A porous medium based heat transfer and fluid flow model for thermal energy storage in packed rock beds

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Abstract. Thermal energy storage in packed rock beds helps to reduce energy costs and carbon footprint’s on an industrial, commercial and residential scale. Fluid flow and heat transfer in large-size packed rock beds used in mining applications such as heating/cooling of mine intake air or ventilation of block-caved mines have recently received significant attention. Understanding the porous structure of such packed rock beds is a necessity in the design of such systems. The pressure drop across a rock bed directly affects its heat exchange performance, as it requires additional fan power to circulate air during periods of storage/extraction. In this study, the fluid flow behavior inside a packed rock bed thermal energy storage system is investigated by developing a computational fluid dynamics model and a heat transfer model. The model offers useful information for evaluating the performance of rock beds packed with large rocks or in caved zones. Finally, the main goal of this study is to perform a practical energy saving analysis for porous media composed of large particles by changing the physical properties of the porous medium, such as porosity and permeability. The findings of this study also show that while the total thermal energy storage capacity of the system is not significantly affected by the mass flow rate, a lower mass flow rate can provide a longer working period for thermal energy storage systems.

1. Introduction

Thermal energy storage (TES) systems help to reduce energy costs and carbon footprint’s on an industrial, commercial and residential scale. It is worthwhile to mention that it is generally desirable to use low-cost materials (i.e., air and broken rock) in TES systems [1]. At some mine sites, a possible opportunity for storing sensible thermal energy is a packed rock bed created by broken rock. Using packed rock beds and air as the storage media and heat transfer fluid (HTF), respectively, is considered as a promising approach for TES systems [2-6]. In the literature, many studies have focused on the heat and mass transfer inside the packed beds [7]. The viability of a packed bed of bricks circulating air as a HTF regarding fluid flow and heat transfer was confirmed by Kuravi et al. [8]. Packed rock beds have also been considered as a desirable thermal storage method for solar energy [9]. However, a high rate of heat transfer between solid and fluid is considered as a key factor in evaluating the performance of TES systems [10]. The performance of TES systems depends on many parameters which are not easy to obtain through analytical correlations. As packed rock bed
storage efficiency depends on many designing and operating factors, computational modeling can be considered as a proper way to study and optimize these systems. Hence it is essential to have computational models to evaluate the performance of TES systems. Two important factors should be taken into consideration for designing and operating such a system: (1) the power required to circulate the HTF, and (2) the heat transfer rate between the solid and fluid phases inside of the packed bed. Understanding the porous structure of such packed rock beds is a necessity in design of such systems. The behavior of packed beds of rocks and sand was studied experimentally and numerically by Mertens et al. [9] and Rodat et al. [11]. They presented the influence of various design and operating conditions on TES performances such as air velocity and air temperature. It is worthwhile to mention that most of the available experimental data are documented from laboratory-scale models. Fluid flow and heat transfer in large-size packed rock beds used in mining applications such as heating/cooling of mine intake air or ventilation of block-caved mines have recently received significant attention. The pressure drop across a rock bed directly affects its heat exchange performance, as it requires an additional fan power to circulate air during storage/extraction periods. The current study considers a hot inlet air (120 °C) for charging the TES system that is captured from the exhaust heat of a power plant. The novel concept of using the hot exhaust gases as the heat source of a TES system is proposed. Otherwise, a considerable amount of thermal energy from thermal industrial processes would be discharged to the ambient air [12]. The main goal of this research is to investigate the feasibility of waste heat recovery by means of TES systems for space heating purposes in a cold-climate remote community. Thus, the fluid flow behaviour inside a packed rock bed TES system is investigated by developing a computational fluid dynamics and heat transfer model.

2. Model description

In this study, a volume-averaged model (VAM) is developed to investigate the mass and heat transfer through a packed bed, due to its low computational cost and time, by considering the macroscale fluid flow behavior in the porous media. Empirical correlations are used to estimate the viscous and inertial resistance coefficients as inputs to the VAM. A representative elementary volume (REV) of the porous structure is shown in Figure 1. It should be noted that in the volume-averaging method \( l \geq 5d \) and \( l \ll L \) should be satisfied [13, 14]; where \( d \) is an average pore diameter, \( L \) and \( l \) are the characteristic length of flow domain and the REV, respectively.

![Figure 1. A porous media representative elementary volume (REV).](image)

The 3D computational VAM is created in ANSYS Design Modeler and then meshed and solved by ANSYS FLUENT 17.2. The mass, momentum, and energy governing equations are solved by finite-volume method under local thermal non-equilibrium (LTNE) conditions. They can be obtained as follows:

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\rho (\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \nabla \cdot \left( \mu \left[ \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right] \right) + \rho g - \alpha \mu \mathbf{u} - \beta \rho \mathbf{u}^2
\]

\[
\frac{\partial (\varepsilon \rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{u} T) = \nabla \cdot (\varepsilon k \nabla T) + h_{fs} A_{fs} (T_s - T_f)
\]

\[
\frac{\partial (1 - \varepsilon) \rho c_p T_s}{\partial t} = \nabla \cdot ((1 - \varepsilon) k \nabla T_s) + h_{fs} A_{fs} (T_f - T_s)
\]
Where \( \mathbf{u} \), is the superficial velocity vector, \( \rho \) is the fluid density, \( p \) is the static pressure, \( \mu \) is the dynamic viscosity, \( \varepsilon \) is the porosity. \( \alpha \) and \( \beta \) are the viscous and inertial resistance coefficient, Eq.5 and Eq.6, respectively. \( T \) is the temperature, \( c_p \) is the specific heat, \( h \) is the heat transfer coefficient, \( A \) is the specific surface area and \( k \) is the thermal conductivity. Subscript \( s \) and \( f \) denote the solid phase and fluid phase, respectively. In the current study, we use the well-known Ergun correlation [15] to estimate \( \alpha \) and \( \beta \), the viscous and inertial resistance coefficients, for different porous structures with a range of porosities (\( \varepsilon \)) from 0.2 to 0.5 and a particle size (\( d \)) of 1.0 metre. It should be mentioned that comprehensive numerical and experimental studies must be conducted to obtain these values, and only then should the validity of the Ergun correlation be assessed for each specific packed bed.

\[
\alpha = \frac{150 \times (1 - \varepsilon)^2}{d^2 \times \varepsilon^3} \tag{5}
\]

\[
\beta = \frac{1.75 \times (1 - \varepsilon)}{d \times \varepsilon^3} \tag{6}
\]

Therefore, within the context of TES, a 3D VAM is proposed to study the pressure drop/fan power requirements of the system as a function of porosity and permeability. Due to simplicity of construction, the TES geometry is created as a truncated cone. Design of TES systems is a trade-off between pressure and thermal loss, as well as constructional limitations. According to the literature, an optimum aspect ratio (\( \gamma = H/D_{upper} \)) of height (\( H \)) to upper diameter (\( D_{upper} \)) for a truncated cone TES system should be more than one [7]. However, it should be noted that the design of each specific system can be affected by different technical and economic limitations. Thus, three different geometries with aspect ratios ranging from 1.0 to 1.35 are created with an identical volume of 1830 m\(^3\). The height (\( H \)) of the truncated cones are 10 m, 12 m, and 13.5 m as illustrated in Figures 2.a, 2.b and 2.c, respectively. The upper diameter in all geometries is 10 m and the lower diameters changes from 20 to 16 m.

**Figure 2.** The developed packed bed geometries with different aspect ratios (a) 1.0, (b) 1.2, and (c) 1.35

The transient fluid flow between the air and the solid parts is considered in this research. Velocity inlet and pressure outlet boundary conditions are applied at the top and bottom of the systems, respectively. Additionally, there is a no-slip condition with a zero heat flux boundary condition at the side walls. During the storage/extraction phase, buoyancy effects may occur due to the presence of hot and cold air in the packed bed. In order to minimize the buoyancy effect in this study, hot inlet air at constant temperature of 120 °C is injected through the top of the packed bed. The presented numerical model is solved by Semi-implicit Method for Pressure-Linked Equation (SIMPLE). Thermophysical properties of the storage medium in this study are summarized in Table 1.

| Property                  | Specific heat capacity of rock (J/kg °K) | Density of rock (kg/m\(^3\)) | Thermal conductivity of rock (W/m °K) | Average diameter of rock (m) |
|---------------------------|----------------------------------------|-------------------------------|--------------------------------------|-------------------------------|
| Value                     | 1000                                   | 3000                          | 2.68                                 | 1.0                           |

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3. Results and discussions

Dimensions of the packed rock bed and the size of particles have an influence on the fluid flow behaviour and velocity profiles, consequently affecting the heat transfer ratio and thermal energy storage capacity of the rock bed. Velocity profiles within the TES system during the storage phase for all of the geometries are illustrated in Figure 3. The outlet air velocity is lowest in the geometry with the lowest aspect ratio as it has larger outlet area. Increasing the Reynolds number results in an increase in both energy efficiency and the exploitation rate during the storage and extraction phase by increasing the mass flow rate [16]. Given that an increase in air velocity through the system decreases the residence time confirms the importance of calculating an optimum fluid velocity which leads to a higher heat exchange ratio within the system.

A range of Reynolds numbers from 100 to 750 are applied and the pressure loss inside the packed beds is calculated numerically (c.f. Figure 4). The meaningful difference between the results in lower porosities implies that the pressure drop is affected more by the permeability of the system than the aspect ratio of the geometry. It should also be noted that a higher fluid velocity results in a higher pressure drop through the system. In the other words, to provide a higher mass flow rate, more fan power has to be supplied.

Furthermore, the outlet temperature is plotted along with the time (day) for different aspect ratios and porosities (c.f. Figure 5). An increase in the outlet air temperature during the charging phase continued until the outlet temperature approached the constant inlet air temperature of 120 °C (i.e., the difference...
between the inlet and outlet air temperatures shrank to less than 1 °C). The outlet temperature increases very fast with higher air velocity compared to lower mass flow rate, remaining independent from the porosity. These results can then be used to obtain the energy stored in the bed. The air velocity at the inlet is varied between 0.01 m/s and 0.07 m/s. Hence, the increase in porosity within the packed bed leads to a significant decrease in the total heat stored in the rock due to a decrease in volume of heat storage media. The TES capacity of the packed bed is enhanced by increasing the rock density and by decreasing the porosity of the TES system, due to the higher heat capacity of rock compared to the HTF (air in this case). However, it is illustrated that the total thermal energy stored in the rock bed is almost identical for different geometric aspect ratios and different Reynolds numbers.

![Diagram](image)

**Figure 5.** Simulated outlet air temperature (°C) versus time (day) for different aspect ratios and porosities (ε) of (a) ε = 0.2, (b) ε = 0.35, and (c) ε = 0.5

It is found that the TES systems with porosities of 0.2, 0.35, and 0.5 have the capability of storing energy up to 540, 450, and 350 GJ, respectively. The stored heat can then be extracted during the cold season for space heating purposes. It was also found that while the total thermal energy storage capacity of the system is not significantly affected by the mass flow rate, a lower mass flow rate can provide a longer working period for TES systems.

4. Conclusion
An unsteady 3D model is developed to analyze fluid flow and heat transfer in truncated cone TES systems. In total, 27 simulations are performed (3 aspect ratios, 3 Reynolds numbers, and 3 porosities) to evaluate TES truncated cone shape systems. It is illustrated that packed bed properties like porosity play a crucial role in improving the performance of the TES system. Results offer useful information for evaluating the performance of rock beds packed with large rocks or in caved zones. The proper range of packed bed properties can lead to considerable energy savings in mining applications such as heating/cooling of mine intake air or ventilation of block-caved mines. It is also shown that for high Reynolds numbers, the energy stored in TES systems are very similar and are affected more by air
velocity than the structure of the packed bed. Pressure drop through the porous media is also investigated by varying the air velocity. It is indicated that the pressure drop can be significantly raised by increasing the Reynolds number and decreasing the porosity. It is also shown that pressure loss through the packed bed and the heat exchange rate between the air and rock depend upon the bed geometry, porosity, air velocity, and Reynolds number. Finally, there is a need to find the optimum key parameters for designing and operating TES systems, which will be the main scope of our future study.

5. References
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