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# Performance response of packed-bed thermal storage to cycle duration perturbations

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ABSTRACT

Packed-bed thermal stores are integral components in numerous bulk electricity storage systems and may also be integrated into renewable generation and process heat systems. In such applications, the store may undergo charging and discharging periods of irregular durations. Previous work has typically concentrated on the initial charging cycles, or on steady-state cyclic operation. Understanding the impact of unpredictable charging periods on the storage behavior is necessary to improve design and operation. In this article, the influence of the cycle duration (or 'partial-charge' cycles) on the performance of such thermal stores is investigated. The response to perturbations is explained and provides a framework for understanding the response to realistic load cycles.

The packed beds considered here have a rock filler material and air as the heat transfer fluid. The thermodynamic model is based on a modified form of the Schumann equations. Major sources of exergy loss are described, and the various irreversibility generating mechanisms are quantified.

It is known that repeated charge-discharge cycles lead to steady-state behavior, which exhibits a trade-off between round-trip efficiency and stored exergy, and the underlying reasons for this are described. The steady state is then perturbed by cycles with a different duration. Short duration perturbations lead to a transient decrease in exergy losses, while longer perturbations increase it. The magnitude of the change in losses is related to the perturbation size and initial cycle period, but changes of 1–10 % are typical. The perturbations also affect the time to return to a steady-state, which may take up to 50 cycles. Segmenting the packed bed into layers reduces the effect of the perturbations, particularly short durations.

Operational guidelines are developed, and it is found that packed beds are more resilient to changes in available energy if the store is not suddenly over-charged (i.e. longer perturbations), and if the steady-state cycle duration is relatively long. Furthermore, using the gas exit temperature to control cycle duration reduces the impact of perturbations on the performance, and reduces the time to return to steady-state operation.

## 1. Introduction

Packed beds have been proposed for a variety of thermal energy storage applications, including bulk electricity storage systems such as advanced-adiabatic compressed-air energy storage (AA-CAES) [1,2], liquid-air energy storage (LAES) [3], and pumped-thermal (or, pumped-heat elsewhere in the literature) electricity storage (PTES/PHES) [4–6]. They have also been suggested for use in other systems that involve thermal processes, such as concentrating solar power, geothermal energy, and process heat. Packed beds are potentially more compact and cost-effective than conventional storage systems, such as two-tank liquid stores. Depending on the heat transfer fluid and storage media, they also tend to use more abundant and locally sourced, lower cost, environmentally-benign, and non-reactive materials than other storage technologies.

Typically, a packed bed is a storage vessel filled with a solid packing medium (the "filler") such as pebbles or gravel, as illustrated in Fig. 1. Energy is transferred to the solid by means of the heat transfer fluid (HTF), which may also be the working fluid in whatever system the packed bed is part of. Many packed bed designs exist in the literature, with variations in the geometry, storage medium, and HTF. Stores are typically cylindrical with the HTF travelling axially. Hot fluid usually enters at the top and leaves at the bottom in order to avoid buoyancy-driven flows. The filler material is generally a solid such as alumina, ceramic, or crushed rock. Such packed beds are classified as 'sensible heat' storage since energy is stored by virtue of the temperature change

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**Nomenclature**

*Abbreviations*

AA-CAES Advanced-adiabatic compressed-air energy storage
CSP Concentrating solar power
HTF Heat transfer fluid
LAES Liquid-air energy storage
PTES/PHES Pumped-thermal electricity storage/pumped-heat electricity storage

*Roman symbols*

$A$ Cross-sectional area ($m^2$)
$A_w$ Wall surface area ($m^2$)

*Roman symbols*

$B$ Exergy (J)
$C_f$ Coefficient of friction
$c_p$ Specific heat capacity of gas or solid (J/kg K)
$\mathscr{C}$ Unsteady gas term (K/m)
$d_p$ Particle diameter (m)
$D$ Diameter (m)
$E$ Energy capacity of packed bed ($Wh_{th}$)
$G$ Mass flow rate per unit area (kg/s $m^2$)
$k_{eff}$ Effective conductivity (W/m K)
$L$ Length (m)
$\ell$ Packed bed length scale (m)
$\dot{m}$ Mass flow rate (kg/s)
$p$ Pressure bar
$\dot{P}$ Power output of packed bed ($W_{th}$)
Re Reynolds number
$S_{irr}$ Entropy (J/K)
$S_v$ Particle surface area to volume ratio ($m^{-1}$)
St Stanton number
$t$ Time (s)
$t_{chg}$ Charging duration (s)
$t_N$ Nominal charging time (s)
$T$ Temperature (°C, K)
$U_w$ Overall heat transfer coefficient (W/$m^2$ K)
$V_f$ Thermal front velocity (m/s)
$x$ Distance (m)

*Greek symbols*

$\alpha$ Packed bed diffusivity ($m^2$/s)
$\beta$ Reduced availability (K)
$\gamma$ Ratio of gas specific heat capacities
$\varepsilon$ Packed bed void fraction
$\rho$ Density (kg/$m^3$)
$\zeta$ Exergy loss coefficient
$\phi$ Packed bed heat leakage time constant ($s^{-1}$)
$\Pi$ Dimensionless cycle duration, $t_{chg}/t_N$
$\eta_{RT}$ Round-trip efficiency (%)
$\theta$ Normalized exit temperature
$\tau$ Packed bed time scale (s)

*Superscripts and subscripts*

c, h Cold, hot
g, s Gas, solid
o Steady-state value
chg, dis Charging, discharging
in, out Inlet, exit
x Exit temperature

of the filler. Encapsulated phase change materials may also be used, however, thereby creating a latent heat storage system [7], but this increases the cost and complexity. HTFs may be gases, such as air [8,9] or argon [10], or liquids, such as thermal oils [11] or molten salts [12]. This article considers a cylindrical store, filled with particles of magnetite ($Fe_3O_4$) and uses air as the heat transfer fluid. The rationale and methodology follows earlier publications of the present authors [10,13–15], and is summarized below.

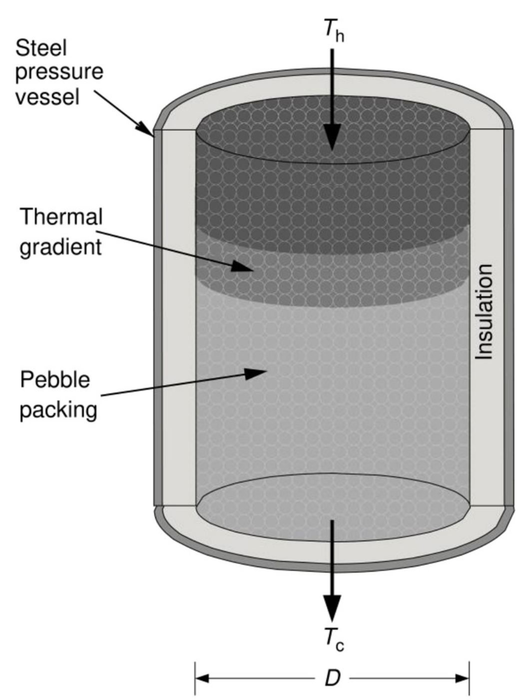


**Fig. 1.** Schematic of a packed-bed thermal store. Hot gas enters at the top at temperature $T_h$ and exits from the bottom at temperature $T_c$.

### 1.1. Packed bed design considerations

Several technical challenges must be resolved before packed-bed thermal stores are likely to become commercially widespread. Careful design is required to mitigate the trade-off between heat transfer losses and frictional pressure losses – these being the exergy loss components that dominate thermal store behavior [13]. Understanding these loss mechanisms, and the influence of design and operational parameters upon them is necessary to improve system performance. Detailed analysis of packed beds has led to several novel designs that optimize storage efficiencies. For instance, the stores may be segmented into layers [15,16] in order to mitigate the inherent conflict between pressure loss and high heat transfer surface. These layers may consist of different materials [17]. Other geometries that have been proposed include conical stores [18,19], and radial-flow stores [10,20] both of which reduce pressure losses by increasing the flow area. Conical stores can also reduce the negative impacts of ‘thermal ratcheting’ which is caused by thermal expansion of particles and which may damage the containment vessel and packing. Radial-flow stores were found to have similar performance to axial-flow stores, but the additional volume required for bypass flows leads to increased capital costs [10].