

Numerical Investigation of Packing Structure and Bed Geometry Effects on Heat Transfer in Granite Rockbed Thermal Energy Storage Systems

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Published October 2026

Abstract

The thermal performance of a packed rockbed thermal energy storage system depends not only on particle properties but also on the spatial arrangement and overall geometry of the storage bed. This paper extracts the thermal and packing-structure component of an MSc numerical study carried out using ANSYS Fluent 19.2. Equal-volume cubical, cylindrical and conical/truncated-conical rockbed configurations were investigated using granite and air. The simulations used an inlet temperature of 500 K, a mass flow rate of 0.15 kg/s for the reported geometry comparison, and a particle-size range of 20–60 mm for the broader study. For the 40 mm particle comparison, the reported heat-transfer rates were 16.599 kW for the cube, 18.108 kW for the cylinder and 19.617 kW for the cone. The conical configuration therefore produced the largest reported heat-transfer rate among the three 40 mm cases, while the cube produced the lowest. The temperature contours show the development of a thermal front, with the hot region advancing from the inlet toward the colder downstream region. The reported outlet-temperature series decreased from 500 K at the start of the plotted charging history to 415 K at 3600 s. The results demonstrate that bed geometry and packing arrangement can materially alter thermal response and should be evaluated together with hydraulic resistance when designing rockbed thermal storage.

Keywords: rockbed thermal energy storage; packing structure; bed geometry; heat transfer; thermal front; granite; CFD

1 Introduction

Packed rockbeds store thermal energy as sensible heat in solid particles while a flowing heat-transfer fluid charges or discharges the bed. Although particle size is important, the spatial distribution of particles and the macroscopic shape of the bed determine the flow path, local velocity field, contact area and progression of the thermal front. Consequently, two beds having the same storage volume and material can exhibit different thermal responses when their packing or overall geometry differs.

The present paper focuses on the second major theme of the MSc project: the effect of packing structure and bed geometry on thermal performance. The central question is how the cubical, cylindrical and conical configurations used in the project differ in temperature distribution and heat-transfer rate under comparable conditions.

2 Materials and methods

2.1 Bed configurations

The project considered cubical, cylindrical, conical/truncated-conical and irregular configurations. For the principal geometry comparison, the bed volumes were designed to be equal so that differences in thermal behaviour could be attributed primarily to geometry and packing rather than storage volume. The three bed geometries are shown in Figure 1, Figure 2 and Figure 3.

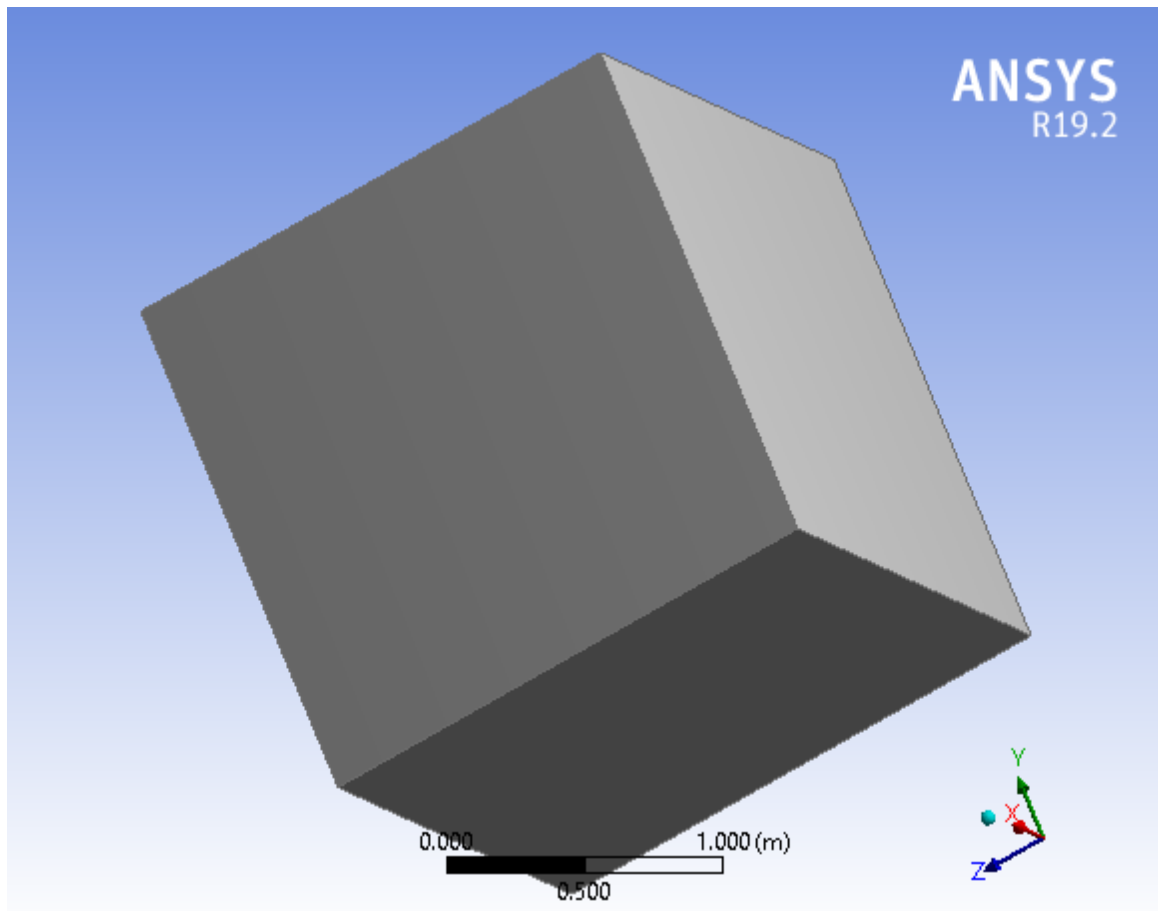


Figure 1. Cubical rockbed geometry.

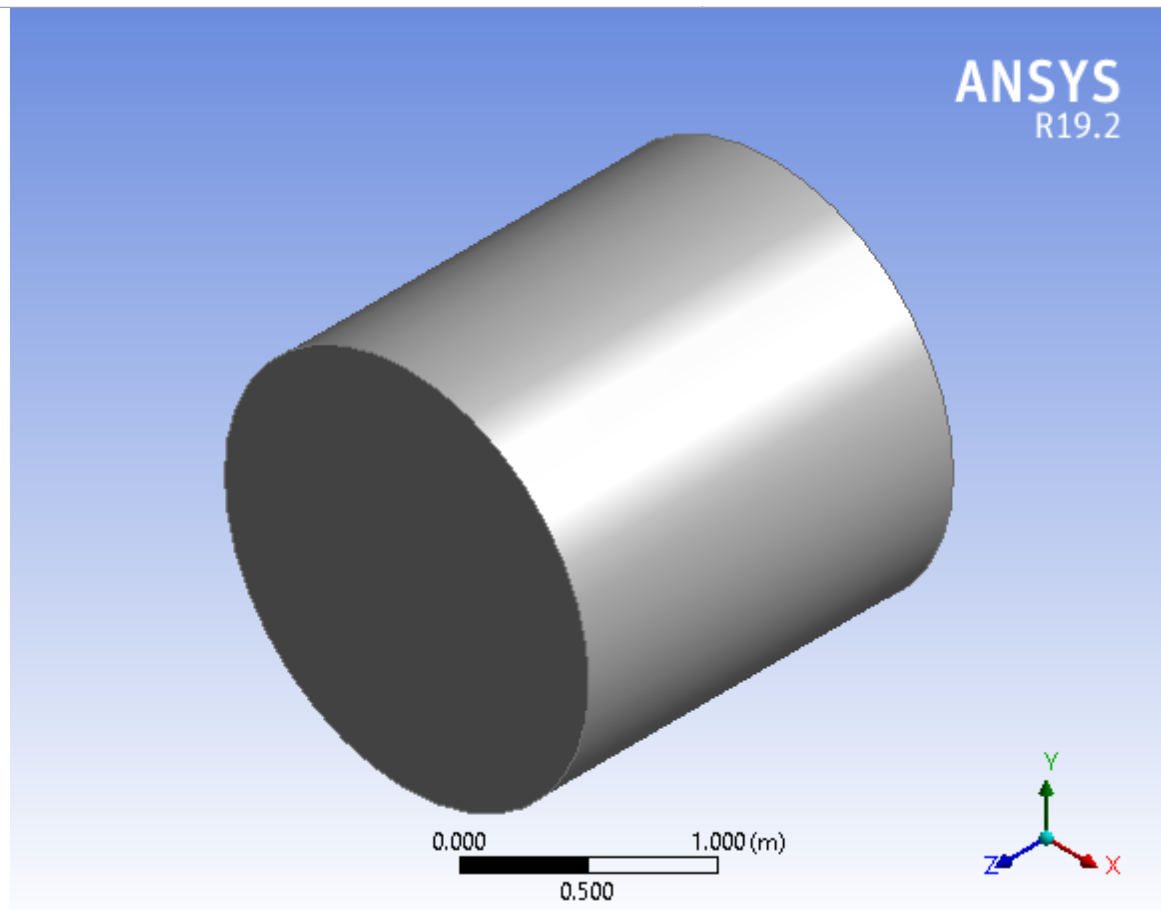


Figure 2. Cylindrical rockbed geometry.

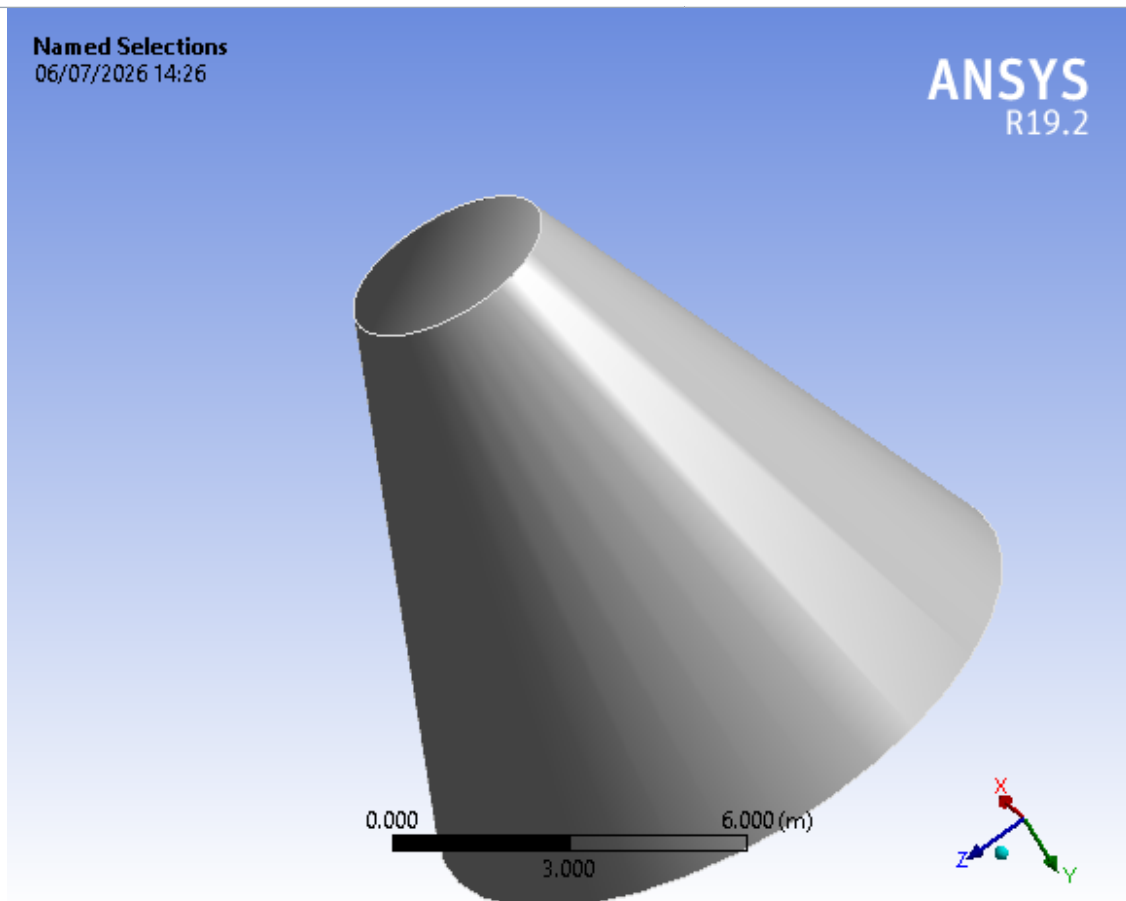


Figure 3. Truncated-conical (frustum) rockbed geometry.

2.2 Operating conditions

The operating conditions of the simulations are listed in Table 1.

Table 1. Operating conditions of the simulations.

Parameter	Value/condition
Storage material	Granite
Heat-transfer fluid	Air
Reference inlet temperature	500 K
Reference inlet velocity	5 m/s
Reference simulation time	3600 s
Particle diameters considered	20, 30, 40, 50 and 60 mm
Porosities considered	0.20, 0.30, 0.35, 0.40 and 0.45
Principal geometry comparison	Cube, cylinder and cone
Equal-volume condition	Yes, for the compared bed geometries

2.3 Thermal model

The thermal model accounts for transient energy storage in the granite and convective heat exchange with the air. For the solid phase, the project used the heat-conduction relation in Equation (1).

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = k_s \nabla^2 T_s \quad (1)$$

The fluid and solid energy equations were treated as coupled through the fluid–solid heat-transfer process. The heat-transfer rate was evaluated from Equation (2):

$$\dot{Q} = \dot{m} c_{p,f} (T_{in} - T_{out}) \quad (2)$$

where $\dot{m}$ is the mass flow rate, $c_{p,f}$ the specific heat capacity of air, and T_{in} and T_{out} the inlet and outlet temperatures.

3 Results and discussion

3.1 Numerical convergence

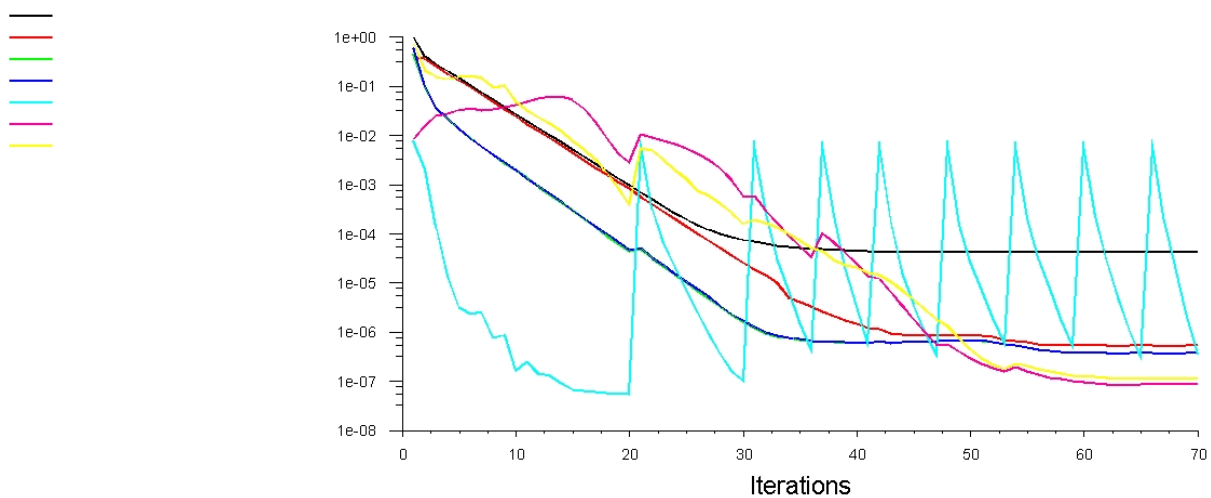


Figure 4. Residual convergence history for the cubical 2 m bed.

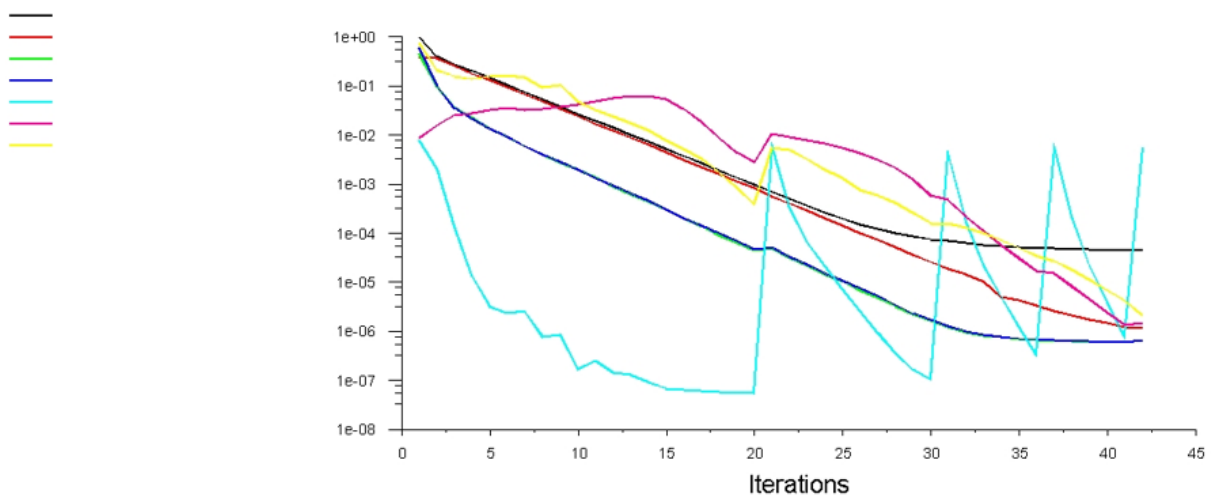


Figure 5. Residual convergence history for the truncated-frustum/conical case.

The project convergence plots (Figure 4 and Figure 5) show substantial reduction in continuity, momentum and energy residuals. The energy residual displays transient oscillations in some cases, consistent with repeated solution of the energy field at successive time steps. The report considered

the monitored solutions sufficiently converged for evaluating temperature, pressure and flow behaviour.

3.2 Temperature contours and thermal-front development

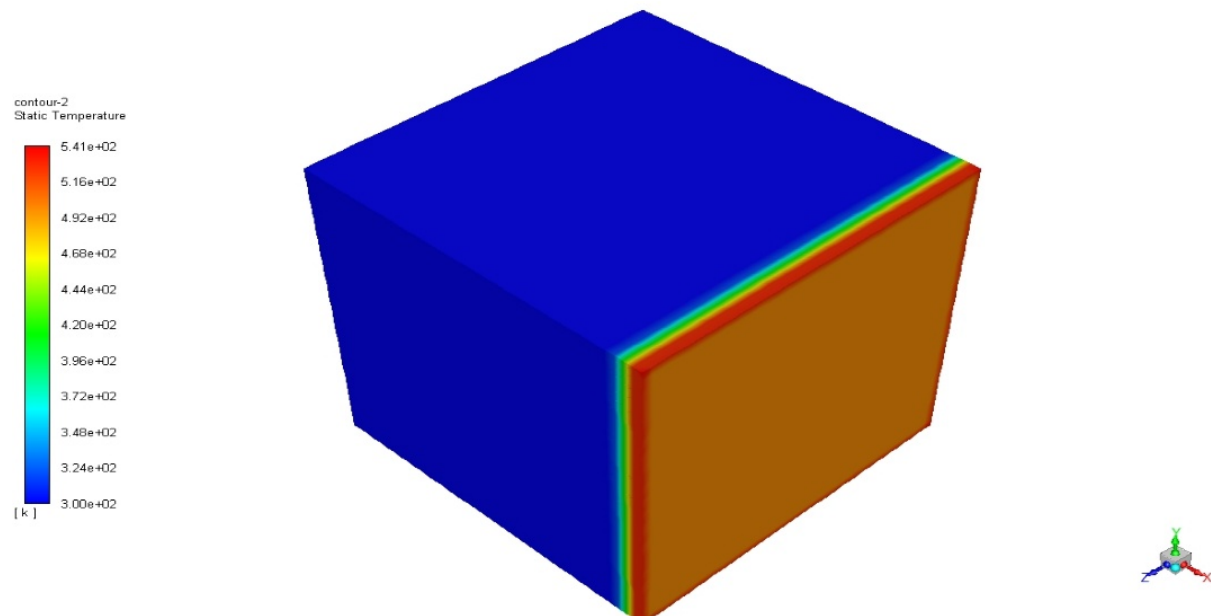


Figure 6. Temperature contour of the cubical rockbed.

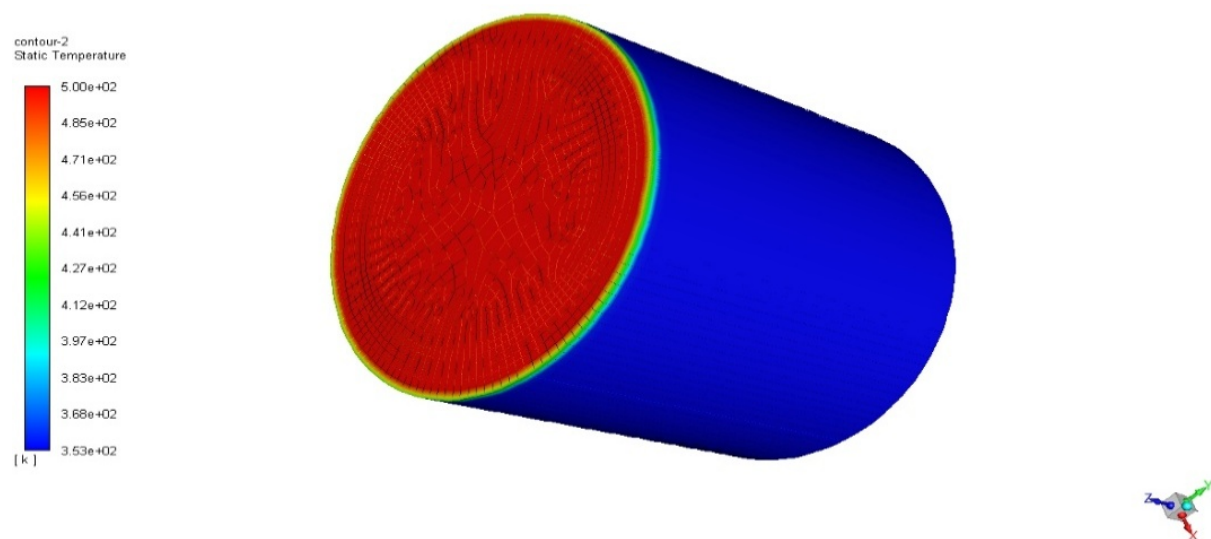


Figure 7. Thermal-front contour for the cylindrical rockbed.

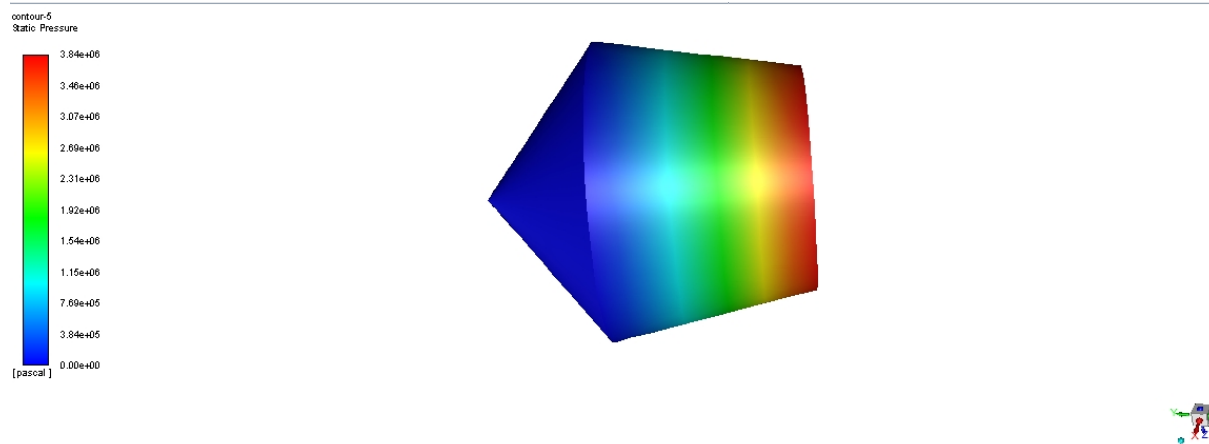


Figure 8. Thermal front for the truncated-frustum/conical rockbed.

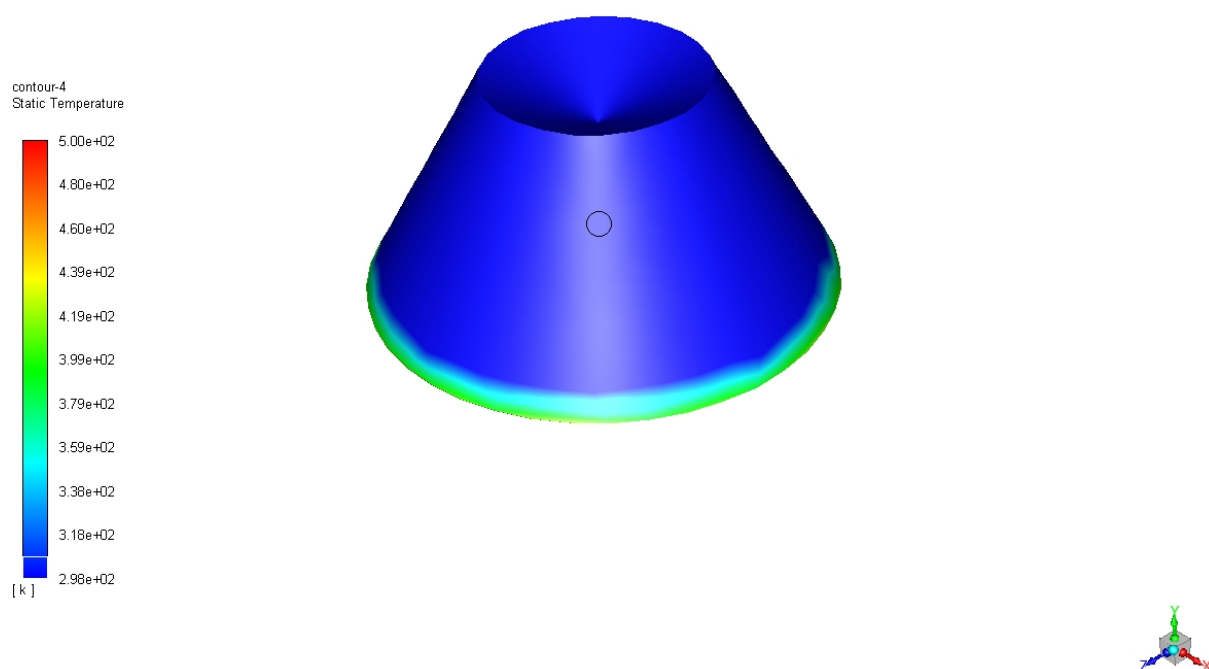


Figure 9. Thermal-front contour for the conical bed.

The contours (Figure 6, Figure 7, Figure 8 and Figure 9) show the characteristic thermal-front behaviour of a packed-bed storage system. Hot air enters the bed and progressively heats the upstream granite, while the downstream region remains comparatively cool during the transient charging period. The conical geometry produces a changing cross-sectional area, which modifies local flow distribution and therefore the spatial pattern of heat transfer. The thermal gradients demonstrate that the bed is not instantaneously at thermal equilibrium; rather, a moving thermal front controls the transient storage response.

3.3 Heat-transfer-rate comparison

Table 2. Heat-transfer rates for the simulated rockbed configurations.

Geometry	Particle size (mm)	Inlet T (K)	Outlet T (K)	Mass flow (kg/s)	Heat-transfer rate (kW)
Cube	20	500	420	0.15	12.684

Geometry	Particle size (mm)	Inlet T (K)	Outlet T (K)	Mass flow (kg/s)	Heat-transfer rate (kW)
Cube	40	500	390	0.15	16.599
Cylinder	40	500	380	0.15	18.108
Cone	40	500	370	0.15	19.617

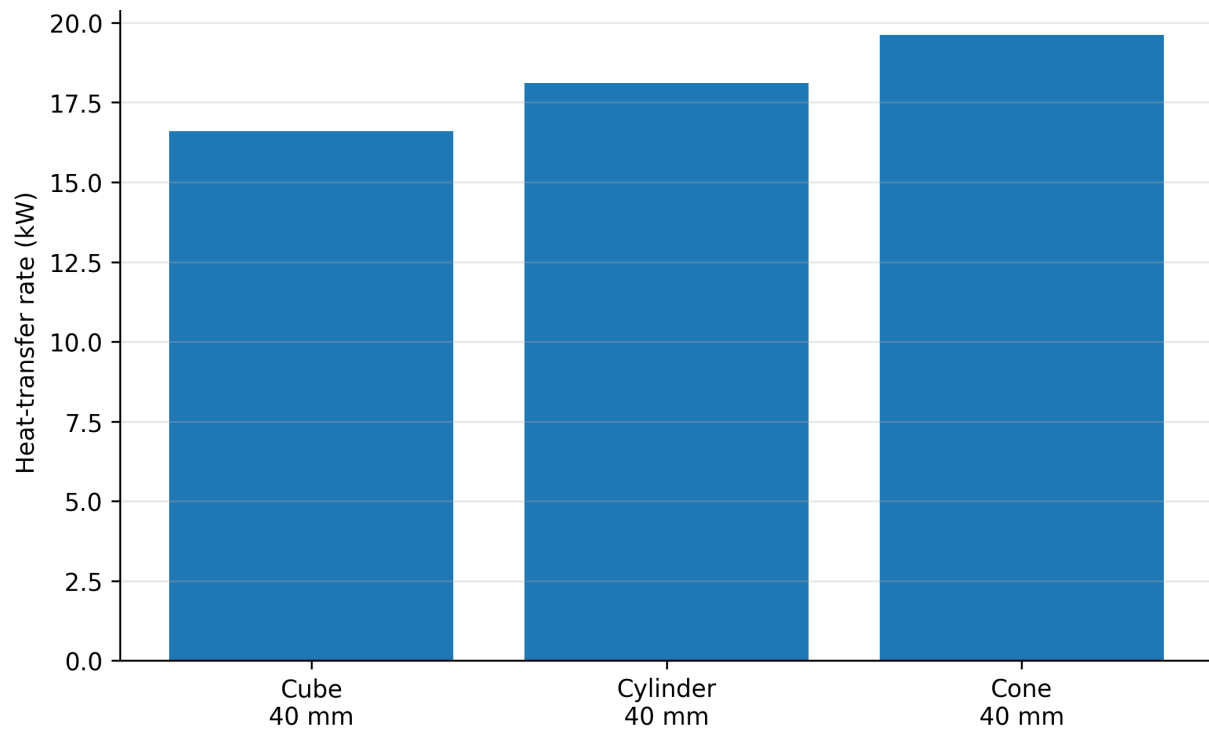


Figure 10. Reported heat-transfer rates for the 40 mm particle geometry comparison.

For the common 40 mm particle size (Table 2, Figure 10), the conical bed gives the highest reported heat-transfer rate (19.617 kW), followed by the cylindrical bed (18.108 kW) and the cubic bed (16.599 kW). Relative to the cube, the cylinder increases the reported heat-transfer rate by approximately 9.1%, while the cone increases it by approximately 18.2%. The outlet temperatures follow the same ordering: 390 K for the cube, 380 K for the cylinder and 370 K for the cone, under the conditions reported in the project.

3.4 Pressure distribution and its relationship with thermal behaviour

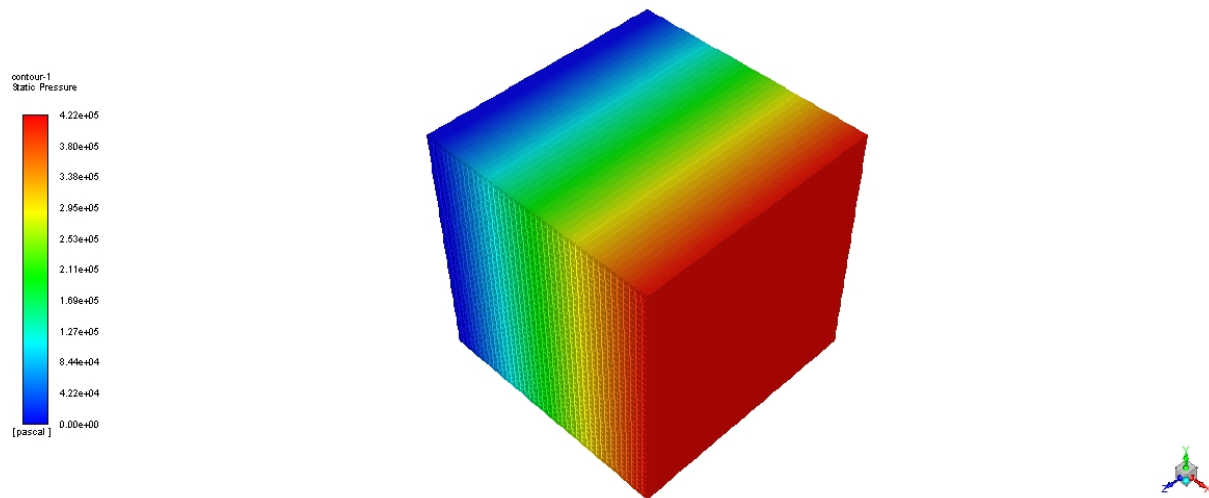


Figure 11. Static-pressure contour for the cubical bed.

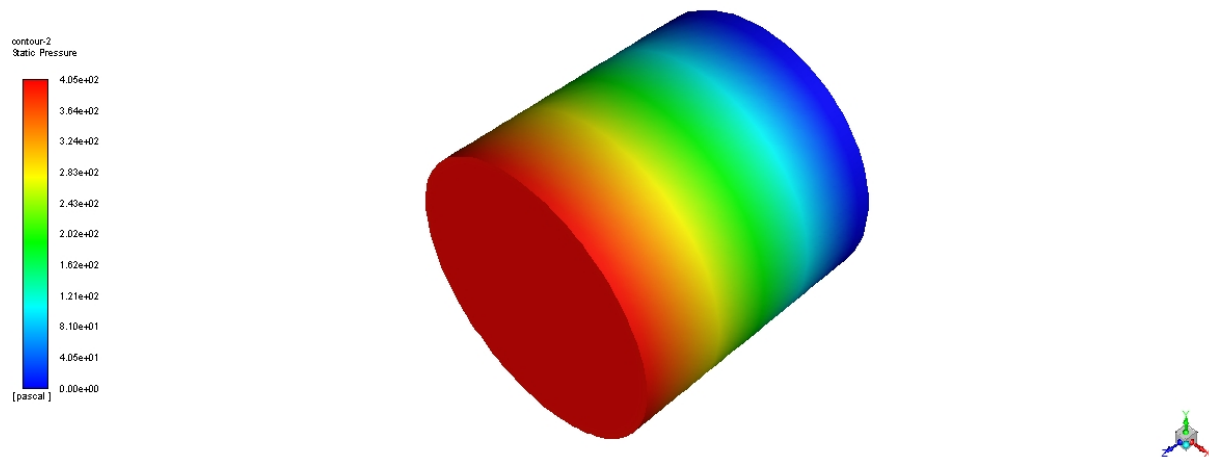


Figure 12. Static-pressure contour for the cylindrical bed.

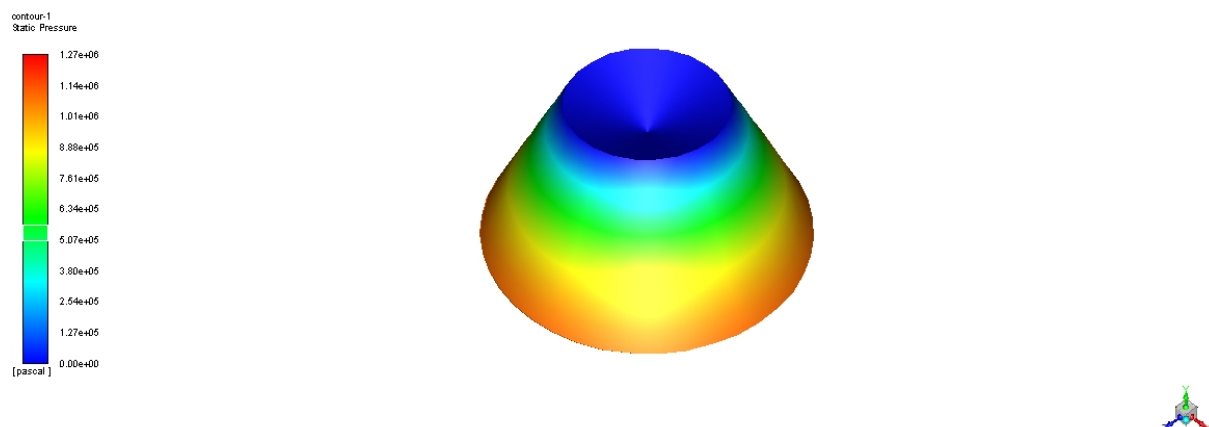


Figure 13. Static-pressure contour for the truncated-frustum/conical bed.

The pressure contours (Figure 11, Figure 12 and Figure 13) show progressive pressure loss along the flow direction. The project reports a relatively smooth pressure variation for the cylindrical case, while the changing cross-sectional area of the conical/frustum geometry produces a more non-

uniform pressure field. This is important because thermal enhancement cannot be considered independently of hydraulic cost. A geometry that produces a larger heat-transfer rate may also modify velocity and pressure distributions.

3.5 Outlet-temperature history

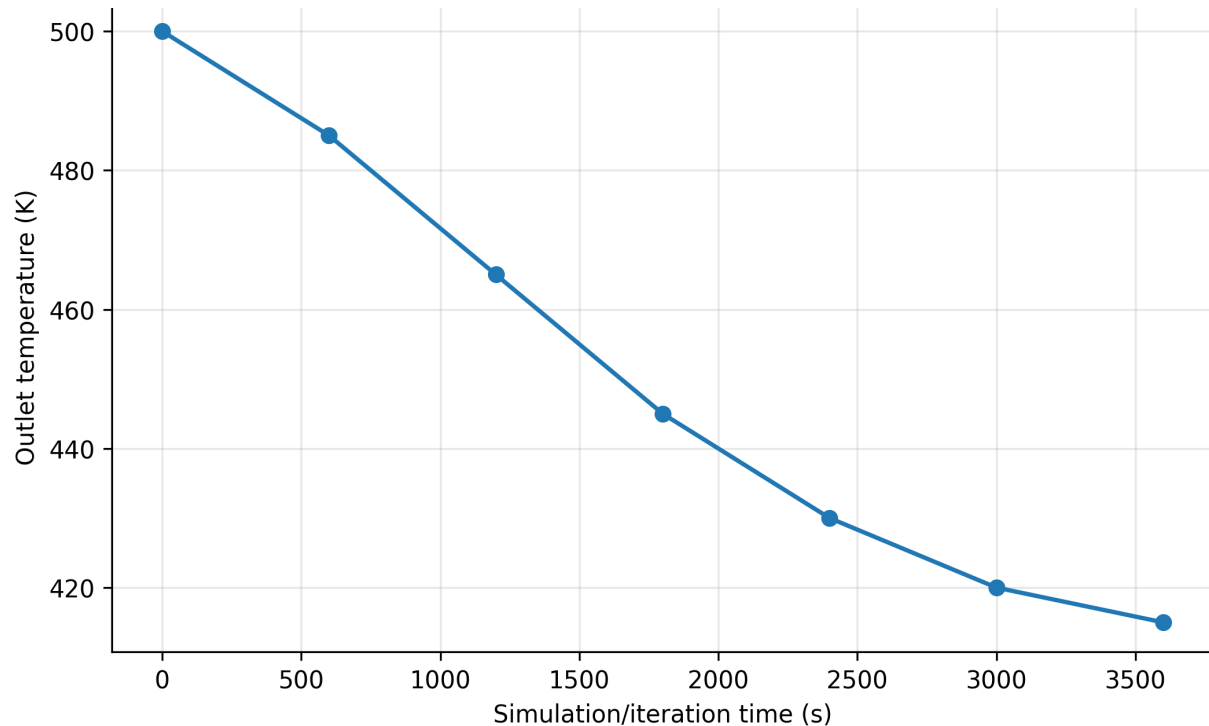


Figure 14. Outlet temperature versus simulation time.

Table 3. Outlet temperature history.

Time (s)	Outlet temperature (K)
0	500
600	485
1200	465
1800	445
2400	430
3000	420
3600	415

The project chart (Figure 14, Table 3) records a progressive reduction in outlet temperature from 500 K at the beginning of the plotted history to 415 K at 3600 s. This trend is consistent with the transient development of the thermal front and the increasing interaction between the hot air and initially cooler storage material.

3.6 Interpretation in terms of packing structure

Packing structure affects thermal performance through the distribution of flow passages and solid surface area. A more tortuous arrangement can increase fluid–solid interaction and local mixing, but

may also increase pressure loss. The geometry results from this project provide numerical evidence that changing the macroscopic bed shape changes the thermal response even when storage volume is held equal. However, the project did not produce a fully resolved quantitative orientation dataset for non-spherical particles. Therefore, the present paper does not claim a measured orientation effect. A rigorous orientation study should use non-spherical particles of equal volume because perfect spheres have no physically distinguishable orientation.

4 Conclusions

- Equal-volume bed geometry significantly influences the thermal response of the investigated granite rockbed TES system.
- For 40 mm particles, the reported heat-transfer rates are 16.599 kW for the cube, 18.108 kW for the cylinder and 19.617 kW for the cone.
- The conical configuration produced the largest reported heat-transfer rate among the compared 40 mm cases.
- The temperature contours demonstrate a moving thermal front, with hot air progressively charging the upstream portion of the bed while cooler regions persist downstream.
- Outlet-temperature history confirms the transient nature of charging, with the reported outlet temperature decreasing from 500 K to 415 K over the plotted 3600 s period.
- Packing and geometry should be assessed jointly with pressure drop because thermal enhancement can be accompanied by additional hydraulic penalties.
- Particle orientation should be investigated separately with non-spherical, equal-volume particles if orientation is to form a defensible independent research variable.

5 Contribution and future work

The paper's main contribution is the extraction of a geometry/packing-focused thermal comparison from the broader MSc study. It provides a numerical basis for comparing alternative equal-volume rockbed geometries and demonstrates how thermal fronts and heat-transfer rates respond to geometry changes.

Future work should resolve the actual particle-scale packing structures explicitly, compare ordered and random arrangements, and use non-spherical particles to quantify orientation effects. The next step should be a multi-objective optimisation in which heat-transfer rate, pressure drop and fan power are considered simultaneously.

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