Chemical Engineering Science 73 (2012) 400–411

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

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

Design loading of free flowing and cohesive solids in flighted rotary dryers

O.O. Ajayi, M.E. Sheehan *

School of Engineering and Physical Sciences, James Cook University, Townsville, QLD 4811, Australia

A R T I C L E I N F O

Article history:
Received 27 February 2011
Received in revised form
15 November 2011
Accepted 17 January 2012
Available online 28 January 2012

Keywords:
Flighted rotary dryer
Design load
Holdup
Image analysis
Computational Fluid Dynamics
Cohesion

A B S T R A C T

Holdup in flighted rotary dryers can be classified according to its loading state as either over, under or at design load. The loading state influences the effectiveness of particle to gas heat and mass transfer as well as the residence time of solids through the dryer. As such, accurate estimation of the design load is critical to the analysis of performance and the optimal design of flighted rotary dryers. In this paper design load experiments carried out in a horizontal, pilot scale flighted rotary dryer at different experimental conditions are described. The design load experiments involved analysis of multiple photographs of the cross sectional area of the solids in the front end of the dryer, at increasing loading conditions. Subsequently, the design load was estimated using conventional criteria based on the saturation of material in the cascading or unloading flights. The study examined both free flowing and cohesive solids with cohesion being controlled through the addition of low volatility fluid to the solids (dynamic angle of repose ranged from 44.7° to 62.3°). The effect of drum rotational speed was also examined (2.5 rpm–4.5 rpm). In order to select an appropriate geometrically derived design load model, comparison with existing design load models from the literature was undertaken. The proportion of airborne to flight borne solids within the drum was characterised through a combination of photographic analysis coupled with Computational Fluid Dynamics (CFD) simulation. In particular, solid volume fractions of the airborne solids with solid flow rate ranging from 0.703 kg/s to 0.134 kg/s were characterised using a CFD technique based on the Eulerian–Eulerian approach. The suitability of using geometric models of flight unloading to predict design loading in flighted rotary dryers is discussed. A modified version of Baker's (1988) design load model is proposed.

1. Introduction

Rotary dryers are commonly used in the food and mineral processing industries for drying granular or particulate solids due to their simplicity, low cost and versatility compared to other dryers. In industry applications the rotary dryer consists of a cylindrical shell slightly inclined towards the outlet and fitted internally with an array of flights. In some dryers, combinations of flighted and unflighted sections are used. The flight configurations vary from spirals to straight, single or multi-serrated flights. Wet feed enters one end of the dryer, dry material discharges at the other. Gas used as drying medium is introduced as either co-current or counter-current to the solid flow.

There are two key property characteristics in dryer performance: residence time (RT) and holdup. Holdup is further characterised into airborne solids, and flight borne solids, which are the solids within the flights and the base of the drum. The degree of flight loading is affected by the operating conditions, physical properties of the material and the geometrical configuration of the dryer (Kelly, 1992). The importance of flight loading cannot be underestimated, as it facilitates the intimacy of contact between the solids and drying gas as well as affecting the residence time of solids within the dryer. Several approaches have been taken to determine the residence time and these approaches varied from empirical correlations to compartment modelling (Friedman and Marshall, 1949; Alvarez and Shene, 1994; Matchett and Baker, 1987; Duchesne et al., 1996; Sheehan et al., 2005). In many of these approaches, the loading capacity of the dryer has been a key requirement to the prediction of the residence time. Furthermore, the proportion of airborne (denoted as *active*) to flight borne (denoted as *passive*) solids is essential to accurate determination of drying efficiency. In many of the flighted rotary dryers (FRD) models in the literature, this proportion has been approximated to between 10% and 15% of the total holdup and is typically considered invariant to loading state. A comprehensive review of the modelling approaches in determining residence time can be found in Sheehan et al. (2005).

In their seminal work using a pilot scale FRD, Matchett and Baker (1987) established the importance of flight loading. Although their model was only applicable to under loaded and design loaded dryers, they described an effective experimental technique for determining the transition between loading states

* Corresponding author. Tel.: +61 7 4781 4153; fax: +61 7 4781 6788.
E-mail address: madoc.sheehan@jcu.edu.au (M.E. Sheehan).

0009-2509/$ - see front matter
doi:10.1016/j.ces.2012.01.033

and demonstrated the saturation of the air borne solids at the design load. In their study, they proposed the characterisation of the Holdup as consisting of an airborne phase and the dense phase and laid the foundations for the incorporation of physical significance into compartment models of flighted rotary dryers. These ideas were further advanced in the compartment models of Duchesne et al. (1996), Sheehan et al. (2005) and Britton et al. (2006) with the latter two models incorporating geometric flight unloading models for predicting rates of transfer between the phases. Limitations to the work of Matchett and Baker (1987) included the requirement for an empirical holdup number determined via dryer specific experiments.

The compartment modelling approaches were developed to provide a more predictive means to estimate the residence time distribution. This compartment modelling approach utilises a series-parallel formulation of well-mixed tanks, which is commonly used in reaction engineering (Levenspiel, 1999). In recent examples of FRD compartment modelling by Sheehan et al. (2005) and Britton et al. (2006) they considered the dryer geometry, solid flow properties and also the drag effect of the air stream on the solids. The model parameters were estimated based on physical descriptions (described in Britton et al. (2006)) and on geometric modelling of flight unloading (described in Britton et al. (2006) and validated experimentally in Lee and Sheehan (2010)). The accurate estimation of the design load and loading state of the dryer directly influenced determination of transport coefficients as well as the mass distribution between the compartments representing the airborne and flight borne solids.

In the rotary dryer, there are three potential degrees of loading namely under-loaded, design loaded and overloaded. Describing these states is facilitated through the definition of the First Unloading Flight (FUF) in a rotating dryer, which is the flight that first (with respect to rotation) discharges solids. In design loaded dryer, The First Unloading Flight (FUF) is located at the 9 o'clock position as shown in Fig. 1(a) for a clockwise rotating drum and is the flight with its tip along the centre axis of the drum. It should be noted from the literature that the cascading of material at the FUF has been previously used as the criterion defining the limits of loading capacity (Matchett and Baker, 1987; Britton et al., 2006). A dryer is defined as operating in an under loaded condition when the flights are not full to their capacity and unloading occurs after the 9 o'clock position. A design loaded dryer is one in which the flights are at their maximum capacity and the first discharge occurs precisely at the 9 o'clock as indicated in Fig. 1(b). The design load condition is assumed to represent the point of operation where there is maximum interaction between the drying gas and the airborne phase. A dryer is classified as over loaded when there are more solids than required to fill the flights as illustrated in Fig. 1(c). In this situation, there is a discharge before the 9 o'clock and the excess material rolls in the base of the dryer. A fundamental and physically realistic assumption of FRD models is that the kilning or rolling solids do not participate in drying to the extent that airborne solids do. As a result their thermal and physical interactions with the gas phase are largely ignored. It can be reasonably assumed that the operation of dryer at under-loaded or overloaded conditions results into poor efficiency of the dryer and optimality will not be achieved. Consequently, the design load of a dryer is an important parameter that should be determined for optimisation, design and modelling of FRD.

Previous studies have used geometric models of flight cross sections to estimate the design load (Porter, 1963; Kelly and O'Donnell, 1977; Baker, 1988; Sherritt et al., 1993). For instance, Porter (1963) and Baker (1988) based their estimation of the design load on the amount of material contained in the FUF and contained in the flights in the upper half of the drum respectively.

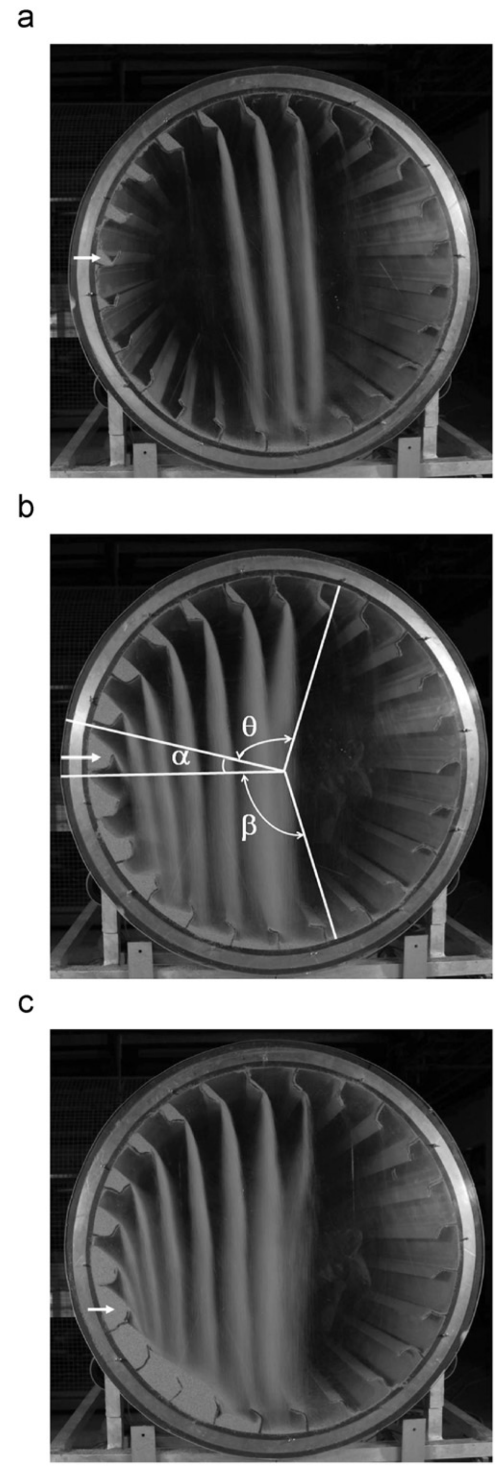

Fig. 1. (a) Under load dryer (arrow indicates the 9 o'clock position and demonstrates that solids are discharged late in the rotation). (b) Intermediate loading assumed close to design load (arrow shows there is discharge at precisely the 9 o'clock position and that the flights underneath the FUF are not overflowing. Angle (α) represents the location of the FUF. Upper half of the drum lies within angle ($\alpha+\theta$) and the lower half of the drum lies within the range of angle (β)). (c) Overloaded dryer load (arrow shows there is discharge before 9 o'clock position and that the flights underneath the FUF are full to the point of overflowing).

To facilitate the following discussion of geometric design load models, a few definitions are necessary. The last discharging flight (LDF) is the last flight that cascades the material into the airborne phase as the drum rotates and the angular position of the LDF can