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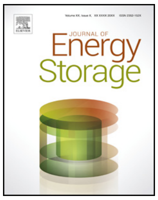

Packed bed thermal energy storage: A simplified experimentally validated model

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ABSTRACT

Thermal energy storage in packed beds is receiving increased attention as a necessary component for efficient implementation of concentrated solar power plants. A simplified, one-equation thermal model for the behavior of a packed bed is presented for α-alumina as solid storage material and air as the heat transfer fluid. The model successfully predicts the thermocline behavior over time. Two flow rates during storage are presented for alumina in a cylindrical packed bed. Temperature-dependent thermophysical properties are utilized to accurately model the systems. An additional study of air and alumina at high temperature (700 °C) is presented to further highlight the importance of variable thermophysical properties in real models. Explicit consideration is given to explain situations where the modeling approach is valid based on a Biot number analysis and the thermal capacities of the solid and fluid.

1. Introduction

Research in sustainable energy sources continues in order to address concerns over climate change, pollution, and non-renewable sources. Concentrating solar power (CSP) plants are emerging as one such sustainable energy option that can generate electricity from solar energy. Systems such as solar power towers, parabolic trough collectors, and linear Fresnel reflectors concentrate solar energy by reflecting sunlight to a receiver. At the receiver, a 'thermal energy carrier' is heated, which is then utilized to generate power [1]. This technology is particularly well suited to areas with high solar irradiation fluxes [2]. However, solar energy availability is variable, such as from night to day or summer to winter [1,3], and the levelized cost of electricity (LCOE) is high [4]. Thermal energy storage (TES) can offset variability and reduce costs [4–6].

However, storage and recovery of thermal energy must be done efficiently to achieve high capacity factors and low LCOE. As described in the review of Kuravi et al. [5], TES technologies must meet several requirements: high energy density, good heat transfer between the heat transfer fluid (HTF) and solid storage media, stability (mechanical and chemical) of the storage medium, low thermal losses, low cost, and reversibility through many charging and discharging cycles. A comparison of thermal energy storage designs is given by Li et al. [7]. TES can be done with sensible heat storage systems (heating a solid material) or latent heat storage (energy associated with phase change from solid to liquid) [5]. The present study explores sensible thermal energy storage; reviews of phase change based systems are provided in [8,9]. The solid storage arrangement studied here is to store the heat in a packed bed [10,11], which is considered an emerging technology to boost total system efficiency [4]. Charging the bed is achieved by flowing fluid, heated by solar radiation, through the packed bed to heat the storage material. To recover the stored energy from the bed (discharge), the flow direction is reversed and low temperature fluid enters the already heated bed. The exiting fluid is at a higher temperature and can then be used in a power cycle.

In packed bed systems like these, experimental and modeling studies have examined the effects of parameters such as void fraction [12], flow rate variations [13,14], wall thermal losses [13,15], particle size [12,14], packing material [16–18], and fluid inlet temperature [19,20]. For packed beds to be efficient in thermal cycling, they must maintain a high degree of thermal stratification [21], which is affected by the aforementioned system parameters. Higher exergy (a measure of useful work in the system) is recovered when little mixing of the hot and cold zones in the storage tank occurs, making the control and shape of the

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Nomenclature

C	Courant number
c_p	Heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
d_p	Particle diameter (m)
ε	Porosity of packed bed
h	Heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
h_{bed}	Packed bed height (m)
k	Thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L_c	Characteristic length (m)
P	Pressure (Pa)
ρ	Density ($\mathrm{kg\,m^{-3}}$)
Q	Heat source/sink (W)
t	Time (s)
T	Temperature (K)
$\bar{u}$	Velocity ($\mathrm{m\,s^{-1}}$)
x	Cell size (m)
Bi	Biot number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Subscripts

eq	Equivalent
f	Fluid
s	Solid

thermal front important [15]; this is readily appreciated when one considers that the maximum thermal efficiency in a Carnot cycle increases with the highest temperature. In addition to the thermal effects in the bed, the fluid flow conditions must be considered to minimize the pressure drop, which can add to exergy destruction [22]. A low void fraction in the bed will lead to a smaller storage vessel for a given amount of energy to be stored, but the pressure drop is increased. Similarly, smaller bead sizes minimize intra-particle temperature gradients (assuming sufficiently high thermal conductivity of the storage media), but also lead to a higher pressure drop. Considering the large number of parameters and potentially competing effects (e.g., the noted high storage density but unacceptable pressure drop at low void fraction), further studies are required to design systems capable of high exergy recovery in packed bed systems.

Four energy balance models typically exist in packed bed systems as reviewed by Ismail et al. [12]. (1) The continuous solid-phase model [12], which treats the solid as a continuum (no individual particles) includes equations for the full energy balance of the solid and fluid phases. This approach takes into account the enthalpy changes, heat conduction in the bed, convective heat transfer between the fluid and solid, and the heat loss from the vessel. (2) Schumann's model [23] is similar to the continuous solid-phase model, but assumes no radial (perpendicular to the flow axis) heat conduction, nor conduction in the fluid or solids. (3) The single-phase/one-equation model assumes thermal equilibrium between the solid and fluid, and the properties are written as equivalent parameters (e.g., an equivalent thermal conductivity k_{eq}) [24]. This model can determine the spatial distribution throughout the packed bed. (4) Lastly, one could solve a model with energy equations for the fluid and solid phases that allows for thermal gradients within the particles themselves. Depending on the solid and fluid materials and on what information is desired, one of these general modeling approaches can be chosen or modified. Previous work explored the air and alumina system with an energy balance for both fluid and solid with coupling via the heat transfer coefficient [13,25]. This approach is needed when thermal equilibrium may not exist between the fluid and solid; however, the temperatures in [13] were quite similar for solid and fluid. Based on that, thermal equilibrium is a reasonable approximation and the one-equation model (Model 3) can be used in such cases [12,26]. This modeling approach is therefore used in this study.

In this work, packed bed thermal energy storage is considered with air as the heat transfer fluid [27], such as could occur with solar receivers utilizing a gaseous heat transfer fluid [4]. The solid storage material is α-alumina spheres, which is considered a good candidate for storage due to its stability (thermal/mechanical/chemical), high heat capacity, and high thermal conductivity [13,28]. This paper presents a simplified, one-equation energy model coupled to a Navier–Stokes solution of the flow to calculate the transient temperature profiles in a packed bed during storage. In calculating the thermal behavior, the model incorporates temperature-dependent thermophysical properties. The model is successfully validated against experimental data for an alumina bed with air as heat transfer fluid at two flow rates. To further highlight the importance of temperature-dependent thermophysical properties, storage results of α-alumina and air are presented for a high-temperature operation. Limitations to the assumption of thermal equilibrium between the fluid and solid phases are presented along with an analysis of the particle Biot number at various conditions. Importantly, this work shows that this one-equation thermal model approach is sufficiently accurate for future design studies.

2. General modeling approach: one-equation thermal model and coupled Navier–Stokes solution

The one-equation approach to the energy balance is presented here. This modeling approach is also referred to as a 'one-phase' model where the bed is reasonably approximated as a quasi-homogeneous medium [24]. This approach assumes thermal equilibrium between the fluid and solid phases, which is reasonable for the materials and conditions considered here. The model also assumes no intra-particle temperature gradients, which is important in energy storage applications [29]. Based on previous results with α-alumina and air [13], estimates for the heat transfer coefficient show the Biot number ($Bi = hL_c/k$) satisfies $Bi < 0.1$. Limitations to this approach and a more detailed analysis of thermal equilibrium and the Biot number are discussed in a later section. The overall thermal model considers heat transfer in a porous media/packed bed domain and in the solid domains of the vessel and insulation.

The velocities and pressure drop in the packed bed are also solved. The generalized Navier–Stokes equations are considered with a velocity-dependent body force accounting for viscous and inertial losses within the porous medium [30–32]. The viscous and inertial coefficients are constants calculated by Ergun [26,33] and then applied before the simulation is run. The one-equation thermal model is coupled to the Navier–Stokes solution of the domain through the porous region. The velocity and pressure results are not presented here as no experimental data was collected for these.

2.1. One-equation thermal model for a packed bed

The one-equation packed bed model uses an energy balance based on equivalent properties [34]. In the packed bed domain, the equations are:

$$(\rho c_p)_{eq}\frac{\partial T}{\partial t} + \rho c_p \bar{u}\cdot\nabla T = \nabla\cdot(k_{eq}\nabla T) + Q_{loss} \tag{1}$$