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Review

A review on experience feedback and numerical modeling of packed-bed thermal energy storage systems

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ABSTRACT

Solar thermal energy is a clean, climate-friendly and inexhaustible energy resource. It is therefore promising to cope with fossil fuel depletion and climate change. Thermal storage enables to make this intermittent energy resource dispatchable, reliable on demand and more competitive. Nowadays, most of the concentrated solar power plants equipped with integrated thermal storage systems use the two-tank molten salt technology. Despite its relative simplicity and efficiency, this technology is expensive and requires huge amounts of nitrate salts. In the short to medium term, packed-bed thermal energy storage with either liquid or gaseous heat transfer fluid is a promising alternative to reduce storage costs and hence improve the development of solar energy. To design reliable, efficient and cost-effective packed-bed storage systems, this technology, which involves many physical phenomena, has to be better understood.

This paper aims to sum up some key aspects about design, operation, and performances of packed-bed storage systems. In the first part, most representative setups and their experience feedback are presented. The controllability of packed-bed storage systems and the special influence of thermal stratification are pointed out. In the second part, the various numerical models used to predict packed-bed storage performances are reviewed. In the last part, some useful correlations enabling to quantify the main physical phenomena involved in packed-bed operation and modeling are presented and compared. The correlations investigated enable to calculate fluid/solid and fluid/wall heat transfer coefficients, effective thermal conductivity and pressure drop in packed beds.

Contents

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Nomenclature

A	viscous parameter in Ergun-type equations
A_s	superficial area of solids (m^2)
a_b	external surface area of packed-bed per unit bed volume ($m^2\,m^{-3}$)
a_s	surface area of solid per unit bed volume ($m^2\,m^{-3}$), see Eq. (4)
a_w	surface area of tank wall per elementary unit wall volume ($m^2\,m^{-3}$)
B	inertial parameter in Ergun-type equations
Bi	dimensionless Biot number, see Eq. (1)
Bi′	dimensionless Biot number as defined by Votyakov and Bonanos (2014), $Bi' = h \cdot a_s \cdot L^2/\lambda_{eff}$
c_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
E	thermal effusivity ($J\,K^{-1}\,m^{-2}\,s^{-1/2}$), $E = \sqrt{\rho \cdot c_p \cdot \lambda}$
f	term of tortuosity, defined in Cheng and Hsu (1998)
f_v	friction factor as defined by Ergun (1952), $f_v = \Delta P \cdot D_s^2 \cdot \varepsilon^3 / \left[L \cdot \mu_f \cdot u_{sup} \cdot (1-\varepsilon)^2\right]$
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
Hg	dimensionless Hagen number, $Hg = \rho_f \cdot \Delta P \cdot D_s^3/(L \cdot \mu_f^2)$
h_v	convective heat transfer coefficient per unit bed volume ($W\,m^{-3}\,K^{-1}$)
L	length of the packed bed in flow direction (m)
m	mass (kg)
Nu	dimensionless Nusselt number, $Nu = h \cdot D_s/\lambda_f$
Pe	dimensionless Péclet number as defined by Votyakov and Bonanos (2014), $Pe = u \cdot L/[\lambda/(\rho \cdot c_p)]_{eff}$
Pr	dimensionless Prandtl number, $Pr = \mu_f \cdot c_{p_f}/\lambda_f$
Q	energy (J)
Q^*	dimensionless energy, $Q^* = Q/\left[(\rho \cdot c_p)_{eff} \cdot V_b \cdot (T_{max} - T_{min})\right]$
r	radial coordinate (m)
R	radius (m)
Re	dimensionless Reynolds number, $Re = \rho_f \cdot u_{sup} \cdot D_s/\mu_f$
T	temperature (K)
T^*	dimensionless temperature, $T^* = (T - T_{ref})/(T_{max} - T_{ref})$
t	time (s)
t^*	dimensionless time, $t^* = t/(L/u)$
u	interstitial fluid velocity ($m\,s^{-1}$), $u = \dot{m}/(\rho_f \cdot \varepsilon \cdot \pi \cdot R_b^2)$
U	overall heat transfer coefficient between the inside and the outside of the tank ($W\,m^{-2}\,K^{-1}$)
u_{sup}	superficial fluid velocity ($m\,s^{-1}$), $u_{sup} = \varepsilon \cdot u$
V	volume (m^3)
w	velocity of the thermal front ($m\,s^{-1}$), see Eq. (10)
x	dimensionless time of the Schumann model, $x = h_v \cdot (t - z/u)/\left[(1-\varepsilon) \cdot \rho_s \cdot c_{p_s}\right]$
y	dimensionless length of the Schumann model, $y = h_v \cdot z/(\varepsilon \cdot \rho_f \cdot c_{p_f} \cdot u)$
z	axial coordinate in flow direction (m)
z^*	dimensionless axial coordinate, $z^* = z/L$

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$), $\alpha = \lambda/(\rho \cdot c_p)$
γ	ratio of volumetric heat capacity ($\rho \cdot c_p$) to effective volumetric heat capacity of the bed
$\delta\Theta$	dimensionless solid–fluid temperature difference
ε	void fraction
ϵ	emissivity
Λ	dimensionless diffusion coefficient as defined by Votyakov and Bonanos (2014), $\Lambda = 1 + (\gamma_s \cdot \gamma_f \cdot Pe)^2/Bi'$
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity (Pa s)
ν_0	cinematic viscosity evaluated for surface conditions ($m^2\,s^{-1}$)
ν_∞	cinematic viscosity evaluated for free stream conditions ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stephan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}\,W\,m^{-2}\,K^{-4}$
τ	dimensionless time as defined by Votyakov and Bonanos (2014), $\tau = t/(L^2/\alpha_{eff})$

Subscripts

∞	relating to ambient
b	relating to the whole packed bed
eff	effective value
eq	relating to/calculated with an equivalent diameter
eq, a	relating to/calculated with the diameter of the sphere of equivalent specific area, see Eq. (37)
eq, V	relating to/calculated with the diameter of the sphere of equivalent volume, see Eq. (38)
ext	relating to the external surface of the walls
f	relating to fluid phase
int	relating to the internal surface of the walls
max	maximal value
min	minimal value
mix	relating to fluid mixing and braiding effect
r	relating to radial direction (perpendicular to flow direction)
ref	relating to the reference condition
s	relating to filler solids
tot	total value
w	relating to the walls of the storage tank
z	relating to axial direction (flow direction)

Superscripts

0	with contribution of conduction in each phase (stagnant effective thermal conductivity)
C	with contribution of conduction through contact surfaces between solids
R	with contribution of radiative heat transfer