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# Effect of buoyancy-driven natural convection in a rock-pit mine air preconditioning system acting as a large-scale thermal energy storage mass☆

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## HIGHLIGHTS

- Novel conjugate heat transfer and fluid dynamics model for thermal energy storage.
- Validation against experimental data.
- Evaluating buoyancy-driven natural convection effects.
- Increasing air flow rate is an effective technique to improve energy storage capacity.
- System performance can be augmented through optimum selection of intake trenches.

## ARTICLE INFO

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## ABSTRACT

Underground mining is among the most energy-intensive industries and ventilation comprises a significant portion of the energy demands of this important industry. Using the vast volume of broken rock, left in a decommissioned mine pit, as a thermal energy storage mass has enormous potential to lower ventilation-related energy costs in deep underground mines. This approach facilitates moderating seasonal air temperature variations. Seasonal thermal energy storage is a cost-effective solution to improve cooling and heating process efficiencies, thereby reducing associated costs. Temperature gradients observed in the proposed storage system suggest the presence of a natural convection heat transfer mechanism that is buoyancy-driven. The effect of natural convection and a variety of heat transfer mechanisms were modeled and simulation results and field-data measurements were compared. The conjugate heat transfer and fluid flow model that was developed considers the porous rock mass in the rock-pit along with the air (i.e. fluid) blanketing the top surface. The effects of rock size, permeability and porosity were studied. It was observed that, for the range of porosities (from 0.45 to 0.20), these parameters have a small effect on the outlet air temperature and the performance of thermal storage phenomenon. The novel model compares forced (from ventilation fan) and natural (result of buoyancy) convection. Further, it incorporates the effect of design factors, such as air trench positions and flow rate of ventilated air, on energy savings.

## 1. Introduction

Energy intensity is a major hurdle to future development of the global mining industry. It derives from two major issues: (1) the insatiable demand of the mining industry for energy for electricity, heating, and cooling; and (2) unpredictable fossil fuel prices caused by numerous political and economic factors. Mining is among the most energy-intensive industries, along with chemical, petroleum, and base metals [1,2]. This enormous energy need is accompanied by a long-term trend for fossil fuel prices to rise. Therefore, energy costs constitute a growing portion of the total operating costs of mining operations, which will be exacerbated by the introduction of carbon taxes by major industrial countries [3]. The unreliable nature of the energy market is a fundamental risk source, making operating costs difficult to predict. These major issues have motivated the mining industry to seek new sources and technologies to help improve the energy efficiency, reduce the energy demand, and the shrink carbon footprint of operations [4].

Among the energy-intensive activities at a mine, ventilation (fresh air, air heating and cooling) is a top contributor. Studies have shown

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## Nomenclature

*Abbreviations*

| | |
|---|---|
| LTE | Local Thermal Equilibrium |
| LTNE | Local Thermal Non-Equilibrium |
| STES | Seasonal Thermal Energy Storage |

*Symbols*

| | |
|---|---|
| $\rho$ | density |
| $\rho_f$ | density of fluid |
| $d_p$ | diameter of the broken rock |
| $\mu$ | dynamic viscosity of the fluid |
| $G_B$ | generation of turbulent kinetic energy due to buoyancy |
| $G_k$ | generation of turbulent kinetic energy due to mean velocity gradients |
| f | fluid phase |
| $\mathbf{u}$ | fluid velocity |
| $\mathbf{g}$ | gravitational acceleration |
| $h$ | heat transfer coefficient |
| $\mathbf{I}$ | identity or second order unit tensor |
| $\nabla$ | Nabla symbol |
| $Nu_{fs}$ | Nusselt between air and rock |
| $\partial$ | Partial differential symbol |
| $\varepsilon$ | porosity |
| $p$ | pressure |
| $p_{op}$ | Operating Pressure |
| $p_{top}$ | air pressure at the top of the ambient air |
| M | molecular weight of the gas |
| R | universal gas constant |
| $Pr$ | Prandtl number |
| $Pr_t$ | turbulent Prandtl number |
| $Re$ | Reynolds number |
| $c_p$ | specific heat |
| s | solid phase |
| $A_{fs}$ | specific surface area |
| $A_s$ | surface area through which convection heat transfer takes place (rock-pit surface) |
| $\langle u \rangle$ | superficial fluid velocity |
| $t$ | time |
| $T$ | temperature |
| $T_s$ | surface temperature |
| $T_\infty$ | temperature of the surrounding ambient air that is sufficiently far from the rock surface |
| $T_{top}$ | temperature at top of the ambient air |
| $\kappa$ | thermal conductivity |
| $\kappa_{eff}$ | thermal conductivity of the fluid |
| $k$ | turbulent kinetic energy |
| $\sigma_k$ | turbulent Prandtl number for $k$ |
| $\sigma_\varepsilon$ | turbulent Prandtl number for $\varepsilon$ |
| $\mu_t$ | turbulent viscosity |

that 40% of the overall electricity consumption in a typical underground mine is due to ventilation [5,6] which roughly results in 60% of the total operating costs in these mines [4,5]. In Canada and other countries such as the USA and Australia, the quality and quantity of the ventilation air is regulated. For example, the fresh air flow required in hard rock mines in the province of Ontario in Canada is regulated at 0.06 $m^3/s$ per kW of diesel engine power at a (wet bulb globe) air temperature below 27 °C. To ensure good air quality, especially in the deepest galleries and work faces, underground mine operators typically require enormous amount of fresh air (100–1000 $m^3/s$). Over the past few years, several studies have focused on cost-effective ventilation solutions for underground mines [7].

Ventilation energy demands are in form of electricity (needed to run main/booster/auxiliary fans for air delivery or mechanical refrigeration for cooling) or thermal heat (sourced from fossil fuels such as natural gas, propane, or diesel) [8]. In extremely cold climates, like winter in Canada and many areas in the USA, intake air must be preheated to above 0 °C before sinking down the main ventilation shaft(s). In summer, air temperature should be maintained below 27 °C (wet bulb globe) with a cooling system [9]. Preheating and cooling practices incur account for 50–80% of annual ventilation operating costs (US$4–15 million), depending on the mine depth, production, temperature and the air flow rate.

Ventilation costs cannot be eliminated, but they can be effectively reduced by employing renewable energy sources at mine site [10,11]. For example, seasonal thermal energy storage (STES) involves collecting thermal energy (heat or cold, depending on the outside temperature) when it is available for future use. Storing thermal energy in waste rock is an elegant approach to improve the performance of the mine ventilation system. To create a STES system, huge volumes of waste rock are dumped into a decommissioned pit to create a large seasonal heat storage mass. This massive STES unit provides the mining operation with a “natural heat exchanger”. The amount of sensible thermal energy stored in the STES system depends on the temperature difference between the air and rock mass. By passing ventilation air through the broken rock mass, seasonal temperature oscillations can be moderated, resulting in 50–80% reduction in ventilation costs [11–13].

As a natural and renewable energy storage technique, STES can help deep underground mines meet refrigeration and air preheating requirements and reduce associated greenhouse gas emissions. For example, employing STES at the Creighton mine in Sudbury, Ontario reduced seasonal variations in the temperature of the intake fresh air passing through the natural heat exchanger unit [14]. As mining extends to depths beyond current norms in the Creighton mine, implementation of STES has improved energy management, and has led to considerable savings in capital/operating costs.

Since large-scale STES systems have been deployed, ventilation engineers have gained engineering tools with which they can assess STES system capacity and improve system performance. Their research initiated development of empirical relations that are backed by extensive amount of field data but lack the means of predicting the capability of system to satisfy a growing ventilation demand [15,16]. Another serious shortcoming of empirical models is that they cannot be applied to assess temperatures and air velocities inside the rock-pit over time [11]. To overcome such limitations, researchers have proposed using three-dimensional (3D) models capable of simulating heat transfer and fluid flow in large-scale STES units [11–13,17]. These 3D models enable engineers to achieve a better understanding of the heat exchange phenomena in the rock-pit and to improve the storage capacity of STES units.

To analyze the storage and extraction of heat in such large-scale STES units, it is necessary to establish a clear understanding of heat exchange and fluid mechanics in the porous structure of the rock-pit. This approach is based on assuming a homogeneous porous medium (i.e. solid rock mass and fluid air) [18–20]. Using a volume averaging technique, researchers have been able to derive amenable fluid flow and heat transfer equations for porous media [21–26].

Interphase exchange of heat plays an important role in the performance of STES systems. The local thermal equilibrium (LTE) assumption can be made when the solid phase and the fluid inside the pores are thermally equilibrated in microscopic (pore) scale [27]. However, this assumption is not valid when interphase exchange of heat cannot be