Applied Thermal Engineering 64 (2014) 201–208

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Sliding flow method for exergetically efficient packed bed thermal storage

Hitesh Bindra [a,c,*], Pablo Bueno [b], Jeffrey F. Morris [c,d]

[a] CUNY Energy Institute, City College of New York, NY 10031, USA
[b] Southwest Research Institute, San Antonio, TX 78238, USA
[c] Levich Institute, City College of New York, NY 10031, USA
[d] Department of Chemical Engineering, City College of New York, NY 10031, USA

HIGHLIGHTS

- The effect of pressure drop on fractional exergy destruction in packed bed thermal storage is quantified, that is 2–6%.
- Sliding flow method (SFM) decouples the thermal behavior and pressure drop effects in packed bed thermal storage.
- The SFM significantly improves the exergy efficiency and also reduces the design constraints on thermal storage systems.

ARTICLE INFO

Article history:
Received 18 July 2013
Accepted 13 December 2013
Available online 24 December 2013

Keywords:
Packed bed
Thermal storage
Exergy
Pressure drop

ABSTRACT

The feasibility of a thermal energy storage method is highly dependent on its exergetic efficiency. The two major components which cause exergy destruction in packed bed thermal energy storage methods are pressure drop and temperature dispersion. It is difficult to prevent exergy destruction with existing packed bed type thermal storage systems because the effect of most physical parameters on the pressure drop is opposite to that on the mixing or axial dispersion. We propose a new sliding flow strategy in which fluid inlet and outlet ports change as the temperature front in the bed moves. In this design the typical distance between two simultaneously active inlet and outlet ports will be approximately equal to twice the axial dispersion length. The computations presented in this paper show that the sliding flow method (SFM) is expected to perform significantly better than existing methods and will result in substantial reduction in exergy destruction. The major advantage of the SFM is its ability to decouple thermal behavior and pressure drop effects, thus reducing the design constraints.

1. Introduction

Economical energy storage is currently in high demand for matching the grid demand curve and providing dispatchability to intermittent renewable energy sources. The existing electrical energy storage, i.e. batteries, is not an economically viable option; therefore, other alternatives are being considered. There are many on-going efforts to develop energy storage ideas – chemical, electrical, mechanical, and thermal methods. Thermal energy is the most common form used in power production so it makes sense to find efficient ways to store it.

As thermal energy has limited capacity to do mechanical work, it is essential to know the amount of useful energy that can be recovered from its storage. The best possible parametric method to evaluate the performance of thermal energy storage is by calculating the fractional exergy recovery or exergy efficiency. Therefore, to achieve higher exergetic performance, several high temperature energy storage ideas are being investigated and improved today. Most of these ideas can be broadly classified as phase change, reversible thermochemical, and sensible heat methods. Phase change and reversible thermochemical methods operate favorably only over limited temperature ranges at which the phase change and chemical reactions occur respectively. Among the sensible heat methods, molten salt tank storage and packed bed solid storage are

* Corresponding author. CUNY Energy Institute, City College of New York, New York, NY 10031, USA.
E-mail addresses: hbindra@che.ccny.cuny.edu, nuchembins@gmail.com (H. Bindra).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.12.028

popular. However, molten salt methods have lower energy densities than packed bed methods because their operating temperature range is narrow owing to upper (decomposition temperature) and lower (solidification temperature) limits on the material. Rock or packed beds for heat storage have been tested for many decades but major technological challenges remain, including difficulty in producing sharp thermal gradients and the presence of high pressure drops. Both of these problems can lead to lower exergy recovery which should be quantified to provide practical design guidelines.

Several researchers have developed methods to evaluate the exergy recovery of generic and mixed tank thermal storage systems [1–3]. Recently, Bindra et al. [4] performed an exergy analysis on packed bed thermal storage based on a multiphase thermal model. The model quantified the drop in exergy efficiency due to heat losses and axial dispersion. This work was validated against experimental data and showed that for large, practical scale systems, heat losses, and therefore exergy destruction due to them, are minimal. Therefore, thermal exergy evaluation on the basis of axial dispersion analysis is sufficient but to compute overall exergy recovered, work done against the pressure drop should also be included.

Here, we will integrate exergy losses due to pressure drop and axial dispersion to evaluate overall exergy recovery. As shown in our previous work, and elsewhere [5], axial dispersion is a cumulative process and results in reduction in utilization fraction of the bed after each cycle if the bed is not filled completely. Therefore, one way to have a constant utilizable bed length is to fill the storage completely up to its steady state and recover the heat until the whole bed is at lowest temperature. Various models to quantify pressure drop inside packed beds have been developed and validated [6,7]. These models can be used to quantify work required to overcome the pressure drop and corresponding exergy destroyed. Now we will integrate both of these models (i.e. axial dispersion and pressure drop) to quantify the overall exergy efficiency.

As some of the important physical parameters have opposing effects on axial dispersion and pressure drop, it is important to use this exergy evaluation method for optimal system design. Their opposing effects limit the number of possible designs which are exergetically feasible. As thermal storage is considered as a new additional system for existing power plants and proven thermal power plant designs, it reduces the practical scope of integration with limited designs and operating range. In the sliding flow method, designed by Bindra & Bueno [8], operation beyond this optimum regime is allowed and results in reduction of exergy loss. The physical principles governing the sliding flow method remain the same as in our previous work but inlet and outlet ports of the bed change as the temperature front moves in the packed bed, effectively following the thermal front. The name sliding flow is used to emphasize that the flow path is also made to slide through the bed. A more detailed description of the method is provided in later sections. This study will extend our previous model by integrating pressure drop into the exergy calculation, introduce the details of the sliding flow method and finally discuss the advantages of the new method based on overall exergy analysis.

2. Pressure drop model

The simplest and most commonly used model to predict pressure drop inside packed beds was developed by Ergun [6]. It has been consistently used for wide range of applications for fixed and fluidized beds. The Ergun equation is as follows,

$$\frac{\Delta P}{\Delta x} = 150\frac{\varepsilon^2}{(1-\varepsilon)^3}\frac{\mu_f v}{d_p^2} + 1.75\frac{\varepsilon}{(1-\varepsilon)^3}\frac{\rho_f v^2}{d_p} \quad (1)$$

where, ΔP is the pressure drop across packed bed, H is the length/height of the packed bed, ε is the porosity, μ_f is viscosity of fluid, ρ_f is the density of fluid, d_p is the diameter of spherical particles, and v is the fluid velocity. This equation provides satisfactory results for spherical particles, but due to its semi-empirical nature it is difficult to adapt it for other types of particles. The derivation of the Ergun model is based on the assumption of straight parallel channels which is very different from the reality of randomly packed beds. After the Ergun equation, various new models were devised to suit particular applications of fixed or fluidized beds. Recently, a general purpose model was introduced by du Plessis and Woudberg [9]. This model considers the flow in the porous regions more realistically by dividing the packed bed into 3-dimensional representative unit cells, with each region having equivalent flow diameter based on the porosity. Due to the division of geometry into representative unit cells, this model is called the RUC model. The accuracy of this model was validated by Allen [10] for several mass velocities and particle sizes. Therefore we will use this model, in which the pressure drop per unit length is given by

$$\frac{\Delta P}{\Delta x} = \frac{\mu_f v}{d_p^2}\left[\frac{25.4(1-\varepsilon)^{\frac{4}{3}}}{\left(1-(1-\varepsilon)^{\frac{1}{3}}\right)\left(1-(1-\varepsilon)^{\frac{2}{3}}\right)^2} + \frac{C_d \mathrm{Re}_p}{2\varepsilon\left(1-(1-\varepsilon)^{\frac{2}{3}}\right)^2}\right] \quad (2)$$

where, C_d is drag coefficient and Re_p is the Reynolds number based on individual particle.

Fig. 1 compares the Ergun equation with the RUC model. For larger particle sizes both the models tend to converge but for smaller particle sizes, the RUC model predicts higher pressure drop as compared to the Ergun equation. Hence, exergy estimates using the RUC model will give conservative values. Work done against

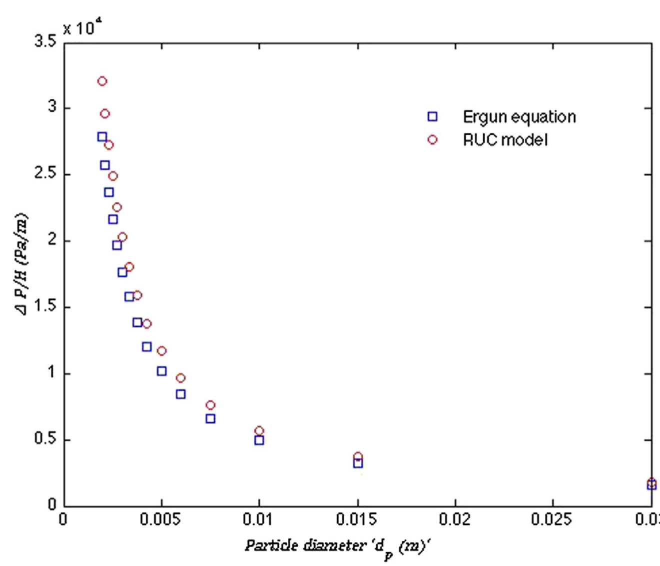

Fig. 1. Comparison of Ergun equation and RUC model for range of particle sizes. Operating conditions and property values: $\rho_f = 20$ kg/m^3, $\mu_f = 3.6 \times 10^{-5}$ Pa s, $\varepsilon = 0.35$ and $v = 0.3$ m/s.