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Constrained multi-objective optimization of thermocline packed-bed thermal-energy storage

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HIGHLIGHTS

- Multi-objective optimization of thermal-energy storage.
- Pareto optimal designs.
- Most efficient storage for given cost.
- Cheapest storage for given efficiency.

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ABSTRACT

A constrained multi-objective optimization approach is applied to optimize the exergy efficiency and material costs of thermocline packed-bed thermal-energy storage systems using air as the heat-transfer fluid. The axisymmetric packed-bed's height, top and bottom radii, insulation-layer thicknesses, and particle diameter were chosen as design variables. The competing objectives of maximizing the exergy efficiency and minimizing the material costs were treated by a Pareto front. The Pareto front allows identifying the most efficient design for a given cost or the cheapest design for a given efficiency and is an important tool to find the best overall design of storage systems for a specific application. Constraints were imposed to obtain storage systems with specified capacities and limits on the air outflow temperatures during charging and discharging. The results showed that a storage shaped as a truncated cone with the smallest cross-section at the top has a higher exergy efficiency than storages shaped as cylinders or truncated cones with the largest cross-section at the top. The higher efficiency is attributed to the axial temperature distribution in the packed bed and the associated conduction heat losses across the insulated walls. The optimization of an industrial-scale storage allowed identifying a design with an exergy efficiency that was only 4.8% below that of the most efficient design, but a cost that was 81.3% lower than the cost of the most efficient design. Compared to brute-force design approaches, the optimization procedure can reduce the computational time by 91–99%.

1. Introduction

Thermal-energy storage (TES) systems are required when a time delay exists between the availability of and the demand for thermal energy. TES systems are key components of concentrated solar power (CSP) and advanced adiabatic compressed air energy storage (AA-CAES) plants. For both CSP and AA-CAES plants, the integration of a TES improves the system efficiency and the competitiveness on the electricity market [1,2]. Thermocline TES systems using a packed bed of rocks as sensible storage material are especially suitable because they require only low-cost storage materials and have been shown to have high thermal efficiencies [3].

The development of a thermocline TES system requires that many designs be investigated and evaluated to select a design that is in some sense optimal. Each design can be characterized by a set of operational, geometrical, thermophysical, and performance parameters, see Table 1.[1] The operational parameters are in general defined by the application in CSP or AA-CAES plants, the geometrical parameters are usually arbitrary but need to satisfy structural constraints, the thermophysical parameters depend on the materials used and are usually a function of the temperature and pressure (and therefore the operational parameters), and the performance parameters are used to assess and

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[1] The pressure drop or pumping power are sometimes used as performance parameters. We do not list them in the table because the pumping power is included in our definition of the exergy efficiency, see Eq. (7).

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Nomenclature

Latin symbols

$\overline{\overline{A}}$	matrix of linear constraints
c	Specific heat capacity [J/kg K]/volumetric cost [$/m^3]
C	cost [$]
$\vec{c}$	vector of non-linear constraints
d	diameter [m]
E	energy [J]
f	objective function/fraction [–]
h	step size [–]/enthalpy [J/kg]
H	height [m]
i	imaginary part [–]
k	thermal conductivity [W/m K]
l	thickness [m]
L	length [m]
$\vec{l}$	vector of lower bounds
N	number [–]
$\dot{m}$	mass flow [kg/s]
p	pressure [Pa]
	radius [m]
s	entropy [J/kg K]
t	time [s]
T	temperature [K]
$\vec{u}$	vector of upper bounds
V	volume [m^3]
w	weight factor [–]
$\vec{x}$	vector of design variables

Greek symbols

Δ	difference
ε	porosity [–]
η	efficiency [–]
μ	viscosity [Pa s]
Ξ	exergy [J]
ρ	density [kg/m^3]
ψ	sphericity [–]

Subscripts

c	charge
d	discharge
el	electricity
en	energy
ex	exergy
f	fluid
HT	heat transfer
in	storage inlet
ins	insulation
int	internal
loss	loss
L	linear
m	material
net	net quantity
N	non-linear
o	objective
out	storage outlet
p	particle
PB	packed bed
pump	pump
ref	reference
s	solid
struc	structure
th	thermal

Abbreviations

AA-CAES	advanced adiabatic compressed air energy storage
CSP	concentrated solar power
FG	foam glass (insulation)
HTF	heat-transfer fluid
LDC	low-density concrete
MP	microporous (insulation)
SQP	sequential quadratic programming
TES	thermal-energy storage
UHPC	ultra-high-performance concrete

compare designs. The large number of geometric parameters results in a very high-dimensional design space. For example, considering ten values each of the storage height, the top and bottom radii, the thicknesses of two insulation layers, and the particle diameter results in 10^6 designs. If, in addition, three storage materials are considered, the number of designs increases to 10^8. Because the experimental investigation of a single design at an industrially relevant scale is already very expensive and time-consuming, TES designs are usually evaluated using simulations. However, even with efficient implementations of simplified physical models, such as one-dimensional thermal non-equilibrium models [4], the computational cost of evaluating O(10^8) designs using a brute-force approach is prohibitive. To decrease the computational cost, the number of designs that need to be evaluated must therefore be reduced. Because we are ultimately interested in identifying a design that is in some sense optimal, the reduction can be accomplished by a numerical optimization procedure. The use of an optimization procedure requires that we define what constitutes an optimal design. In general terms, we define a TES design to be optimal if it combines high efficiency with low costs. It is not possible to provide a more precise definition because high efficiency and low costs are usually contradictory. Therefore, the optimization procedure will provide a series of optimal designs depending on the relative importance of high efficiency compared to low costs.

Table 1
Operational, geometrical, thermophysical, and performance parameters of thermocline packed-bed TES systems. The subscript i indicates that several instances of the given parameter exist, such as for multiple structural and insulation layers.

Operational parameters	Thermophysical parameters
Mass flows: $\dot{m}_c$, $\dot{m}_d$	Thermal conductivities: k_f, k_s, $k_{\text{ins},i}$
Charging/discharging times: t_c, t_d	Densities: ρ_f, ρ_s, $\rho_{\text{ins},i}$
Inflow temperatures: $T_{f,\text{c,in}}$, $T_{f,\text{d,in}}$	Heat capacities: $c_{p,f}$, c_s, $c_{\text{ins},i}$
Charge/discharge pressures: p_c, p_d	Viscosity: μ_f
Geometrical parameters	**Performance parameters**
TES (packed-bed) height: H_{PB}	Outflow temperature changes: ΔT_c, ΔT_d
Top/bottom radii: $r_{\text{PB},t}$, $r_{\text{PB},b}$	Charged capacity: Q_c
Structural thicknesses: $l_{\text{struc},i}$	Net discharged energy: $E_{d,\text{net}}$
Insulation thicknesses: $l_{\text{ins},i}$	Supplied energy: $E_{c,\text{in}}$
Particle diameter: d_p	Efficiencies: η_{en}, η_{ex}
Packed-bed porosity: ε	Cost: C_{TES}

Optimization studies of packed-bed TES systems are relatively rare. In this work, the term "optimization studies" refers to studies that use mathematical optimization algorithms to find an optimum in an automatic manner. We do not apply the term to parametric studies in which an optimum is found by varying selected parameters in a systematic but ad-hoc manner. In general, referring to Table 1, optimization studies