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Verification of a model of thermal storage incorporated with an extended lumped capacitance method for various solid–fluid structural combinations

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Abstract

With an extended lumped capacitance method applied to account for the internal heat conduction resistance in a solid (for Biot number larger than 0.1), a general model of thermal energy storage with various solid–fluid structural combinations is presented and verified using numerical results. The thermal energy storage system has a heat transfer fluid (HTF) flowing through a packed bed of solid materials structured in different configurations, such as in the form of solid pebbles, parallel plates, solid rod-bundles, or solids with fluid tubes imbedded through them. The model of energy conservation in the liquid and solid is transient, one-dimensional in nature, due to the introduction of a modified lumped capacitance method that counts for the effect of three-dimensional heat conduction in the solid structures. The computational workload using this modified model is significantly less compared to that of a comprehensive CFD analysis. Numerical results obtained from a CFD analysis of the thermal energy storage in the solid and liquid are used to verify the model. The CFD simulated results of temperatures of HTF are compared with the 1D model results, and they show excellent agreement. In conclusion, the 1D model is recommended as a convenient and accurate tool for general analysis and sizing of thermal energy storage containers that have various solid–fluid structural combinations.

Keywords: Thermal energy storage; Extended lumped capacitance; Effective heat transfer coefficient; CFD results; Verification

1. Introduction

The recent fast-paced development of solar energy technologies has imposed a great demand for large-quantity energy storage. With the storage of a large amount of solar thermal energy, concentrated solar thermal power (CSP) generation is expected to contribute to the world's energy supply significantly in the future. Technical subjects related to CSP have already drawn a lot of attention during the past decade (Pavlović et al., 2012). With thermal energy storage, most CSP systems can smooth out the short-term transients (e.g., collector shading from passing clouds) and extend the daily operation of solar power plants during the late afternoon and evening hours at a relatively low cost of energy storage (Müller-Steinhagen and Trieb, 2004). Thermal energy storage in CSP systems is the key element that will largely guarantee achievement of the target set by the U.S. Department of Energy (DOE) –that by 2030, retail electricity rates will be as low as 6 cents/kilowatt-hour (kW h) (SunShot Vision Study, 2012). A CSP system uses a solar tower, parabolic troughs, or linear Fresnel lenses

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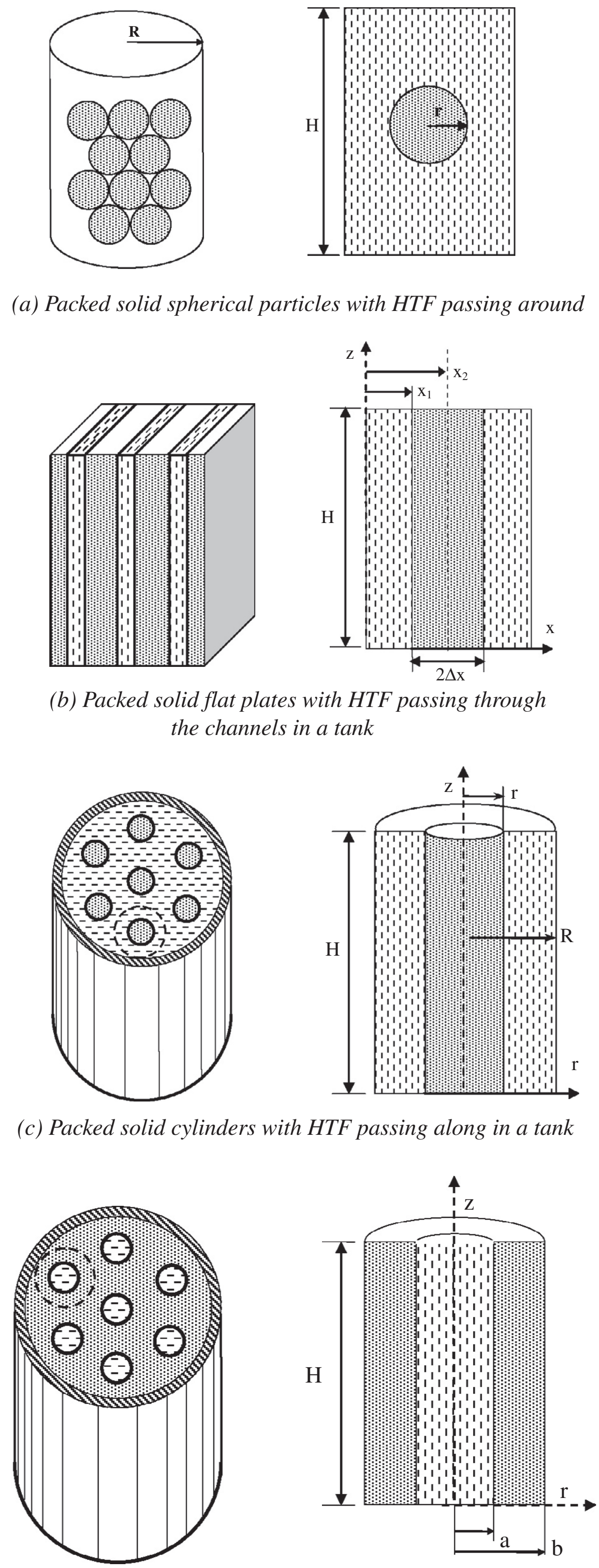
to concentrate sunlight and produce intense heat to transfer to heat transfer fluid (HTF) that carries heat for thermal energy storage as well as for thermal cycles in conventional power plants (Py et al., 2013).

After its temperature rise, the HTF from a concentrated solar collection system can be used directly for thermal energy storage, or can be sent to a solid-packed thermal storage system, which is a dual-media system. The dual-media thermal storage system can significantly reduce the storage cost by introducing low-cost solid thermal-storage materials, but sacrifices efficiency. The heat exchange between the HTF and solid thermal energy storage medium during both energy charge and discharge processes causes a loss in energy storage efficiency. Specifically, a degradation of the temperature of the HTF typically occurs as it is discharged. In order to better understand and design the size of dual-media thermal energy storage systems as shown in Fig. 1, the heat transfer or energy exchange between HTF and a solid medium has to be analyzed thoroughly (Zhang et al., 2013; Zanganeh et al., 2012).

A convenient and effective analytical tool was provided by Li et al. (2011a,b) and Van Lew et al. (2009) who developed a numerical model to solve a group of simplified 1D transient energy equations proposed by Schumann (1929), describing the heat transfer and energy storage/extraction between the HTF and the packed-bed solid material. The numerical model is robust and efficient in carrying out a great number of calculations (for a large number of charging and discharging cycles) for sizing the thermal storage tanks of various levels of energy storage demand. The Schumann equations were constructed without considering the internal heat conduction resistance in the solid thermal storage material, which is commonly known as the lumped capacitance assumption, and are only accurate when the Biot number is sufficiently small, typically less than 0.1.

In practical applications, where the characteristic scale of the solid thermal storage material is large, the internal thermal resistance becomes significant. If one still wants to take the advantage of the 1D model represented by the Schumann equations and the corresponding numerical method of solution as mentioned above, a correction to the lumped capacitance method is inevitable.

Earlier in the 1970s, Bradshaw et al. (1970) and Jeffreson (1972) conducted a pioneering work to extend the use of the lumped capacitance method for spherical solid material to accommodate the circumstances when the temperature distribution within the solid material cannot be ignored (at Biot number larger than 0.1). The key idea of their work is the introduction of a corrected, or an effective heat transfer coefficient, h_{eff}, to replace the intrinsic heat transfer coefficient h between the solid material and the HTF. A very important extension of this method has been conducted by Xu et al. (2012) for solid objects like flat plates, infinite long cylinders, and infinite long tubes for Biot numbers up to 100 with sufficient accuracy. Combining



(a) *Packed solid spherical particles with HTF passing around*

(b) *Packed solid flat plates with HTF passing through the channels in a tank*

(c) *Packed solid cylinders with HTF passing along in a tank*

(d) *Solid thermal storage material with HTF tubes passing through in a tank*

Fig. 1. Four typical solid–fluid structural combinations of thermal storage systems (▒ solid thermal storage material; ▤ HTF).