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A comparison of radial-flow and axial-flow packed beds for thermal energy storage☆

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HIGHLIGHTS

- Packed-bed thermal stores where the heat transfer fluid travels radially are described.
- A thermodynamic model is proposed and the stores are analysed with 2nd Law methods.
- Radial-flow stores exhibit lower pressure losses than corresponding axial-flow stores.
- Thermo-economic optimisation indicates they have competitive round-trip efficiencies.

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ABSTRACT

Packed-bed thermal reservoirs are an integral component in a number of electrical energy storage technologies. The present paper concentrates on packed beds where the heat transfer fluid travels along the radial co-ordinate. The governing energy equations and various mechanisms that cause exergetic losses are discussed. The radial-flow packed bed is compared to a dimensionally similar axial-flow packed bed. This approach provides a fair assessment of the underlying behaviour of the two designs. Multi-objective optimisation allows a wide range of design variables to be considered, and is employed to compare optimal radial-flow and axial-flow stores. Axial-flow stores that have been segmented into layers are also considered. The results indicate that radial-flow stores have a comparable thermodynamic performance, but that the additional volume required for by-pass flows leads to higher capital costs.

1. Introduction

Since the late 20th century there has been a surge in the deployment of renewable energy technologies driven by concerns about anthropogenic climate change, the health impacts of particulate pollution, and diminishing fossil fuel reserves. In 2015, 7.0% of the UK's energy consumption came from renewable sources (up from 5.2% in 2011) [1]. However, to meet the 2009 EU Renewable Directive target, the UK will have to increase renewable energy deployment from around 64 TWh to approximately 230 TWh (for heat, transport and electricity) by 2020 [2]. Fig. 1 shows the predicted capacities of several renewable sources in 2020 and indicates the additional investment in renewable energy that is required. By implementing these changes, it is forecast that around 30% of UK electricity will come from renewable sources [2].

The intermittent nature of renewables creates problems for the electrical grid such as congestion, frequency and voltage control, and balancing of supply and demand. Energy storage, interconnection, and demand side management have the potential to combat these problems, and it is widely accepted that storage will form an essential component in future energy systems [3]. For example, one estimate for the UK is that, over the next few decades, integration of intermittent power sources will require storage capacities of the order of hundreds of GWh – an order of magnitude greater than current capacity [4].

1.1. Packed-bed thermal energy storage

A wide range of energy storage technologies exists and comprehensive reviews can be found in [5,6]. This paper focusses on "sensible heat" thermal energy storage (for electrical applications) in packed beds which comprise cylindrical containers filled with a solid storage

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Nomenclature

CAES	compressed air energy storage
CSP	concentrating solar power
LAES	liquid air energy storage
PHES	pumped hydro energy storage
PTES	pumped thermal energy storage

Greek Symbols

α	packed bed diffusivity, see Eq. (9) ($m^2\,s^{-1}$)
χ	round-trip exergetic efficiency
ΔT	maximum temperature difference, $T_d - T_c$ for a cold store (K)
Γ	dimensionless packed bed charge period, t_c/τ
Λ	dimensionless packed bed length, L/ℓ
ϕ	aspect ratio H/D for axial-flow stores, $H/2(r_o - r_i)$ for radial-flow stores
Π	dimensionless cycle period (or utilisation), $t_c/t_N = \Gamma/\Lambda$
ρ	density ($kg\,m^{-3}$)
τ	packed bed time scale, see Eq. (8) (s)
θ	fractional exit temperature
ε	packed bed void fraction

Roman Symbols

$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
ℓ	packed bed length scale, see Eq. (7) (m)
St	Stanton number, $h/(Gc_{p,g})$
B	exergy (J)
C	capital cost (£)
c	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
C_B	capital cost per exergy output (£/ kWh)
C_f	friction coefficient
D	diameter of the packed bed (m)
d_p	particle diameter (mm)
e	specific internal energy ($J\,kg^{-1}$)
F	unsteady gas terms
G	mass flow rate per unit area ($kg\,m^{-3}\,s^{-1}$)
H	height of the packed bed (m)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_g	specific internal enthalpy ($J\,kg^{-1}$)
k	cost factors
k_{eff}	effective conductivity ($W\,m^{-1}\,K^{-1}$)
L	length of gas flow path. H for axial-flow stores, $r_o - r_i$ for radial-flow stores (m)
N_{seg}	number of segments
p	pressure ($N\,m^{-2}$)
$r_{i,o}$	radius of the inner/outer plenum (m)
S_v	particle surface-area-to-volume ratio $6/d_p$ (m^{-1})
T	temperature (K)
t_c,t_N	charging duration, nominal (fully charged) time (s)
V	volume (m^3)
V_f	thermal front velocity, see Eq. (2) ($m\,s^{-1}$)

Subscripts

c,d	charging, discharging
	gas, solid
p,i,PV	packing, insulation, pressure vessel

medium such as pebbles or gravel. Energy is transferred to the solid by means of a heat transfer fluid. Packed beds are considered to be an attractive storage option as the materials are abundant and relatively cheap. Unlike other bulk electricity storage systems, such as Pumped Hyrdo Energy Storage (PHES) or most forms of Compressed Air Energy Storage (CAES), packed beds have no geographical constraints. Further details on thermal energy storage materials and technologies can be found in [7–9].

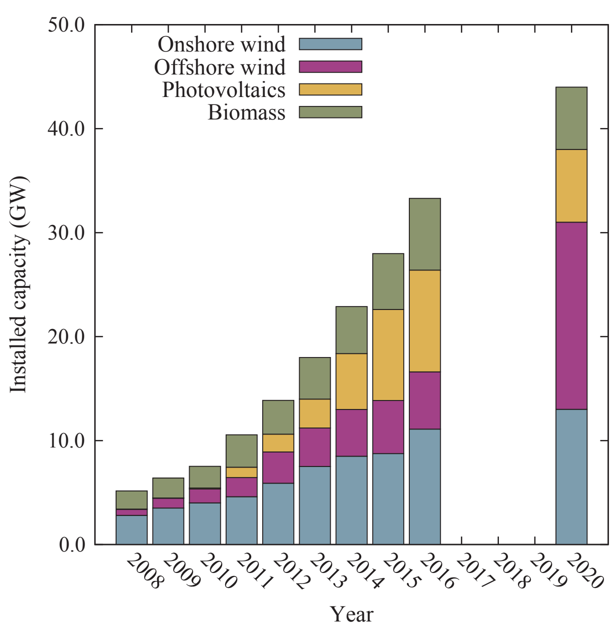

Fig. 1. Installed capacity of various renewable energy sources in the UK. Figure taken from [10]. Values at 2020 are predicted capacities from [1] and are subject to uncertainty (for instance, solar photovoltaics could vary between 7 and 20 GW).

Packed-bed thermal stores may be stand-alone components, such as in heating applications, or part of wider systems, including Concentrated Solar Power (CSP)[11,12], Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), Liquid Air Energy Storage (LAES) and Pumped Thermal Energy Storage (PTES). For example, in LAES systems, the discharge phase involves compressing and heating the liquid air before expanding it through a turbine. Storing the available energy of the cold air in a packed bed prior to expansion reduces the work required to liquefy the air during the following charge cycle and substantially increases round-trip efficiency [13]. In PTES systems all of the stored energy is in the form of "thermal exergy" in either hot or cold stores or both. A heat pump is used to transfer heat from the cold to the hot store during charge and the cycle is reversed and operated as a heat engine to discharge the stores and retrieve electrical work [14–17]. Finally, cold-storage packed beds may also be used in domestic and industrial cooling systems [18,19].

In the above applications, the proposed packed bed designs are normally of the axial-flow variety. However, as discussed in more detail below, there are a number of potential advantages to radial-flow configurations, including "self insulation" and the possibility of mitigating the conflict between heat exchange and pressure losses. The purpose of the current paper is therefore to compare axial- and radial-flow designs using a consistent modelling approach in order to assess their relative merits.

Previous studies have indicated that the behaviour of packed beds can have a significant impact on overall system performance. Furthermore, the shape and thickness of the "thermal fronts" (described further below) depends on history of operation, thus requiring transient methods for accurate modelling. Models that resolve the individual (and often conflicting) loss-generating processes are required so that designs may be optimised. Consequently, an accurate evaluation of different storage technologies (such as PTES and AA-CAES) requires