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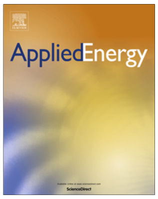

Performance evaluation of large scale rock-pit seasonal thermal energy storage for application in underground mine ventilation

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HIGHLIGHTS

- Model development of seasonal thermal energy storage for underground mine ventilation.
- Model was validated against field measurement data.
- Significant, up to 80%, energy saving due to sensible heat storage.
- Increasing fan pressure gives rise to energy savings, but also increases temperature oscillation.
- Rock properties have marginal effect on thermal storage.

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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 within the rock-pit for cooling during summer. A three-dimensional unsteady local thermal non-equilibrium model is developed to evaluate thermal storage and heat transfer between ventilation air and rock-pit. The results suggest that the seasonal thermal energy storage 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 15–20 °C higher/lower as compared to ambient temperature in winter/summer, respectively. Clearly, this shows potential application of large scale seasonal thermal energy storage systems in mining industry.

1. Introduction

Underground mining operations are commonly associated with very high energy demands in their ventilation side [1]. Studies have shown that, depending on the depth and size of a mine, ventilation costs make up to 40% [2] of the total electricity used, and up to 60% [3] of underground mining operating cost [4]. In addition, mine ventilation is necessary to provide a comfortable and safe working environment underground; and also clear out noxious and flammable gasses [4]. This insatiable demand for heating/cooling is usually met with burning fossil fuels (mostly natural gas, propane or diesel) for heating and electricity (taken from the grid or generated with diesel gen-sets) for cooling. Energy price variations in the last 5 decades and the pending carbon taxation in many countries (including Canada, Australia or USA) have spurred the mining companies towards application of more energy efficient technologies. As a result, many have studied the application of absorption chillers and heat pumps [5]. Furthermore, extensive amount of research work has investigated the application of geothermal energy in mining environment [6,7]. Other studies have shown the techno-economic advantages of using large-scale energy storage units in large-scale heating/cooling systems such as mine ventilation systems [8–10].

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Mining, especially in cold environments like Canada and many US states, requires considerable amount of heat energy for heating purposes. This energy demand cannot be diminished, however renewable heat energy can be extracted from or stored in the resources available at mine side [11]. Storage of large quantities of thermal energy has been distinguished as an effective solution to increase energy efficiency in mine ventilation systems [12]. This unique approach takes advantage of the huge volumes of rock mass available on the surface of the mine for the purpose of seasonal heat storage. The seasonal variations in ambient temperature provides the opportunity of storing thermal energy (hot and cold) in the broken/porous rock mass in form of sensible heat. In Canada and some parts of the USA, to avoid freezing of subsurface facilities during the cold seasons, fresh air has to be pre-heated to slightly above 0 °C temperatures before being blown to the down-cast ventilation shaft(s) of the mine. The costs of propane gas required for this common practice, is between 2 and 4 million dollars per year, depending on ambient air temperature and the amount of air moved by ventilation fans. In summer season, refrigeration costs incur if the mine is deep enough to require pre-cooling of ventilation air. Seasonal heat storage for heating and cooling applications seems to be an effective solution to compensate for seasonal energy demands [13]. Some mining operations, for example Creighton and Kidd Creek mines in Canada, have the opportunity to make use of 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 considerable, between 50% and 80% [12], decrease in ventilation costs in these mines for both winter and summer times.

While significant numbers of authors have based their work on design and understanding of ground-coupled heat exchangers [14–16], using rock mass for thermal energy storage in mining operation is a fairly futile research domain. 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 empirical in nature [17,18]. While field data and empirical model available in literature provides details and insight into the overall behavior, they cannot do so on the local level; for example, spatial variation of temperature and air velocity inside the rock-pit over time is very difficult to be measured directly, and they cannot be predicted by using empirical model. Three-dimensional model, on the other hand, can resolve not only global behavior but also local level of transport phenomena at any given position and time. Thus, the three-dimensional model is the starting point to gain more in-depth information into phenomena occurring inside the rock-pit which later can be used to improve heating and cooling capacity. Moreover, three-dimensional model can also be used as a tool for design, optimization and even innovation. To the best of our knowledge, there is no single validated 3-D model of rock-pit Se-TES available in literature. There is thus need to develop a multi-dimensional model for a rock-pit Se-TES which is able to capture all the transient transport phenomena involved. The present work aims to develop three-dimensional mathematical modeling and numerical simulation to assist scientists and engineers with acquiring an in-depth understanding of heat transfer in these large scale seasonal thermal energy storage systems and improving heating and cooling capacity.

To understand storage/extraction of thermal energy in the rock mass of a Se-TES system, one should focus on heat transfer in this porous medium which comprises air and broken rocks. Numerous computer programs have been developed to investigate the flow of compressible and incompressible fluids through strata [12,19]. Most of these models are based upon the porous media concept assuming that the medium is formed by evenly distributed interconnected pores [12,20,21]. Others adopt a fractured medium approach and assume that all flow occurs through discrete but interconnected fractures within the strata. Extensive studies of fluid flow and heat transfer in porous media were undertaken by Whitaker [22], Vafai and Tien [23,24], Quintard et al. [25], Carbonell and Whitaker [26] and Ghoreishi-Madiseh et al. [27] who have also analyzed fluid flow and heat transfer in saturated porous media profoundly. Hamm and Sabet [28] have used the FLUENT software (Fluent Inc., 2010) to conduct heat transfer analysis to evaluate the extraction of geothermal energy from flooded coal mines in France. To investigate thermal conduction, the values of effective ground thermal conductivity, including the effect of groundwater flow and natural convection in boreholes has been studied by Kyoungbin et al. [29]. The determination of undisturbed ground temperature in a borehole for ground heating/cooling and its effect on the exactness of a thermal response test analysis also has been a related topic of discussion [30].

Limited number of research work, most important of them [12,31], have been dedicated to the study of heat transfer in large scale thermal energy storage systems for mine ventilation purposes. However, there is an essential need for amenable engineering tools such as numerical heat transfer models to understand and improve the performance of these large scale thermal energy storage systems [32]. The empirical approach suggested by Sylvester [12] can be used to estimate the heat storage capacity of Creighton mine rock-pit. While this approach is based on empirical thermodynamic approach, it does not provide applicable engineering tools for design such systems. Later, Schafrik [31] 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 is yet to be examined in real scale. While, the main focus of this Computational Fluid Dynamics (CFD) model is on estimation of air flow through the porous matrix of broken rock mass, it does not provide a substantial study of various heat transfer mechanisms involved in heat storage phenomena.

Interphase heat exchange is of significant importance in modeling heat transfer in porous media. Local Thermal Equilibrium (LTE) approach implies that fluid and solid phases are in thermal equilibrium in pore (microscopic) scale. However, this approach is not valid where heat transfer in one phase dominates interphase heat exchange [33]. Alternatively, Local Thermal Non-Equilibrium (LTNE) approach has been developed for such heat transfer regimes [34]. Thus, one of the main objectives of the present study is to examine thermal equilibrium between the broken rock mass and the air flowing through this solid matrix [35]. Another objective to study the effect of fan pressure (i.e. vented air flow) on the performance heat exchange phenomenon taking place inside the Se-TES [12,31]. While raising the suction of fan(s) increases the air flow, it will shorten the time for heat exchange between the air flow and the rocks. Therefore, the present study investigates how fan pressure will affect volumetric flow rate, rate of heat exchange and the temperature change in large-scale Se-TES systems.

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 LTE vs 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.

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