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Characterization of dry and wet sawdust porous beds

Nicolas Parmentier [a], Erwan Plougonven [b,1], Angélique Léonard [b], Hervé Jeanmart [a,*]

[a] Institute of Mechanics, Materials, and Civil Engineering, Université catholique de Louvain, 1348 Louvain-la-neuve, Belgium
[b] Laboratoire de Génie Chimique, Procédés et développement durable, Département de Chimie Appliquée, Université de Liège - Sart-Tilman, 4000 Liège, Belgium

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ABSTRACT

The microstructures of six sawdust packings, three fresh and three dried, are studied by using three-dimensional X-ray microtomography data.
Packings are highly disordered and are considered as porous media resulting from a stochastic process. To describe the packings, three categories of properties are defined and exploited. They are all based on the phase indicator function. The first set gives information about the geometry of the packings. The second set covers morphological parameters linked with the particles and the pores of the packings. The third set describes the connectedness of the porosity, i.e. the topology of the packings. Fresh and dried sawdust packings are compared based on the three sets of properties. The packing topology is the same for dry and wet sawdust. Dry packings have a slightly larger porosity than wet packings, by about 4%. The pore diameters are also larger in dry packings, by about a factor 2. But the specific surfaces are smaller for dry packings, by about 30%. Finally, while the sawdust particles are anisotropic, all categories of parameters show that beds are isotropic.

1. Introduction

Inside a porous medium such as a packed bed of biomass particles, processes like drying and pyrolysis are influenced by both chemical and physical properties. Of course, physical properties are defined by the particles themselves, e.g. their shape, surface area, and thermal conductivity, but the physical properties of the bed are mainly influenced by the particular stacking of particles inside it.

There are multiple reasons that motivate studying the microstructure of packings; for example, in order to compare the compactness of packed materials for transport or to validate a particle stacking model. But, usually, the characteristics of a bed are of interest because of their influence on transfer phenomena. In this case, determination of the micro-structure characteristics is essential to accurately model the processes inside the packed bed.

One application, for granular media, on which the microstructure has a significant impact is convective drying. This paper focuses on sawdust packings. The drying for this material is typically performed by blowing hot air through a thick layer. For the technicians who operate the equipment several parameters are critical to efficiently manage the drying. One of those is the pressure drop through the layer of sawdust which is linked to the permeability of the bed. The permeability, as other macro parameters, is highly dependent on the microstructure. Indeed, there are numerous ways to determine a value for the permeability and all of them are dependent on the characteristics of the microstructure. For instance, Ergun's equation uses the values of porosity and equivalent spherical diameter of the packing for an empirical law [1]. To determine the permeability by simulation, a periodic cell based on the microstructure of the porous medium can be used [2]. The requirements are the same for the construction of a representative network in order to compute the pressure drop (e.g. [3–6]). Even if only experimental measures are used to find the pressure drop [7], an estimation of the size of the representative volume is needed, since experiments made in volumes which are too small do not allow extracting a reliable measurement. Therefore, knowing some characteristics of the micro-structure is always necessary to determine the macroscopic parameters.

Characterization of porous media has progressed with technology. In the 1960s, Benenati and Brosilow [8] poured uniformly sized spheres in a container and filled the interstices with liquid epoxy resin. The resulting solid cylinder was then machined into successively smaller diameters. After each machining, the weight and diameter of the cylinder were measured and the average void fraction of each part was deduced. With this method, very few characteristics of the fluid phase were made available. More extensive characterizations would combine serial transverse sectioning and image analysis of the digitized slices (e.g. [9–11]). Advantages of such methods are low cost and easy access to scalar geometric values such as porosity and specific surface. However, the three-dimensional pore structure appears in the 2D sections as a collection of disconnected void areas that cannot be directly associated with individual pores or throats [12]. Moreover, besides the destructive

* Corresponding author. Tel.: +32 10 47 22 09.
E-mail addresses: nicolas.parmentier@uclouvain.be (N. Parmentier), eplougonven@icmcb-bordeaux.cnrs.fr (E. Plougonven), A.Leonard@ulg.ac.be (A. Léonard), herve.jeanmart@uclouvain.be (H. Jeanmart).
[1] Present address: CMCB-CNRS/Group 4, ICMCB-CNRS, 87, Avenue du Docteur Albert Schweitzer, 33608 PESSAC Cedex, France.

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nature of this technique, sectioning methods involve many man hours in slicing, polishing and digitization. Another issue is that slice thickness versus digitization resolution involves an anisotropic sampling. Finally, strong assumptions on the particle shape must be made to extract three-dimensional data from two dimensional images using stereological methods [13]. Until the 1990s, pore space characterization was largely restricted to such stereological approaches [14].

With the advent of tomographic techniques, it is possible to obtain a real three-dimensional internal view of a porous medium in a non-destructive way. Depending on the physical excitation measured, different tools can be used to obtain an image of a section. Among others, the following methods should be mentioned: ultrasonics photoacoustic tomography [15]; magnetic resonance imaging [16,17]; electrical tomography (resistance [18], impedance [19] or capacitance tomographies [20]); gamma rays [21] and, finally, X-rays [22,23] that were used in this document. The principle of X-ray tomography is based on X-ray radiography, where the rays are attenuated as they cross the matter. If radiograms are acquired from different points (typically in a circle around the sample), then it is possible to algorithmically reconstruct a 3D X-ray attenuation map of the sample.

In this document, we use X-ray micro-tomographic scans of fresh and dry sawdust samples for an in-depth characterization of the void space micro-structure. The volume fractions and specific area have been determined, as well as the anisotropy, the representative elementary volume: REV, and the required parameters for building equivalent domains suitable to carry out flow simulations. All the extracted characteristics have been interpreted in order to compare packings of fresh and dry sawdust.

To meet these objectives, geometric parameters, derived from a statistical description of the phase indicator function, are first considered. Morphological parameters, associated with the local spatial properties of particles and pores, are described. Finally, some topological parameters which provide information on the connectedness of the void space are discussed.

The next section describes sample preparation, imaging and binarization where fluid from solid is distinguished. Due to inhomogeneities inside wood particles, the segmentation is challenging. Section 3 describes how the parameters mentioned previously are computed. Finally, Section 4 presents relevant conclusions.

2. Material and methods

A common source for wood pellet production is fresh sawdust from sawmills. The sawdust studied here comes from the sawing of logs into boards. Its raw moisture reaches 0.94 $\mathrm{kg_{H_2O}\ kg_{dry}^{-1}}$ and it is thus dried before pelletization. Its sieving size distribution is shown in Fig. 1. Less than 8$\%_w$ of the particles have a screening size larger than 9.51 mm, and more than 30$\%_w$ of the sawdust has a size ranging from 2 to 4 mm. The biggest particles have a strong impact on the drying time but they are not numerous and they only locally modify the packing. Because of the dimension of the experimental measurement facility, the sawdust particles that were retained by the grid with apertures of 12.7 mm have been removed.

The particles were poured inside a cylindrical container with a diameter of 40 mm and a height of 40 mm. To mimic the bed in a dryer, particles have been randomly discharged without any post-processing treatment such as vibrations. Six packings were made, three with wet sawdust (W_1, W_2 and W_3) and three with dried sawdust (D_1, D_2 and D_3). It is noteworthy that the bed construction process allows particles to rearrange. Then, dry beds do not directly derive from fresh beds. This fact seems to be an issue for an accurate comparison. But, in a conveyor belt dryer, solid particles are also put into movement during the drying process. It is then assumed that the samples are representative of an actual packing in an actual dryer.

X-ray microtomographic acquisitions were made for all 6 packings, using a Skyscan 1172 tomograph (Kontich, Belgium). The X-ray source was set at a voltage of 100 kV and a filter made with 0.5 mm of copper and 0.125 mm of aluminum was used to attenuate weaker X-rays out of the polychromatic beam and avoid too much beam hardening artifacts in the reconstructions. Radiographs were taken over 360° in steps of 0.05°, using 4 × 4 camera binning, a distance to the object of 258.7 mm, a distance to the detector of 343.88 mm and a pixel spacing of 11.48 μm. For each radiogram, several frames have been taken and an averaging of the frames was performed by the image acquisition tool to further reduce noise. Since field of view was too narrow to view the entire width of the beds, camera offset was used in which two acquisition cycles are performed with offset horizontal camera positions. At each rotation step, the two radiograms are combined into one with twice the horizontal field of view. The resulting radiograms were around 2000 pixels wide and 524 high, at a resolution of 34.55 μm pixel^{-1}.

Reconstructions were performed using the Skyscan's Nrecon software version 1.6.6, using the included ring artifact and postalignment correction options. Only the central portions of the beds were used in this study in order to avoid the influence of the cylinder on the packing structure. The final 3D tomographic reconstructions comprise 850 × 8520 × 450 voxels.

After this step of the process, one voxel appears as a gray value scaled on a range of 8 bits. An intensity value $\mathcal{I}(x)$ in the range from 0 to 255 is assigned to each voxel located at x inside the domain $\Omega \subset \mathbb{R}^3$ (i.e. $\mathcal{I} : \Omega \rightarrow \mathbb{N}$). A typical packing section is shown in Fig. 2 and the histogram of the data is given in Fig. 3.

The axes of Fig. 2 have been chosen so that an interval between two ticks corresponds approximately to 100 pixels. On the histogram, in Fig. 3, two peaks corresponding to the two phases are visible. The first

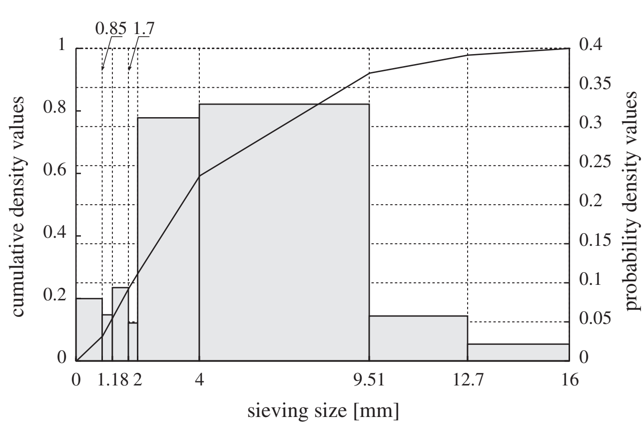

Fig. 1. Distribution of the weight fraction of sawdust as a function of the size of the particles that are retained by the grids of the sieves. Bars stand for probability density values while the continuous line represents the cumulative density values.

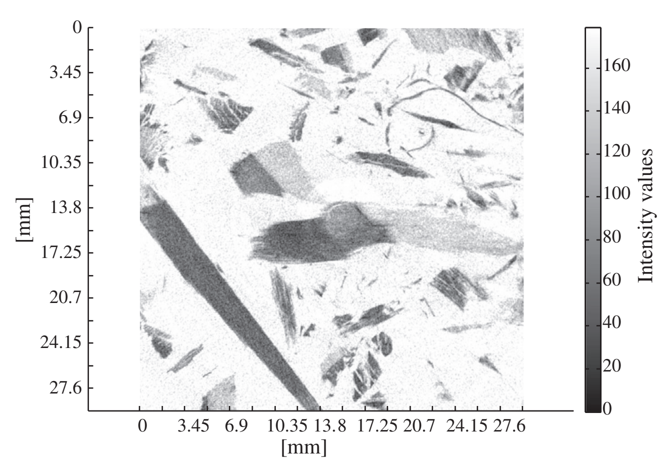

Fig. 2. Sample of a scanned section of sawdust packing (W1, 850 × 850 pixels).