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Heat transfer analysis of large scale seasonal thermal energy storage for underground mine ventilation

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Abstract

Deep underground mining is highly energy intensive due to the need to overcome high pressure rise required by ventilation fans, high cooling load in summer due to rise in rock temperature and the auto-compression effect, and heating requirement in winter. Rising energy costs have led the mining industry to look for alternatives in energy-efficient systems to reduce the operating costs as well as to reduce the carbon footprint. This paper addresses the challenge by utilizing naturally available renewable energy source from seasonal cycle for heating and cooling of underground mines: heat in the summer is stored in the rock-pit to be used for heating in winter, and the "cold" energy in winter is captured and is stored in the rock-pit for cooling during summer. A three-dimensional unsteady local thermal non-equilibrium (LTNE) model is developed to evaluate thermal storage and heat transfer between ventilation air and rock-pit (large broken rock mass). The results suggest that the seasonal thermal energy storage (Se-TES) of rock-pit is able to assist thermal management in underground mine and to reduce energy consumption for winter heating and summer cooling. The ventilation air temperature is about 15 to 20 ˚C higher/lower as compared to ambient temperature in winter/summer, respectively. Clearly, this shows potential application of large scale Se-TES in mining industry.

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Keywords: Seasonal thermal energy storage (Se-TES); Mine ventilation; Porous medium; Rock-pit; energy efficiency

Introduction

Recent decades have witnessed an increasing worldwide popularity of absorption chillers and heat pumps due to their irreplaceable advantages in renewable energy utilization and waste heat recovery [1]. The rate of change of rock temperature with depth is expressed as the geothermal gradient and vary substantially in different mining areas in Canada and elsewhere [2,3], and to a lesser extent within a large deep mine. Mining, especially in cold environments, also require considerable amount of heat energy for heating and other purposes**.**

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Some mining operations, for example Creighton and Kidd Creek mines in Canada, have the opportunity to use the huge mass of their waste rock as a massive seasonal thermal energy storage (Se-TES) unit in order to create a unique type of heat exchanger; namely “Natural Heat Exchanger”. In this type of heat exchanger, fresh air is moved through the huge mass of broken rocks dumped in to an open pit. The heat exchange between the broken rocks and the fresh air will lead to significant decrease in ventilation costs in these mines for both winter and summer times. Analysis of the accepted methods for the design and understanding of airflow and heat exchange through large fragmented rock bodies in mines, such as those at Creighton and Kidd Creek Mines, reveal them to be still fundamentally only empirical in nature [4,5]. To the best of author’s knowledge, none of them had focused on the three-dimensional analysis of heat transfer and fluid flow in the rockpit seasonal thermal energy storage. Mathematical modeling and numerical simulation help engineers to understand in-depth heat transfer in these large scale seasonal thermal energy storage systems which are the theme of this paper.

Numerous computer programs have been developed to investigate the flow of compressible and incompressible fluids through strata [6,7]. Most of these programs are based upon the porous media concept in which it is assumed that any one stratum contains evenly distributed interconnected pores [6,8,9]. Others adopt a fractured media approach and assume that all flow occurs through discrete but interconnected fractures within the strata. An extensive study of fluid flow and heat transfer in porous media was undertaken by Whitaker [10], Vafai and Tien [11] and Ghoreishi-Madiseh et al. [12] who have also analyzed fluid flow and heat transfer in saturated porous media profoundly. Hamm and Sabet [13] have used the FLUENT software (Fluent Inc., 2010) to conduct heat transfer analysis to evaluate whether thermal energy in flooded coal mines in France can be used for district heating purposes.

Limited number of research work, most important of them [6,14], have been dedicated to the study of heat transfer in large scale thermal energy storage systems for mine ventilation purposes. The empirical approach suggested by Sylvester [6] can be used to estimate the heat storage capacity of Creighton mine rock-pit which is based on thermodynamics approach; it, however, does not provide applicable engineering tools for design such systems. Later, Schafrik [14] developed a numerical simulation model for Creighton mine and tried to validate its results in laboratory (small) scale. However, the validity of the results of this method in real scale is yet to be examined. Furthermore, their CFD model only focused on the isothermal flow behavior without taking into account transient 3D heat transfer and storage system.

To conclude, there is a fundamental need for a generally applicable, but sufficiently reliable, engineering design method based on which the thermal energy storage capacity of broken rock mass of any mine can be assessed. Therefore, the aim of this paper is threefold: (*i*) to developed a three-dimensional transient mathematical model of fluid flow and heat transfer of large scale SeTES; (*ii*) to quantitatively compare the effect of local thermal equilibrium (LTE) versus local thermal non-equilibrium (LTNE) approximation to the heat transfer performance; and (*iii*) to evaluate the effect of exhaust fan pressure with regards to the annual evolution of air temperature, thermal storage performance as well as potential energy savings and carbon footprint reduction.

2. Model description

Here, a 3D model of the rockpit – a large mass of broken rock - for seasonal thermal energy storage system of Creighton mine in Canada is proposed. This rockpit model is assumed to be placed over a cone-shaped mine pit which is 697 m in diameter and 330 m deep. Filling the pit with rocks has created a porous rockpit mass. The thickness of the rockpit mass at its very bottom is 133 m. This porous medium is accessed from the underground through 6 trenches. These trenches are connected to mine ventilation shaft(s) where ventilation fans will continuously move fresh air through rock pit, trenches, mine shaft(s) and other underground openings. It is expected that due to seasonal temperature difference, thermal energy (hot and cold) can be stored in the broken rock as a sensible heat.

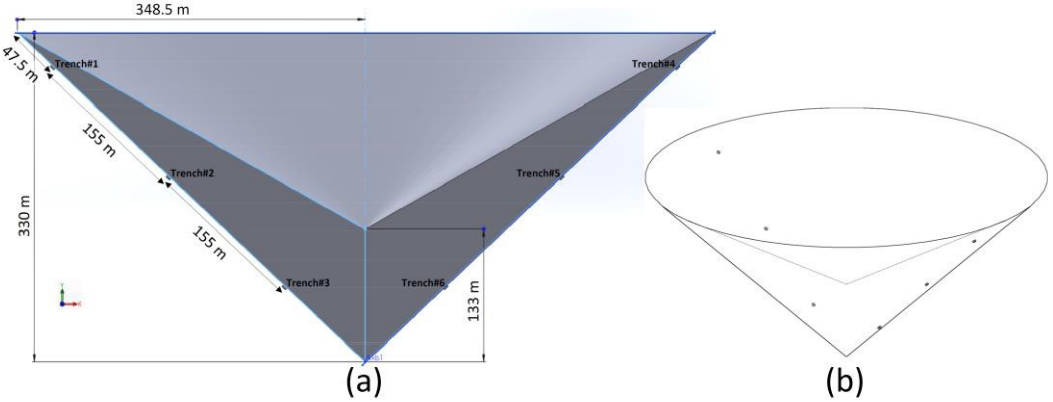

Fig. 1. (a) Mid-plane view of rock pit and trenches; (b) 3D view of the rock pit and trenches; not the same scale as Fig.1a

The model considers transient fluid flow and heat transfer between ambient air and the broken rock at local thermal non-equilibrium (LTNE) by accounting for the interphase energy transfer between two phases (namely, fluid air and solid rock). The air temperature at the top of the rock is varied according to weather conditions following sinusoidal function with the lowest temperature in the winter -25 ˚C and the highest temperature in the summer 25 ˚C. The outlet air pressure at the six trenches is prescribed according to the suction pressure from the ventilation fans. Thermo-physical properties of the model are given in Table 1. Air is assumed to be ideal gas and its properties are calculated based on standard thermodynamic charts.

The governing equations for conservation of mass, momentum and energy for air and rock are

$$\partial \varepsilon\rho_{\mathrm{f}} / \partial t + \nabla\cdot\left(\rho_{\mathrm{f}}\mathbf{u}\right) = 0 \tag{1}$$

$$\partial\left(\varepsilon\rho_{\mathrm{f}}\mathbf{u}\right)/\partial t + \nabla\cdot(\rho_{\mathrm{f}}\mathbf{u}\otimes\mathbf{u}) = -\nabla p + \nabla\cdot\left[\mu_{\mathrm{f}}\left(\nabla\mathbf{u}+\left(\nabla\mathbf{u}\right)^{\mathrm{T}}\right)-\frac{2}{3}\mu_{\mathrm{f}}\left(\nabla\cdot\mathbf{u}\right)\mathbf{I}\right]+\rho_{\mathrm{f}}\mathbf{g}-\frac{\mu_{\mathrm{f}}}{\kappa}\mathbf{u} \tag{2}$$

$$\partial\left(\varepsilon\rho_{\mathrm{f}}c_{\mathrm{p,f}}T_{\mathrm{f}}\right)/\partial t + \nabla\cdot\left(\rho_{\mathrm{f}}c_{\mathrm{p,f}}\mathbf{u}T_{\mathrm{f}}\right) = \nabla\cdot\left(\varepsilon k_{\mathrm{f}}\nabla T_{\mathrm{f}}\right)+h_{\mathrm{fs}}A_{\mathrm{fs}}\left(T_{\mathrm{s}}-T_{\mathrm{f}}\right) \tag{3}$$

$$\partial\left(\left(1-\varepsilon\right)\rho_{\mathrm{s}}c_{\mathrm{p,s}}T_{\mathrm{s}}\right)/\partial t = \nabla\cdot\left(\left(1-\varepsilon\right)k_{\mathrm{s}}\nabla T_{\mathrm{s}}\right)+h_{\mathrm{fs}}A_{\mathrm{fs}}\left(T_{\mathrm{f}}-T_{\mathrm{s}}\right) \tag{4}$$

where subscript $_{\mathrm{f}}$ and $_{\mathrm{s}}$ represents the fluid and solid phase, respectively. ρ is the density, **u** is the fluid velocity, p is the pressure, ε is porosity, μ is the dynamic viscosity of the fluid, c_p is the specific heat, k is thermal conductivity and T is the temperature. The interphase mass transfer is taking into account the specific surface are, A_{fs}, defined as [15]

$$A_{\mathrm{fs}} = 6\left(1-\varepsilon\right)/d_{\mathrm{p}} \tag{5}$$

where d_{p} is the diameter of broken rock. The heat transfer coefficient h, is given by [15]

$$1/h = d_{\mathrm{p}}/Nu_{\mathrm{fs}}k_{\mathrm{f}} + d_{\mathrm{p}}/\beta k_{\mathrm{s}} \tag{6}$$

and the Nusselt between air and rock is defined as [15]

$$Nu_{\mathrm{fs}} = \left(0.255/\varepsilon\right)\mathrm{Pr}^{1/3}\,\mathrm{Re}^{2/3} \tag{7}$$

The boundary conditions is as follows

- *at top of the rockpit*: we prescribe constant ambient pressure, while the temperature is dynamics depending on the weather condition

$$p_{\mathrm{top}} = p_{\mathrm{amb}},\ T_{\mathrm{top}} = T_{\mathrm{amb}} = 25\times\left(\sin\left(2\pi\left(t-7884000\right)\right)/31536000\right) \tag{8}$$

- *at side and bottom pit walls*: no slip condition and zero heat flux is applied.

$$\mathbf{u}=0,\ \mathbf{n}\cdot\nabla T=0 \tag{9}$$

- *at the trenches outlet*: we set the exhaust ventilation fan pressure.

$$p_{\mathrm{out}} = p_{\mathrm{fan}},\ \mathbf{n}\cdot\nabla T=0 \tag{10}$$

Table 1. Thermo-physical properties of the model

Property	Value
Thermal conductivity of rock (W/m.K)	2
Specific heat capacity of rock (J/kg.K)	10^3
Density of rock (kg/m^3)	3×10^3
Permeability of porous rockpit (m^2)	9.26×10^{-8}
Average rock diameter (m)	1.2
Porosity	0.4

The governing equations were solved using a finite volume based user-defined numerical simulation code developed in ANSYS Fluent 15 and user-defined functions (UDF) written in C language to take into account the interphase energy transfer and transient boundary condition. The numerical model was solved with Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm, second-order upwind discretization and Algebraic Multi-grid (AMG) method.

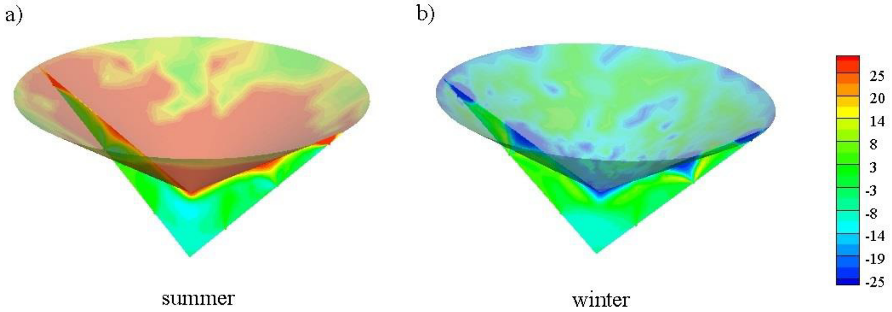

Fig. 2. Temperature contours of the top surface and mid-plane cross section of the rock pit at (a) 9th year summer; (b) 9th year winter

Results and discussions

Fig. 2 shows the resulting temperature contours of the top surface and mid-plane cross section of the rock pit at the summer and winter of the 9th year of system operation. Effect of ambient temperature on the rockpit is mostly observed on its surface which is in contact with ambient air. But, as air travels deeper into the rockpit mass, it will exchange heat with it and its temperature will approach that of the rocks. Since ventilation engineers are primarily interested in predicting the temperature of fresh air as it reaches the ventilation fans, Fig. 3 shows the mass averaged outlet temperature of air (after heat exchange between air and rockpit mass is complete) along the ambient air temperature at mine site. According to Fig. 3, the results of LTE and LTNE models are very similar with less than 2% difference. Also, Fig. 3 shows that the seasonal thermal energy storage has led to a considerable decrease in annual oscillation of ventilated air: ambient air oscillates between -25 °C to +25 °C while the outlet air temperature varies between -8 °C to +7 °C. These results are qualitatively in-line with findings of Sylvester [6] which showed an average outlet temperature between +3 to -3 °C. Note, however, that quantitative comparison is not possible at this time since in our model the ambient temperature is assumed to be sinusoidal function from -25 to +25 °C, whereas Sylvester assumed the average summer temperature as 10.2 °C and winter is -7.3 °C. A more precise geometrical model and real seasonal temperature data simulation is underway to improve the accuracy of its prediction and for validation purpose.

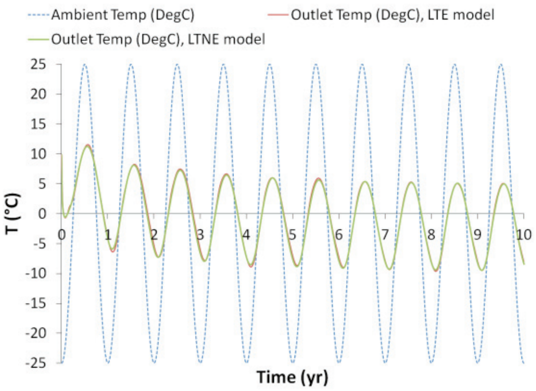

Fig. 3. Ambient air temperature at mine site and average outlet air temperature for LTE and NLTE models

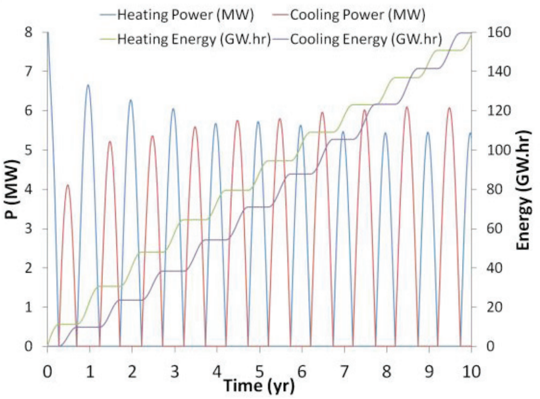

Fig. 4. Heating/cooling power and their associated energy savings

Fig. 4 illustrates the resulting heating/cooling power and their associated energy savings. Note that heating and cooling power are zero during summer and winter, respectively. Fig. 5 shows the outlet air temperature for different fan intake pressure values. For instance, gradual increase of the fan suction pressure, from -1380 Pa to -5520 Pa, will gradually – but not significantly – increase the annual oscillation of outlet air temperature. However, as shown in Fig. 6, this change in fan pressure has led to a considerable increase in economic savings. Fig. 6 includes the two following trends. Firstly, the relationship between the savings and time, for a constant fan pressure, is almost linear. Secondly, doubling fan suction (from -1380 Pa to -2760 Pa) has almost doubled the slope of this linear regression (from 0.658 M$/yr to 1.264 M$/yr). However, further doubling of the suction (from -2760 Pa to -5520 Pa) will increase the slope by only 85% (from 1.264 M$/yr to 2.3405 M$/yr).

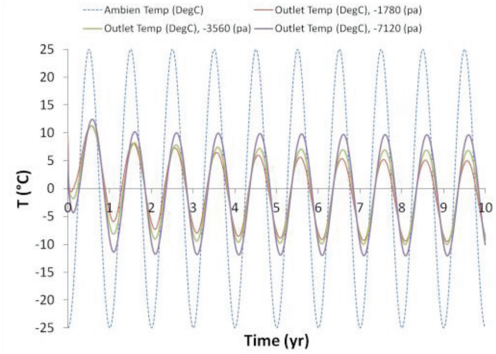

Fig. 5. Effect of fan intake pressure on average outlet air temperature

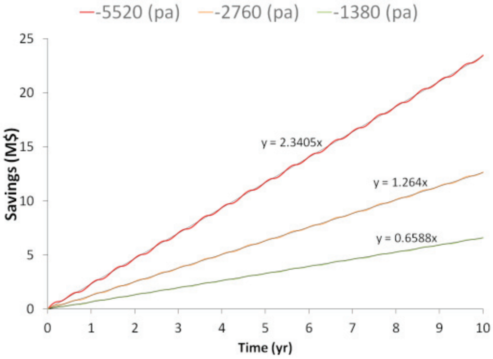

Fig. 6. Effect of fan intake pressure on total savings

Conclusion

An unsteady LTNE model was developed to study heat transfer in large scale seasonal thermal energy storage systems for mine ventilation purposes. It was shown that application of such thermal storage systems will lead to significant energy savings in mine ventilation costs. It was also found that for low Reynolds numbers, the results of LTE and LTNE models are very similar. Energy storage capacity of thermal storage system was further examined by increasing fan suction. It was found that the annual energy savings (M$/yr) can be considerably augmented by increasing fan suction. However, the increase in fan suction will result in a higher annual oscillation of ventilated air temperature. Hence, an optimum combination of design and operating parameters needs to establish which will be the focus of future work.

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Biography

Dr. Ghoreishi-Madiseh has a PhD in Mechanical Engineering from McGill University. He is a research associate at Earth/Mine Energy Research Group at McGill University. He has 8 years of leadership experience in research and development of energy systems and 2 years of hands-on industrial experience in design of thermo-fluid systems.