Chemical Engineering Science 134 (2015) 222–229

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Image analysis of X-ray tomograms of sludge during convective drying in a pilot-scale fixed bed

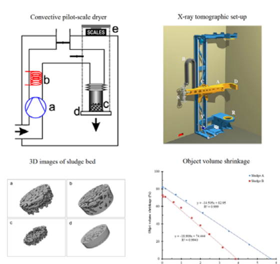
Jie Li*, Erwan Plougonven, Laurent Fraikin, Thierry Salmon, Dominique Toye, Angélique Léonard

Laboratory of Chemical Engineering, Department of Applied Chemistry, University of Liège, Liège, Belgium

HIGHLIGHTS

- The shrinkage phenomenon is highlighted in sludge drying.
- Structures of the two sludges evolve quite differently during the drying process.
- X-ray tomography is an efficient tool for visualizing structural changes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form
7 May 2015
Accepted 10 May 2015
Available online 16 May 2015

Keywords:
Sewage sludge
Pilot-scale drying
X-ray tomography
Image analysis
Structure
Shrinkage

ABSTRACT

Shrinkage is an important phenomenon during sludge drying, as a significant reduction in volume occurs during the loss of moisture. As the structure changes, the drying area decreases and the drying rate reduces accordingly. X-ray tomography is used to explore the structure evolution that a sludge bed undergoes in a convective pilot-scale fixed bed dryer. A high energy (420 kV), large-scale (max. 0.45 m in diameter and max. 4 m in height) X-ray tomograph with a spatial resolution of approximately 0.36 mm was chosen. Two types of sludge samples collected in two wastewater treatment plants (Grosses Battes WWTP and Oupeye WWTP, Belgium) were chosen for this study. Continuous and intermittent drying experiments were both carried out to study the drying kinetics and structure evolutions (volume, shrinkage, void, exchange surface). After experiments, 2D cross-sections and 3D images were obtained, which provide a convenient way to obtain global and quantitative information on the evolution of the sludge bed structure during the entire drying process. The results show that the volume, shrinkage, void, and exchange surface all substantially change during the drying process. Moreover, the structures of the two sludges evolve quite differently during the drying process. Image analysis of the X-ray tomograms is used to gain insight on the transport phenomena that occur during the drying process.

1. Introduction

Convective drying is used on a large scale in numerous industrial processes such as food (Putranto et al., 2011), ceramics (Hasatani et al., 1993), wood (Rémond et al., 2005), and sludge (Léonard et al., 2004a; Vaxelaire et al., 2000) processing. The final quality of these materials is strongly dependent on structural properties resulting from drying operating conditions. Sludge exhibits a complex drying behavior because of intercoupled phenomena of shrinkage and crack development, which gives rise to a heterogeneous three-dimensional (3D) porous structure (Léonard et al., 2003).

X-ray tomography can provide 3D structural information by performing a series of non-destructive radiographies at different view angles, a technique used in various domains (Brown et al.,

* Corresponding author.
E-mail address: jeff_lee@foxmail.com (J. Li).

http://dx.doi.org/10.1016/j.ces.2015.05.010
0009-2509/© 2015 Elsevier Ltd. All rights reserved.

2014; Davit et al., 2011; Pauwels et al., 2013; Parrilli et al., 2014). Léonard et al. (2002, 2003) used X-ray microtomography for detection and quantification of 3D volume, shrinkage, crack, moisture profile, and other characteristics of sludge during drying. However, it was used in a microdrying set-up, i.e. at a small scale. A typical industrial set-up consists in a belt dryer, using extrusion as feeding system. In order to better represent the industrial set-up, a pilot-scale fixed bed with sludge extrusion is used in our experiment. According to the size of the bed (about 160 mm diameter × 60 mm height), it was necessary to use a high energy and large-scale X-ray tomograph.

The first large-scale X-ray tomograph was built at the University of Liège at the end of the 1990s. Marchot et al. (2001) designed a 160 kV fan beam system to image gas–liquid flow patterns in fixed beds filled with plastic packings. In 2005, the same group built the first European high energy (420 kV), large-scale (max. 0.45 m in diameter and max. 4 m in height) X-ray tomograph (Toye et al., 2005), initially for the same field of study (Calvo et al., 2009; Aferka et al., 2010; Viva et al., 2011). The 420 kV source allows investigation of highly absorbing materials, such as thin metallic objects, and was used to study the structure of a packed bed during drying with a resolution of 0.36 mm. Three other research groups developed large-scale X-ray CT systems for chemical engineering applications, namely those of R. B. Eldridge at the University of Texas at Austin (Schmit et al., 2001, 2004; Schmit and Eldridge, 2004), D. Mewes at the Leibniz University of Hannover (Mahr and Mewes, 2007; Gulati et al., 2010; Athe et al., 2013), and T. Heindel at the Iowa State University (Hubers et al., 2005; Ford et al., 2008; Franka and Heindel, 2009).

Beyond that, the high energy and large-scale X-ray tomograph can also be used in the field of drying research. Léonard et al. (2008) already used the high-energy tomograph for investigating the influence of back mixing on convective drying of residual sludges in a pilot-scale fixed bed. However, they only determined the structural characteristics before and after drying, but not during the whole process. The convective drying of sawdust/sludge was also investigated in a pilot-scale fixed bed by using this high-energy X-ray tomograph, and the shrinkage, diffusion coefficient, and mass transfer coefficient were obtained (Li et al., 2014a, 2015). This research mainly focused on the influence of sawdust addition on sludge drying. There still is a lack of information regarding the differences in fixed bed structure evolution during the entire course of drying for sludges from different origins.

In this work, we use this high-energy X-ray tomograph, associated with image analysis, to characterize the 3D bed structures during the entire course of convective drying in a pilot-scale fixed bed. The tomographic reconstructions are used to characterize the sample bed in terms of volume, void fraction, and exchange surface. By comparing the images during the drying process, the evolution of these characteristics will help understand the transport phenomena undergone during drying. Two types of sludge samples collected in two different WWTPs are considered. They present different drying behaviors and structure evolutions of the sludge bed during the drying process, illustrating that sludge drying is a complex unit operation very sensitive to the material's origin and properties.

2. Materials and methods

2.1. Materials

Sludges were collected in two wastewater treatment plants (Grosses Battes WWTP and Oupeye WWTP) located near the University of Liège (Belgium). The initial moisture contents were determined according to standard methods (ASAE, 1996). Before drying, the sludges were stored at a temperature of 4 °C, to preserve drying properties during storage (Fraikin et al., 2010). Table 1 provides physical and chemical characteristics of the sludges used.

Before drying, these sludges were extruded through a disk with circular dies of 12 mm, forming a bed of extrudates on the dryer perforated grid. The initial mass of the bed of extrudates was fixed at 500 g in all experiments.

2.2. Convective pilot-scale dryer

Drying experiments were carried out in a discontinuous pilot-scale dryer reproducing most of the operating conditions prevailing in a full-scale continuous belt dryer (Léonard et al., 2008; Li et al., 2014a, 2015), as shown in Fig. 1. A fan (a) drawn in ambient air which is heated up to the desired temperature by a set of electrical resistances (b). If needed, the air is humidified after heating by adding vapor from a vapor generator. The hot air flows through the sludge extrudates (c), which lies on a perforated grid (d) linked to a scale (e). The inner diameter of the sample holder is 160 mm. Three operating parameters can be controlled: air temperature, superficial velocity, and humidity. In this study, the temperature was set at 80 °C, with air velocity fixed 2 m/s and no additional air

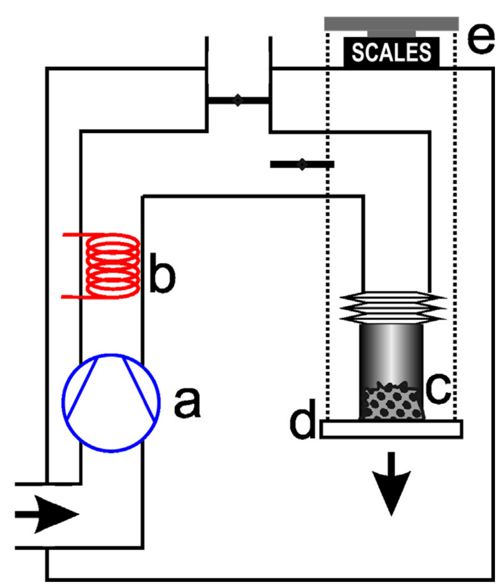


Fig. 1. Convective pilot-scale dryer. (a) Fan. (b) Electrical resistances. (c) Bed. (d) Perforated grid. (e) Scales.

Table 1
Characteristics of the sludges used.

No.	Sludge origin	Equivalent population[a]	Effluent	Dewatering	Initial moisture content (wet basis)
Sludge A	WWTP of Grosses Battes, Liège, Belgium	59,040	Domestic	Belt filter	85.5%
Sludge B	WWTP of Oupeye, Liège, Belgium	446,500	Domestic	Centrifuge	80.0%

[a] Equivalent population (EH) corresponds to an average daily discharge of 180 L of effluent with a load of 90 g of MES, 60 g of BOD5, 135 g of COD, 9.9 g of total nitrogen, and 2 g of total phosphorus.