilling a borehole into an area with potash deposits and using three concentric tubes to insert water and a blanket fluid into the shaft created. The water then dissolves the potash in the cavern, creating variously shaped sumps depending on the pipe positioning (Remson et al., 1965 and Hartman, 1992). The blanket fluid sits on the top of the water to ensure that the cavern develops outwards instead of back up around the pipes (Kogel, 2006), as the fluid is less dense than the water and immiscible (Bartlett, 1998). Common blanket fluids include petroleum, diesel fuel and pressurized natural gas (Bartlett, 1998 and Hartman, 1992). The saturated water is then pumped out of the cavern and treated to leave the desired product behind, as shown in
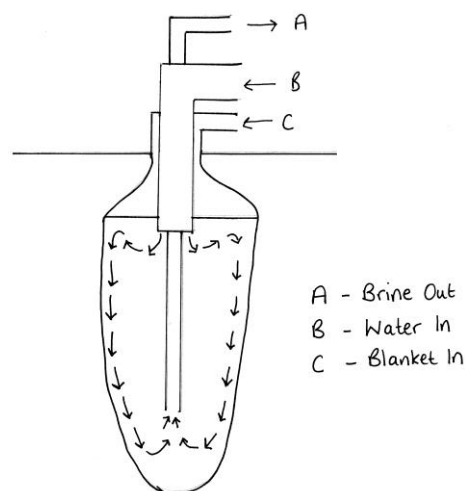Figure 1.

Figure 1: Solution Mining Process.

Flow in the pipes

Simple Heat Exchangers

The methods of analysing simple double pipe heat exchangers have been widely documented in academic papers. The Log Mean Temperature Difference and Effectiveness–NTU methods are the most common methods, both taking into account the ratios of temperatures of the hot and cold fluids (Walsh, 2011, and Thirumarimurugan et al., 2008). In addition to the methods for calculating the performance of a shell and tube exchanger, it is also widely accepted that

turbulent flow allows for higher heat transfer rates, as turbulent flow enables a mixing of the fluid, whereas laminar flow has 'temperature nonuniformities' (Simpson, 2010).

In addition to the widely accepted ways to analyse the effectiveness of heat exchangers, Mozley (1956) presents a simplified analytical model for simple concentric tube heat exchangers. Although the model presented is validated by experimental results, there are some problems associated with it that the Mozley is aware of. For example, the model shows that the analysis of a heat exchanger not only relies on the design but also the 'properties of the materials', and therefore it is not possible to 'ascribe a definite dynamic behaviour to a particular heat exchanger design'. As the mathematical model proposed by Mozley (1956) does not include heat transfer from an additional source, such as surrounding rocks, the model is not that applicable to the mining problem.

Heat exchangers underground
Oliver and Braud (1981) present a mathematical model for a ground source heat pump which features a very similar set up to the solution mine explored in this report. However, the assumption made for this mathematical model is that 'all physical parameters are independent of time'. Although this assumption makes the modelling simpler, it also over simplifies the problem. For example, as heat is transferred from the surrounding rock into the water in the pipes, the temperature of the surrounding rock will drop following the first law of thermodynamics that states that energy in a system must be conserved (Kondepudi, 2008). Despite this, the model presented could still be useful for initial calculations, especially if the time taken for the system to reach a steady state condition is negligible.

Mel and Fischer (1983) present a range of equations used to analyse the energy transfer from an underground concentric tube heat exchanger, but consider that the system is not necessarily performing under steady state conditions. They assume the heat transfer between the pipes and the ground to be 'radial conduction' and with no vertical heat transfer. The equations presented mirror those demonstrated by Almada et al. (2010), who analysed a set up similar to that investigated in this report. However, the pipes used by Almada et al. (2010) vary in direction instead of being strictly vertical. This causes the model presented within the literature to become more complex; as the heat transfer has to be modelled in three dimensions. Although this is similar to the mine being modelled, it is not entirely necessary for this report.

With the consideration of unsteady-state heat transfer in the system, comes the increased complication of partial derivatives throughout any mathematical model. However, Rees et al. (2004), through the analysis of a ground source heat pump and standing column well, have taken the equations described by Mel and Fischer (1983) and presented them in a way that yields a series of simultaneous equations that can be solved using a iterative method. Although these are useful for the solution-mining problem, the example presented in the literature also takes into consideration the permeability of the surrounding rock and its effect upon heat transfer. This is not necessary for the mining situation, as the process of dissolving salt and transporting it to the surface is not effected by porosity, as

evaporites lose their porosity when buried due to their grain structure (Einsele, 2000).

In addition to these publications, Hamm and Peterson (2012) present a ground source heat pump system with corrugated walls. Despite the complication of corrugated walls not being applicable to the mining problem, the basic heat transfer principles applied mirror, and therefore validate, those presented in previous publications discussed.

Entrance region
There is a range of publications that discuss the heat transfer in the entrance region of a pipe. The flow through the water and brine pipes is turbulent, but the blanket fluid is stationary or very laminar so two separate analyses will be needed. In this case, the work of Al-Arabi (1982) and Deissler (1953) for turbulent flow, and Worsoe-Schmidt (1966) for fully developed laminar flow can be used if the entrance region needs to be analysed.

Flow and dissolution in the cavern
There is a range of sources that analyse the rates of dissolution of salts in cavities. Husband and Ozsahin (1967) have developed a model that simulates the dissolution rates in potash caverns assuming 'a laminar boundary layer exists' and 'that free convection mass transfer occurs'. These are both reasonable assumptions, however the authors do not provide enough information to estimate the width-wise Reynolds number or a Richardson number to calculate the bulk flow. Their model is validated by experimental procedures and can be applied to various ore types and temperature 'for a surface of unit height'. Although this can only be applied to vertical walls of a cavern, Husband and Ozsahin (1967) justify this, as this is the best way to achieve dissolved ore under free convection conditions, and the flow is stopped from travelling upwards by the oil blanket described previously. In addition to this Wagner (1949) developed a model from theory and experimental results for the dissolution of vertical sodium chloride surfaces with free convection which supports Husband and Ozsahin's model.

As previously set out in the objectives of this report, the modelling of the flow in the mine has been considered to be an unrealistic objective for this time frame allowed. Due to this, published work, such as those previously outlined, will be used with any quantitative predictions.

Temperature variation with depth
It is important to know the amount of variation of temperature as the depth below the earth's surface increases, as this will determine the heat transfer between the rocks and the water used in the mining process. Many publications agree on the general trend of temperature variation with depth; the near-surface temperature depends on the time of year, but below 40m the temperature changes linearly with depth (Lee, 2012, Taniguchi, 2011, and Gornitz, 2009). Fridleifsson et al. (2008) state that temperatures increase 'on average 25-30°C/km', with a one kilometre well reaching 'a bottom temperature near 40°C in many parts of the world'.

Solubility of potassium salts
The International Union of Pure and Applied Chemistry's Solubility Data Series (1991) shows that as temperature increases, the solubility of Potassium Chloride (KCl) also increases, from a value of 21.74 mass percentage at 10 degrees Celsius to 36.05 mass percentage at 100 Degrees Celsius. These values are validated by the range of solubility data presented in a variety of publications (Holman and Stone, 2001, Hocking, 2006 and Beckmann, 2013), as shown in Figure 2. This data set can be used to determine the temperature of water necessary to acquire the correct mass percentage of KCl for the downstream plant.
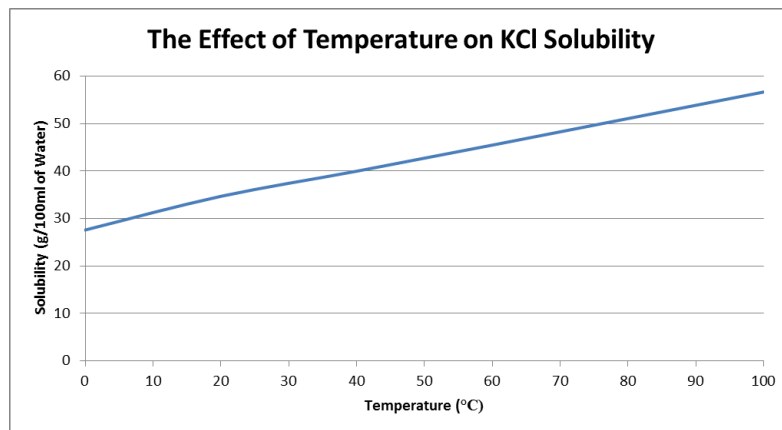
Figure 2: Solubility Curves of Potassium Chloride in Water. Reproduced from data provided by Hocking, 2006.

The solubility of KCl increases with temperature because the reaction between the water and the salt is endothermic, meaning that heat is consumed during the reaction (Reger et al., 2009 and Pruppacher and Klett, 2010). As this reaction is endothermic, the temperature of the KCl and water solution will decrease from that of the water on its own at the bottom of the mining shaft. This will have to be taken into consideration during the analysis. The effects of saturated potash on the properties of water also have to be discussed, such as thermal conductivity, as this may affect the flow and heat transfer in the exterior concentric tube. Geo Drilling Fluids (2010) provide a list of the effects of percentage weight of KCl on the properties of water. This data is validated by data also provided by Caenn et al., (2011) and Bellarby (2009).

Ideal concentration of Potash
Once the potash has been extracted from the ground using the solution mining process, the mineral is sometimes recovered by evaporating the water in solar ponds (Hartman and Mutmansky, 2002 and Bartlett, 1998). Bartlett (1998) describes how the management of the ponds depends greatly on the evaporation rates, which in turn are a function of the brine density. Therefore, the process very much relies on the concentration of potash delivered to the ponds. Chouzadjian (2005, personal communication), the Vice President of Project Development at Rio Tinto, states that the concentration used at their solution mining facility is 160 kg/m^3. This equates to 82% of the maximum theoretical

concentration they can expect at 328 K, allowing for inefficiencies in the system (Chouzadjian, 2005, personal communication).

Method

Model dimensions
The model dimensions used for the simulation are based on the specification proposed for a solution mine in Ethiopia (Environmental Resources Management, 2012). Pipe 1 has an inner diameter of 0.3m, Pipe 2 an inner diameter of 0.2m and Pipe 3 an inner diameter of 0.1m. Each pipe has a thickness of 0.02m, as shown in Figure 3.
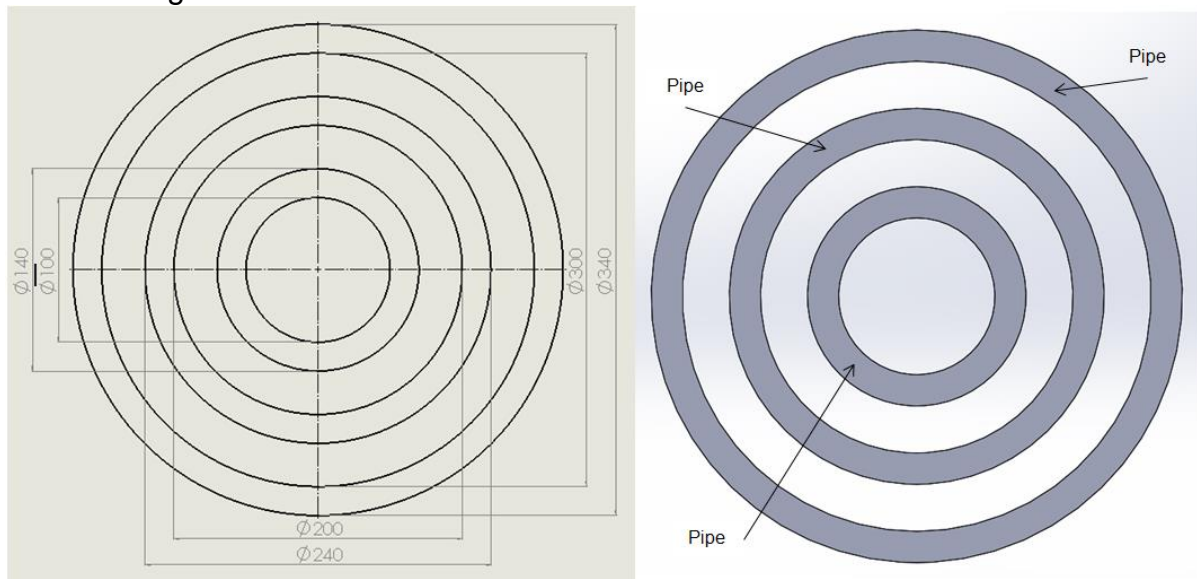
Figure 3: Model Dimensions

As previously discussed, potash solution mines reach one kilometre underground; however, the flow simulation software cannot mesh a model of this size. Instead, a finite difference method (FDM) will simulate a 100 m mine, and use the flow simulation to validate the results. Once validated, the FDM can be expanded to one kilometre.

Assumptions Made
The following assumptions were made during the simulations:

- The flow rate through the mine is large enough to pump the brine out at the same volumetric flow rate as it entered. This stems from an assumption that the water is being injected in to the mine using a pump that can control the flow rate.
- The surrounding earth is large enough to maintain a constant temperature so that heat transfer through the mine is steady state.

Finite Difference Method Model
The mechanism of heat transfer through the solid region of the model is conduction. The steady state conduction heat equation in two dimensions given by Jeffrey (2003) as;

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

Equation 1: General Heat Transfer Equation in Two Dimensions

By dividing a body into nodes, Equation 1 can be approximated by using a 'finite linear difference equation' (Rathmore and Kapuno, 2011). These equations vary for main body nodes, corner nodes and isothermal nodes, as shown in Appendix A.

As the mine is symmetrical along its central y-axis, only a thin sector needs to be modelled, as the fluid temperatures will be constant around the mine at each depth. The FDM will therefore model a one degree slice of the mine to reduce the computational demands of modelling the whole mine.

Defining finite difference method equations
The standard finite difference method equations depend on each node being square, as the temperature in each node is calculated from the average temperature at each of its four surfaces (Chari and Salon, 2000). However, the model used with this method has a height to width ratio of 1:0.0034; leading to the conclusion that rectangular nodes would be more suitable for accurate results in both directions.

In order to use rectangular nodes, the FDM equations were re-derived. Equation 2 shows the original equation for an interior node, whereas Equation 3 shows the new equation for rectangular interior nodes. The full derivation of Equation 3 is shown in Appendix A, and the full equations for varying types of nodes shown in Appendix B.

$$T_0 = \frac{T_1 + T_2 + T_3 + T_4}{4}$$

Equation 2: Interior Node Equation

$$T_0 = \frac{b^2\left(T_2 + T_4\right) + a^2\left(T_1 + T_3\right)}{2\left(b^2 + a^2\right)}$$

Equation 3: Rectangular Interior Node Equations

Modelling heat transfer across fluid
The finite difference equations derived previously can only be used for heat transfer by conduction. However, the heat transfer across the fluid occurs by convection. Therefore, the heat transfer coefficient is used to calculate the

temperature change across the solid fluid boundary. The heat transfer coefficient is calculated using the method by Brenni et al. (2002), as shown in Equation 4 and Equation 5. These equations were validated by the authors using experimental data which showed a temperature deviation of only 0.5°C from their simulations. The laminar flow equation is used for the blanket fluid, and the turbulent for the water and brine.

$$Nu = 1.86 \left(\frac{Re\,Pr\,D_i}{L} \right)^{\frac{1}{3}} (\mu)^{0.14} \quad \text{for Laminar Flow}$$

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.3} \quad \text{for Turbulent Flow}$$

Equation 4: Nusselt Number Equations

$$h = \frac{Nu\,\lambda}{D_i}$$

Equation 5: Heat Transfer Coefficient Equations

Using these equations gives the advantage of not having to derive a numerical method for the flow in the pipes from the similar derivations described earlier. However, there is a range for which Equation 4 can be valid, as the Nusselt number has a lower limit of one where heat transfer occurs only through conduction and so the Reynolds number equals zero (Esch, 2004). Equation 4 shows that equating the Reynolds number to zero results in a Nusslet number of zero, which is incorrect and shows that there is a range of validity for the equation. As the Reynolds numbers for all three fluids within the FDM model result in a Nusselt number above one this is not a problem affecting the results, however it should be considered when changing the fluid properties.

The convection heat transfer equation across the boundary (Sawhney, 2010) and the heat transfer downwards through the fluid using a Semi-Lagrangian time step and advection (Kjerfve, 1994), Equation 6 and Equation 7 respectively, can be used iteratively to calculate the fluid temperature. The Semi-Lagrangian time step allows for the analysis of the heat transfer of a single particle flowing through the pipes, while the rest of the system stays at a constant point in time (Boyd, 2013).

$$\dot{Q} = h\Delta T_{SL}\,ac$$

Equation 6: Heat Transfer across the Pipe Wall

$$T_b = T_t - \frac{\dot{Q}\,\Delta z}{\rho C_p uV}$$

Equation 7: Heat Transfer through the Fluid

These equations are applied at both walls to calculate the heat entering and leaving the fluid. Assuming a well-mixed fluid, the final temperature is taken as the average of the temperatures at each wall.

Heat transfer in the sump
As stated previously, the heat transfer within the sump is too complex to be modelled in this project. Instead, the temperature at the bottom of Pipe 2 is determined by the heat loss resulting from the dissolution of potash. The enthalpy change of solution of KCl and Water, as given in Mittal (2007), can be used with Equation 8 (Jenkins, 2008) to calculate the temperature of the brine.

$$\Delta H = C_p \dot{m} \Delta T$$

Equation 8: Change in Enthalpy Equation

Flow Simulation Model
SolidWorks Flow Simulation 2013 software was used to simulate the heat transfer throughout the mine.

Boundary conditions
The computational domain within the model uses symmetry planes to reduce the computational power required to converge to a solution. This is shown in Figure 4, where the bold lines show the computational domain, and the dotted lines show the area covered by the symmetry setting. Ideally, the domain would be equal in size to the one degree sector used within the FDM model, however a 90 degree sector is the smallest that SolidWorks allows within its software.
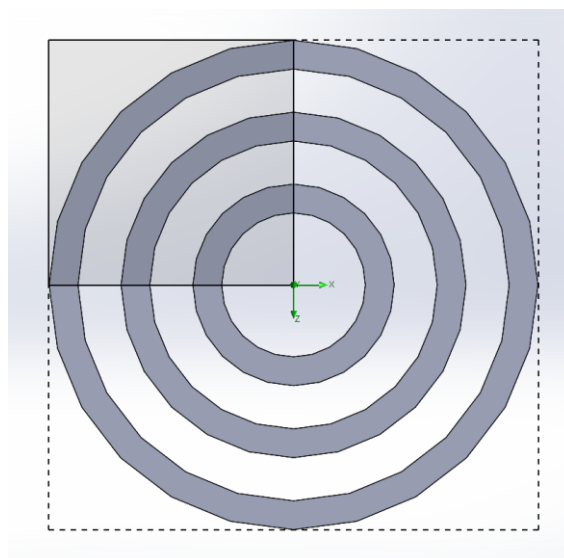
Figure 4: Computational Domain

Table 1 shows the boundary conditions set within the model, and the justification for using each setting. As the inlet temperature of Pipe 3 depends on the outlet temperature of Pipe 1, iterative simulations will be run.

Mesh independence

In order to create a balance between the computational resources needed and accurate results, a mesh independency study is carried out. This shows which mesh refinement level, a setting that defines the maximum element size, should be used for the simulations. As the mesh refinement level increases, the maximum element size decreases, leading to a larger number of elements. Figure 5 shows the variance between the temperatures at the bottom of Pipe 1 with the number of elements used within the mesh. From mesh refinement levels of three to five, 55370 and 199440 elements respectively, the temperature varies by 0.06 K, a percentage difference of 0.0001%. This shows that the simulations can be carried out using a mesh refinement level of three.

Table 1: Boundary Conditions

Section of Model	Boundary Condition	Justification
Pipe 1 Inlet	Volumetric Flow Rate of 0.011m^3/s	Data from Environmental Resources Management (2012) for Allana Potash Corp.
	Temperature of 292.9 K	The average atmospheric temperature on the 19th of August 2013 in Saskatchewan, the know location of a potash solution mine. (Government of Canada, 2013)
	Fluid	Water
Pipe 2 Inlet	Velocity of 0.045 m/s	The blanket fluid within the mine will be stationary, but in order for the simulation to work it needs to be moving. Therefore, a very small velocity was chosen.
	Temperature of 292.9 K	The average atmospheric temperature on the 19th of August 2013 in Saskatchewan, the know location of a potash solution mine. (Government of Canada, 2013)
	Fluid	Diesel Fuel
Pipe 3 Inlet	Dependant on Pipe 1 outlet temperature	
	Fluid	Brine

[52]

| Pipe 1, 2 and 3 Outlet | Environmental Pressure of 101325 Pa | Standard Sea Level Conditions. As the flow rate through the mine is assumed to be constant keeping the pressure at inlet and outlet the same will stop any acceleration or temperature changes due to a pressure difference. |
| | Environment Temperature of 292.9 K | The average atmospheric temperature on the 19th of August 2013 in Saskatchewan, the know location of a potash solution mine. (Government of Canada, 2013) |
| Pipe 1 Wall | Wall Temperature Dependency of 292.9+0.0275y where y is the depth underground in meters and 292.9 is the atmospheric temperature in Kelvin | Applied to the outside of the mine to simulate the varying temperatures |
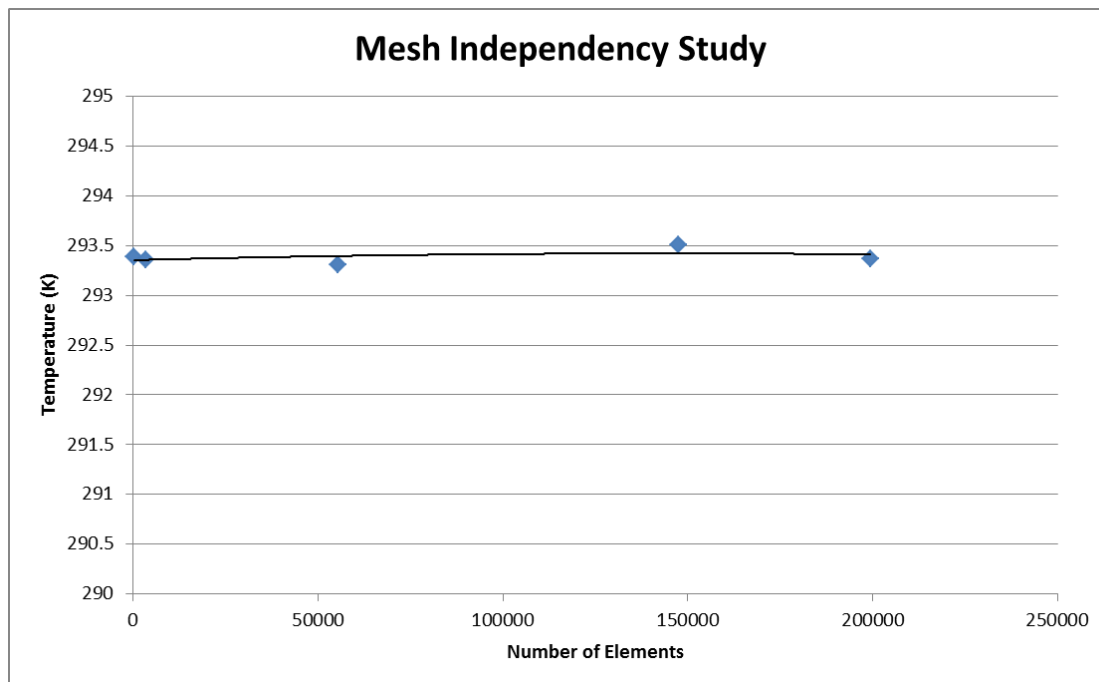
Figure 5: Mesh Independency Study Graph

Iterative simulations

The inlet flow temperature of Pipe 3 depends on the outlet temperature of Pipe 1, as discussed previously. However, the outlet temperature of Pipe 1 also depends on the heat transfer from Pipe 3. Where the FDM model calculates this iteratively using circular referencing, the SolidWorks simulation cannot do this. Instead several simulations were carried out, varying Pipe 3 inlet by using Equation 8. The results from the simulations are shown in Table 2, where the Initial Pipe 1 Outlet Temperature is the temperature from the previous iteration. This value in Iteration 1 was taken from running the simulation with no flow in Pipe 3.

**Table 2:** Iterative Simulation Results

Iteration	Initial Pipe 1 Outlet Temperature	Pipe 3 Inlet Temperature	Final Pipe 1 Outlet Temperature
1	293.31	292.9371	293.29
2	293.29	292.9171	293.28
3	293.28	292.9071	293.28

Table 2 shows that the simulations converged to an inlet temperature of 292.9071 K and this will be used to compare with the FDM model.

Results

Validation study

It is important that the results from the simulations and the FDM model are similar so that any results provided are validated. Figure 6 shows the temperature variation through Pipe 3, and the difference between the FDM and flow simulation results. It shows that the maximum difference in results is 0.24 K. However, the flow simulation results show a slight increase in temperature with depth underground whereas the FDM model shows a constant temperature. This could be due to the FDM model being less accurate because of the number of nodes used. Increasing the amount of nodes used within the model would increase the demand on computational resources and increase the time needed for a result to converge. Therefore, the difference between the two results can be considered to be small enough to validate the FDM model.
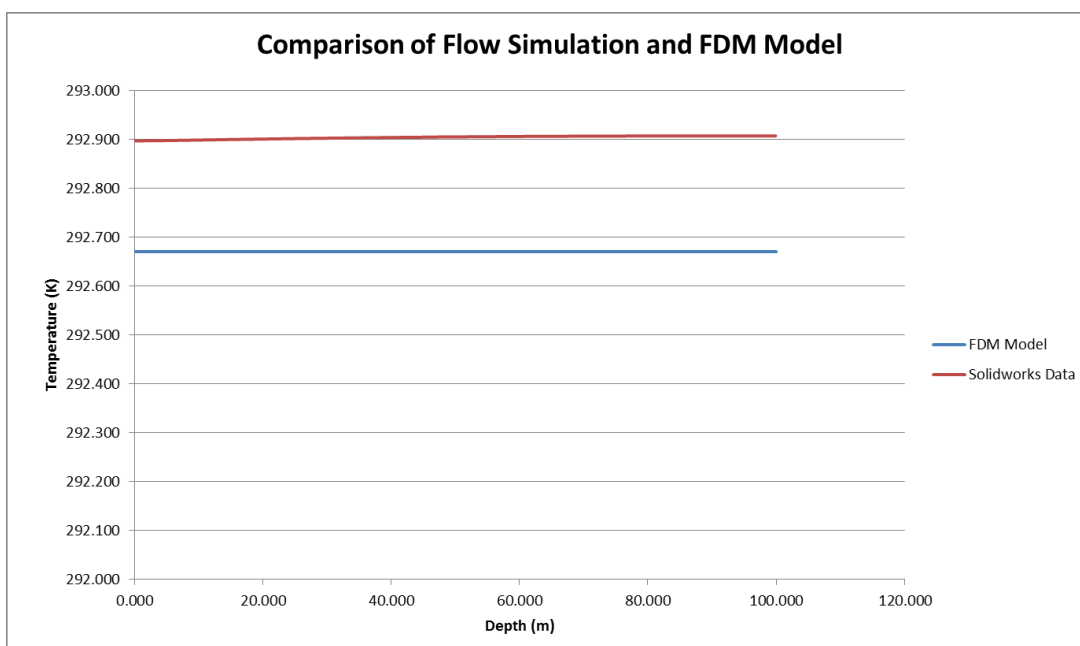
Figure 6: Flow Simulation and FDM Model Graph

Initial results

Setting the FDM model with the conditions stated in Table 1, results in the temperature distribution at the bottom of Pipe 1 as shown in Figure 7. It is clear that the temperature increases with depth, following a 2nd order polynomial shape. However, it also shows that the temperature of water entering the sump at 1000 m does not reach 328 K, it only reaches 301 K. This means that the concentration of potash described earlier is not achieved.
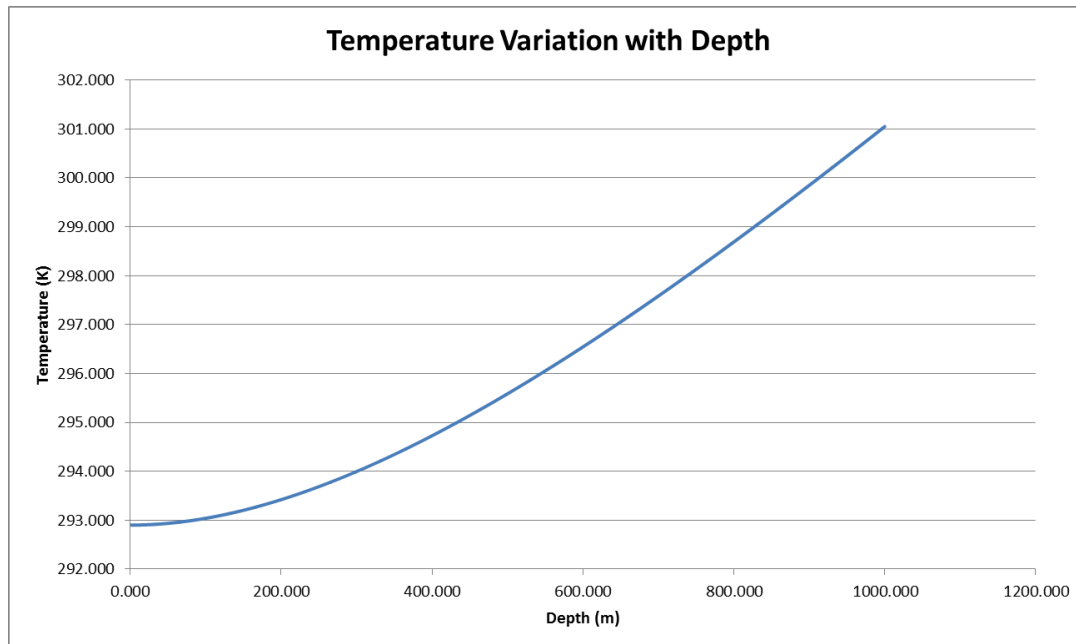
Figure 7: Graph showing the variation in Temperature of Water with Depth

The equation of the graph is shown in Equation 9, taken from the Microsoft Excel equation feature, where y is the depth underground and x is the temperature of the water.

$$y = 5e\text{-}6x^2 + 0.0031x + 292.67$$

**Equation 9:** Temperature Variation with Depth

Rearranging Equation 9 and solving for x shows that the sump would have to lie at 2366.21m underground to provide a temperature of 328 K (Full calculation in Appendix C). This is an assumption based on the data available following a constant trend, and so cannot be relied on fully. Additionally, there are obvious problems with having a mine at this depth, the most important being that the depth depends on the location of the potash deposits. Therefore, with any design of a solution mine, the depth of the mine should be kept as a constant.

Varying inlet temperatures

To provide realistic results, it must be remembered that the atmospheric temperature at any location will not be constant throughout the year. Running the FDM model with varying atmospheric temperatures shows the variation in

temperatures at the bottom of Pipe 1, as shown in Figure 8. Figure 8 uses the data from atmospheric temperatures in Saskatchewan on the 19th day of each month in 2013 (Government of Canada, 2013).
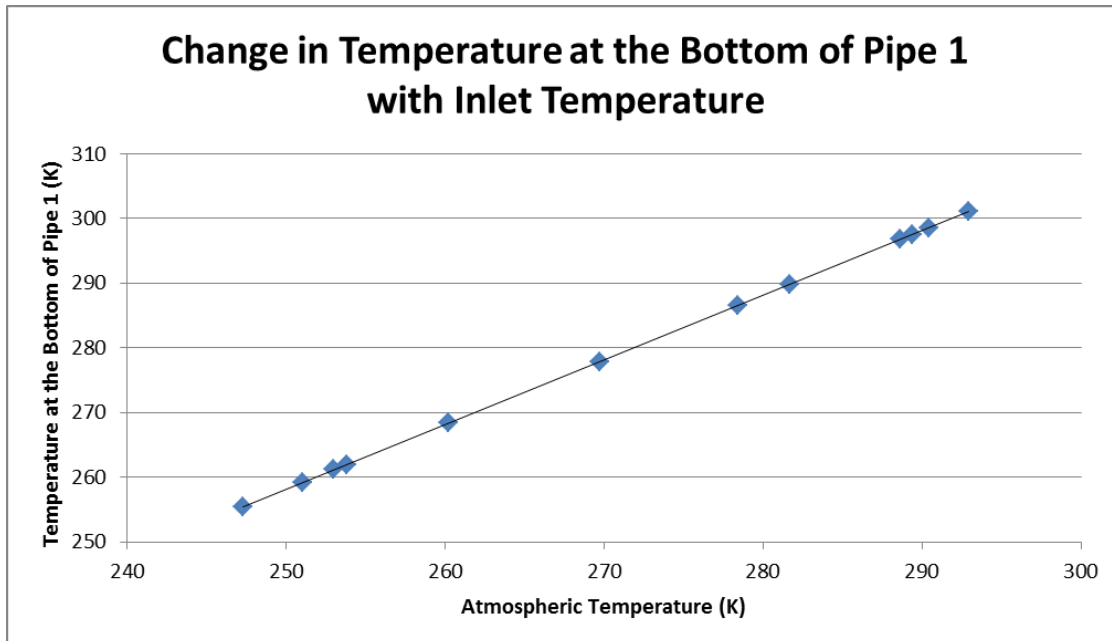
Figure 8: Graph showing the Variation of Temperature at the bottom of Pipe 1 with Atmospheric Temperature

Figure 8 shows that as the atmospheric temperature decreases, the temperature at the bottom of Pipe 1 also decreases. The relationship between the two variables is linear, allowing for the calculation of the ideal atmospheric temperature for a temperature of 328 K. Equation 10 shows this relationship, with y equalling the temperature at the bottom of pipe 1 and x equalling the atmospheric temperature.

$$y = 0.9999x + 8.182$$

Equation 10: Temperature Variation with Atmospheric Temperature

Equation 10 can be rearranged in terms of temperature at the bottom of the mine, to give Equation 11.

$$x = \frac{y-8.182}{0.9999}$$

Equation 11: Rearranged Temperature Relationship

Setting the temperature at the bottom of the mine shows that the atmospheric temperature would have to be 319.85 K. As with Equation 9, this is an assumption based on the data available following a constant trend, and so cannot be relied on fully. However, it strongly suggests that In order to achieve this temperature the input water would have to be heated using a fossil fuels or renewable energy sources.

Varying flow rates

The initial results used a volumetric flow rate of 0.011 m^3 (Environmental Resources Management, 2012) and shows that the temperature of 328 K is not achieved at the bottom of the water inlet pipe. As the ground temperature at 1000 m is only 320 K, it is clear why this is the case and an external energy source will be required to reach a water temperature of 328 K. However, by changing the flow rate and increasing the heat transfer, the temperature at the bottom of Pipe 1 could be increase and the need for an external energy source could be reduced.
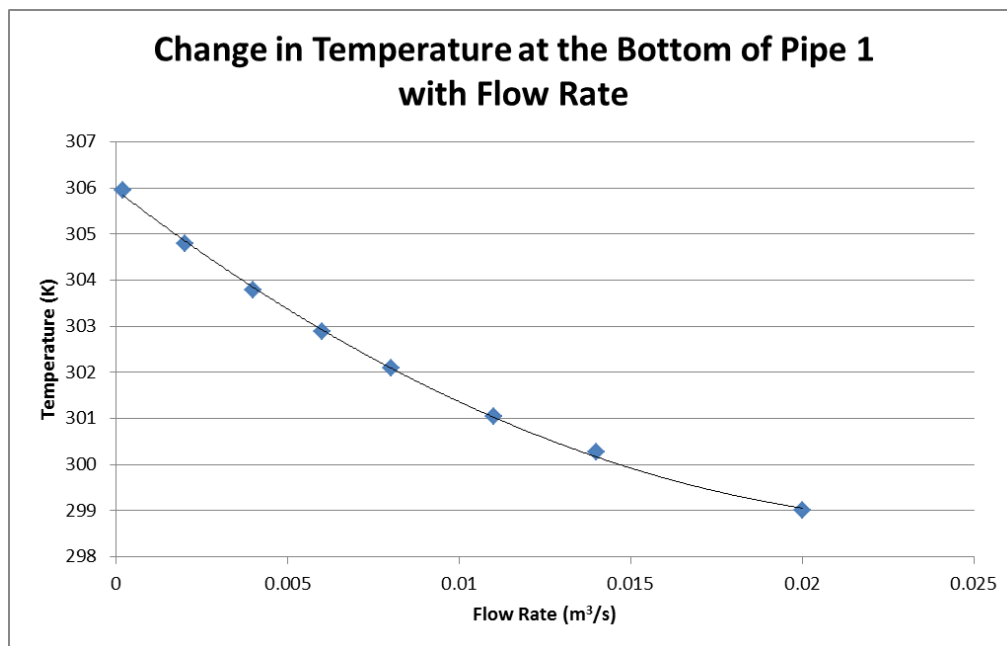
Figure 9: Graph showing Temperature Variation with Flow Rate

Figure 9 shows that as the volumetric flow rate reduces the temperature at the bottom of the water inlet pipe increases to a value of 305.95 K at a flow rate of 0.0002 m^3/s. This is an unexpected result, as the heat transfer at constant volume, shown in Equation 12, shows that as flow rate increases, so should heat transfer.

$$\dot{Q} = \dot{m}C_p\Delta T$$

Equation 12: Heat Transfer Equation

However, the heat transfer across the boundary between the pipe and the water causes the temperature to decrease with an increase in flow rate. By rearranging Equation 7 for Q, equating to Equation 6 and rearranging to make the change in temperature across the pipe wall the subject of the equation, gives the formula shown in Equation 13 (Full calculation shown in Appendix D).

$$\Delta T_{SL} = \frac{\Delta T_{tb}\rho C_p uV}{\Delta zhac}$$

Equation 13: Temperature Change Across the Pipe Walls

Equation 13 shows that the temperature change is governed by a factor of 1/h. As the heat transfer coefficient decreases, the temperature across the pipe wall will increase. Equation 13 also shows a factor of velocity effects the temperature change, which also decreases with flow rate. However, plotting velocity against heat transfer coefficient, as shown in Figure 10, shows that for every 1 m/s velocity decreases, the heat transfer coefficient decreases by 1838 w/m²K. This means that the heat transfer coefficient has a much larger effect than the velocity.
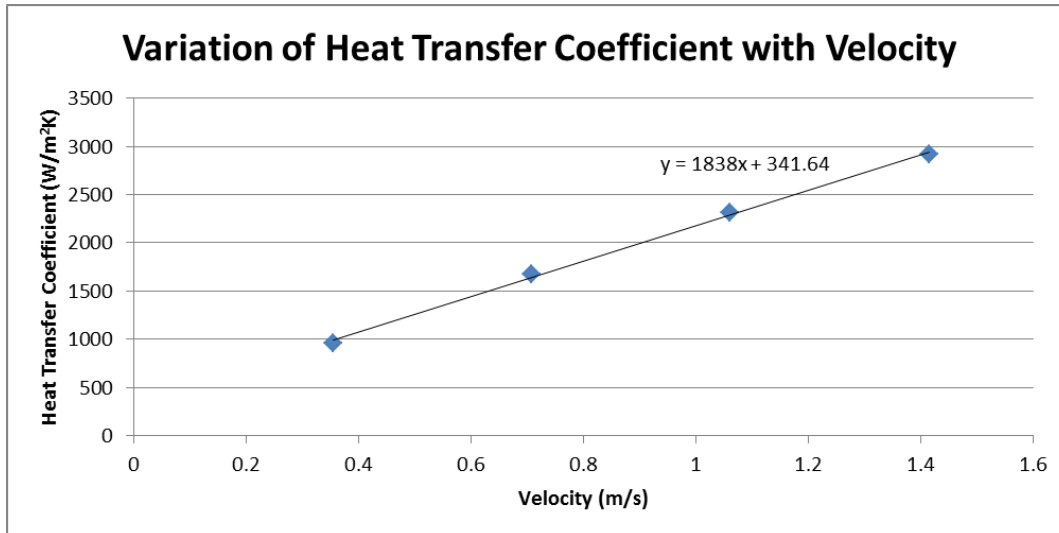

Figure 10: Graph of Heat Transfer Coefficient and Velocity

Varying blanket fluids
As previously discussed, the heat transfer to the water comes from both the underground temperature and the heat of the brine travelling through pipe 3. However, the blanket fluid lies between the two fluids and is acting as an insulator. This can be shown through Equation 6 as the blanket fluid has a low heat transfer coefficient, causing low heat transfer through the walls. The blanket fluid is used to stop the flow of water dissolving the roof of the cavern, and for that reason is a fluid that is less dense than water and immiscible. Table 3 shows the results of running the FDM model with a range of fluids that fit this specification. Appendix E gives the properties for all fluids used within the FDM model and the various blanket fluids.

Table 3: Effect of Blanket Fluid on Temperature at the Bottom of Pipe 1

Fluid	Heat Transfer Coefficient	Temperature at the Bottom of Pipe 1
Diesel Fuel	13.151	301.053
Gasoline	4.493	301.053
Kerosene	7.516	301.053
Naphtha	38.757	301.053

Table 3 shows that within the range of fluids which are both immiscible in water, and have a lower density than water, there are none that have a high enough

heat transfer coefficient to allow for the heat of the brine to reach the water in pipe 1.

Discussion

General findings of the project
The previous sections show that in order to reach the specified temperature of 328 K the mine input water must be pre-heated with an external energy source as the heat transfer from the surrounding ground is not sufficient. Reducing the flow rate of the water increases the heat transfer into the water from the pipe walls and this can be used to increase the efficiency of the mine. However, it must also be considered that there will be a limit to how much the flow rate can be decreased in order to pump the brine out of the mine.

In addition, the results also show that the main reason that the heat from the hot brine cannot reach the water is the properties of the blanket fluid. This is due to the heat transfer coefficient of the various blanket fluids appropriate for use in the process. The results showed that Naptha would be the best fluid to use, however it still only had a coefficient of 38.757, compared to 1024.770 and 1082.5 calculated for the water and brine respectively. However, the process of solution mining cannot be completed without a blanket fluid or a major redesign of the apparatus used.

Limitations in the project
There is a range of limitations within the project which mean that the results provided will not fully reflect a working solution mine. The main limitation is the lack of modelling within the sump of the mine. The FDM model assumed that no heat transfer occurs within the mine; this would not be the case. However, modelling the boundary conditions, heat transfer and endothermic reaction due to the dissolving of potash within a sump that expands as the walls are dissolved would be very complex.

This means that the results do not fully reflect the results from a real mine. As the temperature of the brine as it leaves the sump is inaccurate, the heat transfer from the brine across the pipes to the water inlet will also be inaccurate.

Limitations of FDM model
There are limitations of the model created due to the size of the mine being analysed. The more nodes used within the model increases the accuracy of the results; however, Microsoft Excel has a limit on the number of cells within a worksheet.

In addition, the model created does not allow for the change of properties with a change in temperature, for example thermal conductivity or density. These parameters have an effect on the heat transfer, and the use of Excel 'IF Statements' was attempted; however this exceeded the computational resources available for the project.

Finally, the properties of brine within the model are not accurate. The properties depend on temperature and salinity of the brine, and are not readily available in publications. Therefore, the model uses the density and thermal conductivity of brine, but the rest of the properties were assumed to be the same value as water.

Conclusion

In conclusion, a numerical method has been designed to predict the performance of a solution mine. The use of the finite difference method has allowed for a range of quantitative results to be calculated in order to discover whether a solution mine can be used without heating up the input water. The model was validated by the use of SolidWorks flow simulations, however the limitations of the model also show that any results must be further validated to be used in any professional situation.

The results show that with the mine analysed, the input water would have to be heated to maintain a constant concentration. As flow rate can be varied, the main variable affecting the mine is atmospheric temperature. The atmospheric temperature also does not allow for a constant concentration of brine to be produced, as it varies dramatically throughout the year in Saskatchewan. An ideal location for a solution mine, therefore, would be an area with high temperatures that vary minimally throughout the year, for example countries that lie near the equator.

Recommendations

Recommendations for the project

The finite difference model can be improved by allowing for the properties of water to change with temperature. An increase in nodes, if computational resources allowed it, would also result in more accurate temperature variations through the mine. In addition, further research into the thermodynamic properties of the brine at difference salinities and temperatures would improve the model.

The simulations used within the validation study could be further used as a means to gather quantitative results; however greater understanding of the boundary layers and an improved mesh with inflation layers and bodies of influence may be necessary. In order to carry this out a more sophisticated computational fluid dynamics program would be required, such as ANSYS.

In addition, information from experimental data could further validate the FDM model and provide a full comparison of results.

The model could be taken forward by considering the heat transfer as transient, and whether this would affect the results provided.

Finally, further research and calculation of the relationship between flow rate and input water temperature could be used as a method to design the ideal parameters for a solution mine to maximise efficiency.

Recommendations for industrial operations
In order to achieve a more efficient mining set up where running costs of heating the inlet water are reduced, the use of blanket fluids could be reduced or removed altogether. For example this could by reducing the diameter of the pipe holding the brine, reducing the thickness of the blanket layer and reducing its insulating properties.

In addition, the use of a double-pass system whereby the brine removed from the system is then used as the inlet fluid could reduce the need to heat any water. Assuming that the brine is not fully saturated would allow for more potash to be dissolved through the second pass of fluid.

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