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Applicability of the local thermal equilibrium assumption in the performance modelling of CSP plant rock bed thermal energy storage systems

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ABSTRACT

Gas-solid packed beds have been widely studied as a cost-effective means of thermal energy storage in concentrating solar power (CSP) plants. Typically, the operation of packed beds in such systems is modelled by accounting for a finite rate of heat transfer between the fluid and solid media. This approach requires the coupled solution of the fluid- and solid-phase energy equations, which is computationally-costly, especially for year-long performance simulations. The local thermal equilibrium assumption, which assumes an infinite inter-phase heat transfer rate, can be applied to reduce the complexity and thus computational cost of packed bed models. However, the implications of making such an assumption in the context of CSP thermal energy storage system performance modelling is poorly understood. In fact, the application of the approach in long-term simulations has not been investigated before. This work addresses the topic by comparatively evaluating the performance of local thermal equilibrium and local thermal non-equilibrium models in the annual simulation of an air-rock packed bed, hypothetically operating in an open volumetric receiver CSP plant. The level of inter-model agreement is assessed in terms of annual bed exergy yield, bed blowing work, and plant power generation time. In addition, solution times are compared to establish the extent of computational cost savings. A parametric study examining the effect of variations in key bed design parameters on inter-model agreement is also conducted. The results obtained provide a clear indication of the strengths and weaknesses of either modelling approach, as well as of the suitability of the local thermal equilibrium assumption in general.

1. Introduction

1.1. Background

The use of packed beds with gaseous heat transfer fluids for sensible heat storage in concentrating solar power (CSP) plants has been widely considered for various forms of the technology. These include central receiver technologies such as open volumetric receiver (OVR) plants [1], fuel-hybridised OVR plants [2], solarised gas turbine [3] and combined cycles [4], in addition to parabolic trough plants utilising air as a heat transfer fluid (HTF) [5].

The general operating principle of gas-solid packed bed TES systems is straightforward. During charging, hot gas is passed through the packed bed, convectively heating the solid medium and establishing a thermal gradient, or thermocline, within it. This hot gas can comprise air heated by a volumetric or tubular receiver, or combustion products emanating from the exhaust of a gas turbine. When the system is discharged, ambient air is passed through the bed in the reverse direction and is subsequently heated by the solid medium. The hot air leaving the bed is then passed through a heat exchanger to provide heat input to the plant's power block.

Fig. 1 comparatively illustrates normalised thermoclines in the fluid and solid media of a typical packed bed at an instant in time. The shape and speed of the thermocline are dependent upon a number of effects related to heat transfer and fluid flow within the bed. For packed bed models applied in CSP plant simulations, it is especially important that thermocline evolution is accurately predicted, since the calculation of overall plant performance is strongly sensitive to this characteristic.

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Nomenclature

Symbols

a	Particle surface area per unit volume
$A_{b,c}$	Bed cross-sectional area
Bi_p	Particle Biot number
$c_{p,f}$	Fluid isobaric specific heat capacity
c_s	Solid specific heat capacity
D_b	Bed diameter
D_p	Mean equivalent particle diameter
DNI	Direct normal irradiance
DNI_{des}	Design-point direct normal irradiance
f_a	Apparent friction factor
$\bar{F}_{12}$	Inter-particle view factor
G_f	Fluid mass flux
$G_{f,dis}$	Design-point fluid mass flux for bed discharging
h	Heat transfer coefficient
H_b	Bed height
h_f	Fluid specific enthalpy
$h_{f,0}$	Fluid dead state specific enthalpy
$h_{v,c}$	Corrected volumetric heat transfer coefficient
$h_{v,eff}$	Effective volumetric heat transfer coefficient
h_v	Volumetric heat transfer coefficient
k_b	Bed conductivity
k^0_{con}	Stagnant bed conductivity
k_{eff}	Effective bed conductivity
k^0_{eff}	Effective idle bed conductivity
k_f	Fluid thermal conductivity
k_{rad}	Radiative conductivity
k_s	Solid thermal conductivity
m	Arbitrary node/segment
m_f	Fluid mass
$\dot{m}_f$	Fluid mass flow rate
$\dot{m}_{f,cha}$	Design-point fluid mass flow rate for bed charging
$\dot{m}_{f,dis}$	Design-point fluid mass flow rate for bed discharging
n	Node count
NTU	Number of transfer units
Nu	Nusselt number
Pr	Prandtl number
p_0	Dead state pressure
$\dot{Q}_{loss,v,m}$	Volumetric rate of heat loss from bed segment
Re	Reynolds number
Re_p	Particle Reynolds number
s_f	Fluid specific entropy
$s_{f,0}$	Fluid dead state specific entropy
t	Time
T_{amb}	Ambient temperature
T_b	Equivalent bed temperature
$T_{b,in}$	Bed inlet temperature
$T_{b,\,out,\,low}$	Minimum allowable bed outlet temperature during bed discharge
T_f	Fluid temperature
T_s	Solid temperature
T_0	Dead state temperature
U_{wall}	Wall overall heat transfer coefficient
v_s	Superficial bed velocity
W_{blo}	Cumulative annual blowing work
$\dot{W}_{blo}$	Blowing power at a given simulation hour
X_f	Cumulative annual exergy yield
$\dot{X}_f$	Rate of exergy yield at a given simulation hour
z	Bed axial location
γ	Time step size fraction
Δp_b	Bed pressure drop
Δp_{buoy}	Buoyancy-based pressure difference
Δp_m	Segment pressure drop
$\in$	Bed void fraction
ε	Radiative emissivity
μ_f	Fluid dynamic viscosity
ρ_f	Fluid density
ρ_s	Solid density
τ	Thermal time constant
σ	Stefan-Boltzmann constant, $5.67\times10^{-8}\,W/(m^2\,K^4)$

Abbreviations

CFD	Computational fluid dynamics
CSP	Concentrating solar power
DNI	Direct normal irradiance
HRSG	Heat recovery steam generator
HTF	Heat transfer fluid
LTE	Local thermal equilibrium
LTNE	Local thermal non-equilibrium
NTU	Number of transfer units
OVR	Open volumetric receiver
TES	Thermal energy storage
TMY3	Typical Meteorological Year 3

This is as a consequence of a number of factors. The first is that the exergy contained by the bed is directly associated with thermocline shape. An acute thermocline indicates a higher exergy content than a more obtuse temperature profile. In turn, exergy content directly affects the energy yielded by the downstream power cycle, and thus overall plant performance. Secondly, since TES system operation is guided by the gas phase temperature at the bed outlet, excessively acute or obtuse thermoclines will give rise to premature or delayed activation or deactivation of the TES system. Deviations of this nature have a direct impact upon plant output. Thirdly, since the estimation of packed bed pressure drop relies on a knowledge of the bed's gas phase temperature distribution, an unrealistic thermocline will lead to an inaccurate evaluation of pressure losses. In turn, this will lead to an inaccurate estimate of parasitic losses and thus plant performance.

As the rate at which heat is transferred between the HTF and storage medium is, in reality, finite, the gas and solid phases will not be in exact thermal equilibrium within the majority of a packed bed. Two-phase thermal performance models that account for this reality are therefore classified as Local Thermal Non-Equilibrium (LTNE) models. In various forms, LTNE models have been applied in the performance modelling of CSP-based gas-solid packed beds in numerous prior studies.

Durisch et al. [6] applied an LTNE model to predict the performance of the proposed METAROZ plant [7]. The model was later enhanced and validated by Meier et al. [8]. Fricker [9] studied the operational characteristics of the TES system of the original PS10 plant design [10]. As part of a study on the thermo-mechanical behaviour of packed bed TES systems, Dreißigacker [11] applied an LTNE model to predict bed temperature distributions. Zunft et al. [1] went on to apply this model in a performance analysis of the TES system of the Solar Tower Jülich OVR plant [12]. Allen [13] employed the LTNE modelling approach to study the performance of rock bed TES systems, in the context of the SUNSPOT solarised combined cycle [14].

Hänchen et al. [15] applied an LTNE model to parametrically investigate the performance of a high temperature rock bed. In associated work, Zanganeh et al. [16] studied the performance of a large-scale TES system utilising the same technology. Zanganeh et al. [17] went on to use a similar modelling approach to design a rock bed TES system for use in an air HTF parabolic trough plant.