Chemical Engineering Science 152 (2016) 45–54

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Prediction of conductive heating time scales of particles in a rotary drum

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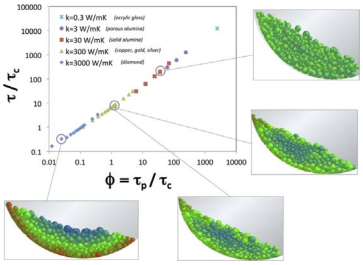
HIGHLIGHTS

- We use discrete element method simulations to study heat transfer in a rotary drum.
- We identify three heating time scales for particle conduction in rotary drums.
- Combining the heating time scales leads to a monotonic relationship.
- Distinct heating regimes are present along the heating time scale curve.
- Results are valid over a wide range of rotation rates and thermal conductivities.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 December 2015
Received in revised form
20 April 2016
Accepted 16 May 2016
Available online 24 May 2016

Keywords:
Particle technology
Heat transfer
Discrete element method
Conduction
Calcination
Catalyst manufacture

ABSTRACT

Modeling conductive heat transfer from rotary drum walls to a particle bed via discrete element method simulations, three time scales were determined: 1) the characteristic heating time of the bed, τ; 2) the particle thermal time constant, τ_p; and 3) the contact time between a particle and the wall, τ_c. Results fall onto a monotonic curve of τ/τ_c vs. ϕ (τ_p/τ_c), with three heating regimes. At low ϕ, conduction dominates, and the system heats quickly as a solid body. At high ϕ, granular convection dominates, and the bed heats slowly at a nearly uniform temperature. At intermediate ϕ, the system heats as a cool core with warmer outer layers. The results of this work have important implications for improving the design and operation of rotary drums (e.g., energy-intensive calcination processes). By calculating τ_p and τ_c from material and operating parameters, the characteristic heating time, τ, can be predicted *a priori*.

1. Introduction

Many industries utilize rotary kilns, or drums, for particulate mass and heat transfer. Applications vary from calcination processes (e.g., petroleum coke, limestone, catalyst manufacturing) to drying of solids to the reclamation of contaminated solid wastes (Yang and Farouk, 1997). These can be very energy intensive processes. For example, the clinkering of cement requires from 3 to 7 GJ per ton produced, which accounts for roughly 1–3% of the world's energy (Engin and Ari, 2005; van Oss and Padovani, 2003). Thus, optimizing the process has tremendous potential for reducing energy consumption.

Developing a better process understanding of rotary kilns can significantly improve the quality of the end product as well as save

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http://dx.doi.org/10.1016/j.ces.2016.05.022
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energy and material costs. Currently, predictive models for material flow and heat transfer are lacking, particularly upon scale-up from the lab and pilot scale to the manufacturing scale. Important processes within the drum that are affected by scale include radial heat transfer, radial mixing, and possibly axial dispersion. Because of the nature of these operations (e.g., material and device availability, high temperature requirements, sampling issues, time and personnel costs), it is not always practical to do detailed experimental studies. Recently, computer modeling and process simulations of particulate processes, particularly discrete element method (DEM) modeling (Zhu et al., 2008), have made significant advances both in accuracy and in computational speed. In some cases, it is now possible to design realistic models of devices and simulate their performance at full scale.

The two important indices for any continuous rotary kiln process are: (1) the characteristic time of heat transfer and (2) the residence time of the particles in the drum (Gao et al., 2013). Desired performance can be obtained only when the residence time of the particles inside the drum is longer than the time necessary for cross-sectional heat transfer. As a result, better understanding of the effects of operating conditions (e.g., rotary speed, incline angle, feed rate, fill level, hold-up), geometry design (e.g., drum diameter, drum length, baffles, dams), and material properties (e.g., particle size, size distribution, shape, density, cohesiveness, Young's modulus, thermal conductivity, specific heat) on both indices is critical in providing reliable quality control and process design methods.

The focus of this work is on the radial heat transfer process in a rotary drum, and specifically on the characteristic time scale to heat the particle bed. Since this overall heating time is so important, we aim to quantify the factors relevant to heating a particle bed, as well as to investigate the effects of many different variables on the heating time. The primary variables of interest are the drum rotation rate and particle thermal conductivity, as these parameters are expected to most influence heat transfer. In order to characterize the radial temperature distribution profiles, slice simulations based on the discrete element method (DEM) are performed using the commercial software package EDEM with a user-defined Application Programming Interface (API) code developed in-house to model the heat transfer between the drum walls and the particles.

2. Heating in rotary drums

The behavior of particles in rotary drums has been widely studied, with a primary focus on mixing (Ingram et al., 2005; Kwapinska et al., 2006; Van Puyvelde, 2006). The most common way to characterize particle flow and mixing in a rotating drum is by the Froude number, *Fr*, which is the ratio of inertial to gravitational force in the particle bed:

$$Fr = \frac{\omega^2 R}{g} \tag{1}$$

The Froude number along with fill level can be used to estimate the flow regime, but material properties also play a non-trivial role (Ding et al., 2001; Mellmann, 2001).

Some attention has been given to the heat transfer mechanisms in these systems through experiments (Liu and Specht, 2010; Thammavong et al., 2011; Wes et al., 1976), continuum modeling (Boateng and Barr, 1996; Dhanjal et al., 2004), DEM modeling (Chaudhuri et al., 2006; Figueroa et al., 2010; Gui et al., 2013; Nguyen et al., 2014; Schmidt and Nikrityuk, 2011; Shi et al., 2008), a comparison of both types of modeling (Kwapinska et al., 2008), or a combination of modeling and experiments (Chaudhuri et al., 2010; Kwapinska et al., 2006). Although continuum models generally match experimental trends, DEM provides new information about individual particle behavior (e.g., temperature distributions), which can aid in understanding the link from single particle to bulk particle bed behavior. Experimental studies are rare due to the high temperature environments and often the large amounts of material required to run each experiment at full scale. These factors make it difficult to investigate a wide range of parameters, and thus the applicability of these results is limited. In experiments, bed temperature at different locations can be monitored with thermocouples, but it is not possible to track each particle's temperature. The results generally include the determination of heat transfer coefficients that are valid under the specific set of conditions studied (Thammavong et al., 2011). Thus, discrete computational simulations are a useful way to study heat transfer in rotary drums due to the ability to investigate the effects of various operating parameters and material properties, and to track each particle's temperature.

In rotary drums, heat transfer can occur by conduction, convection, and radiation. There is also the possibility of the generation of heat due to friction between the particles, which we do not consider in this work. In our system, we only consider contact conduction between the heated drum walls and the particle bed, and between particles. Contact conduction is expected to dominate in operations where the fluid phase is stationary and its thermal conductivity is small, and where temperatures are moderate (<500 °C) (Chaudhuri et al., 2010; Schmidt and Nikrityuk, 2011; Thammavong et al., 2011). Although conduction-only heat transfer may be a simplification of the heating occurring in real systems, it is essential to focus first on understanding the governing phenomena involved in this primary heat transfer mode before further complexities are added.

A few researchers have investigated the effects of operating and material parameters on conductive heat transfer in rotary drums with heated walls (Chaudhuri et al., 2010; Figueroa et al., 2010; Nguyen et al., 2014). Figueroa et al. (2010) compared mixing versus heating rates in various rotating systems. They discovered that mixing can either enhance or worsen heat transfer, depending on the Peclet number. Chaudhuri et al. (2010) studied alumina and silica in 15 cm calciners through experiments and EDEM simulations. The drums were filled at 50%, and the walls were kept constant at 100 °C. They found that a higher thermal conductivity material heated faster, as expected. But, surprisingly, rotation rate did not impact heat transfer. Also, baffles were found to promote heat transfer and more uniform particle temperatures within the bed. Recently, Nguyen et al. (2014) performed 2D DEM simulations of 10 cm diameter drums, investigating the effects of thermal conductivity, heat capacity, fill level, rotation rate, and particle size on heat transfer. Always operating in rolling mode, the particle bed heating progressed as a cool core with a warmer outer layer in all cases. They found that small particle size, high rotation rate, low fill level, low heat capacity, and high thermal conductivity each resulted in faster heating.

In our study, we aim to explain these previous results on the effects of different variables on conductive heat transfer to particles in rotary drums, as well as to uncover a unified relationship between the overall heating time and system parameters in order to predict heating behavior.

3. Heat transfer theory

Heat conduction from rotary drum walls to the interior particle bed is a primarily radial process. Previous researchers have shown that radial dispersion is much more rapid than axial dispersion in rotary drums (Ding et al., 2001; Figueroa et al., 2010). Therefore,