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Short communication

Quantification of powder wetting by drop penetration time

Merel L.M. Oostveen [a,b], Gabrie M.H. Meesters [a,b,*], J. Ruud van Ommen [a]

[a] Delft University of Technology, Department of Chemical Engineering, Product and Process Engineering, Julianalaan 136, 2628 BL Delft, The Netherlands
[b] DSM Biotechnology Center, Alexander Fleminglaan 1, 2613 AX Delft, The Netherlands

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ABSTRACT

We quantify the wetting step of rehydration of a food powder by studying drop penetration times (DPTs) in powder beds. A single droplet is placed on powder beds with various porosities and DPT is recorded by a digital microscope camera. DPTs for corn starch, potato starch and wheat starch are compared to the model proposed by Hapgood et al. (2002). Characterization of the internal structure of miniature powder beds is performed using a Phoenix microCT.

Loosely packed powder beds show expected macrovoids and recorded DPTs are within an order of magnitude of the theoretical predictions. However, DPTs for starches deviate from predicted values. We study the effect of moisture content and internal porosity and suggest two model adaptions.

Visual observations indicate that the drop penetration area within the bed exceeds the drawing area of the droplet itself. Adaptation of the model for the drop penetration area by constant factor increases DPTs, leading to better correspondence between experimental and theoretical DPTs. Most promising results are obtained by replacement of the effective pore radius predicted by the Carman–Kozeny equation with the experimentally observed pore radius seen in microCT imaging. Theoretical DPTs predicted by this semi-empirical model are in good agreement with experimental results. This is promising for the application of the current method to various food powders, to control quality, optimize properties or tackle problems during production.

1. Introduction

Powdered ingredients are common in food formulations, such as milk powder, coffee, soup mixes and cocoa drinks. They are usually intended for rehydration in water and their reconstitution should be rapid and complete. Reconstitution consists of four steps: wetting, sinking, dispersing and dissolving [1,2]. Ideally, the powder wets quickly and thoroughly, sinks rather than floats, disperses rapidly and dissolves within a short period of time, without lump formation. If so, proper instant foods provide convenience and quality to the customer.

Imbibition of a single drop has been described by Middleman and Denesuk [3,4]. The porous substrate is modeled as a set of parallel, cylindrical pores of constant radius. The corresponding drop penetration time (DPT) for a drop with constant drawing area (CDA) is obtained is shown in Eq. (1).

$$\tau_{CDA} = \frac{V0^{2/3}}{\left(\frac{3}{4\pi}\right)^{4/3}\pi^2\varepsilon^2 Rpore}\frac{\mu}{\gamma_{LV}\cos\theta} = 1.35\,\frac{V0^{2/3}}{\varepsilon^2 Rpore}\frac{\mu}{\gamma_{LV}\cos\theta}. \tag{1}$$

This model was adapted by Hapgood et al. [5] and takes the presence of macrovoids into account, as shown in Fig. 1. These macrovoids can inhibit the flow of liquid due to sudden expansion of the pore radius, which decreases the curvature of the liquid and the driving force for liquid flow. This results in Eq. (4), referred to in this article as the theoretical DPT.

$$\varepsilon_{eff} = \varepsilon_{tap}\,(1-\varepsilon_{macrovoids}) = \varepsilon_{tap}\left(1-\varepsilon+\varepsilon_{tap}\right) \tag{2}$$

$$R_{eff} = \frac{\phi d_{3,2}}{3}\frac{\varepsilon_{eff}}{\left(1-\varepsilon_{eff}\right)} \tag{3}$$

$$\tau_{CDA} = 1.35\,\frac{V0^{2/3}}{{\varepsilon_{eff}}^2 R_{eff}}\frac{\mu}{\gamma_{LV}\cos\theta}. \tag{4}$$

The DPT depends strongly on the contact angle of the material. However, measurement of the contact angle is not trivial for powders, because of the irregular and porous surface [6]. The droplet of liquid can spread and sink into the pores of the powder. When assessing soluble material, further complications arise, as explained by Fang et al. [7].

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[*] Corresponding author at: Delft University of Technology, Department of Chemical Engineering, Product and Process Engineering, Julianalaan 136, 2628 BL Delft, The Netherlands. Tel.: +31 618168811.
E-mail address: G.M.H.Meesters@tudelft.nl (G.M.H. Meesters).

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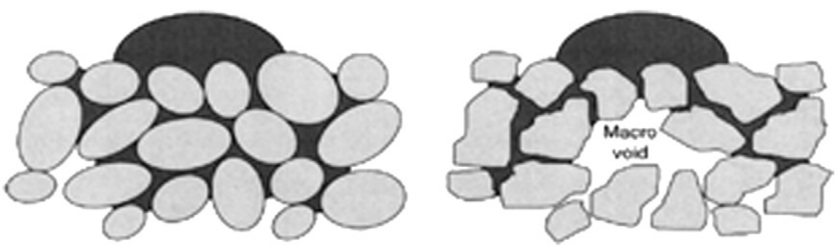

Fig. 1. Schematic of macrovoids that can be present in loosely packed beds and hinder liquid flow. From [1].

As such, non-soluble powders are used to assess the applicability of this model to food powders.

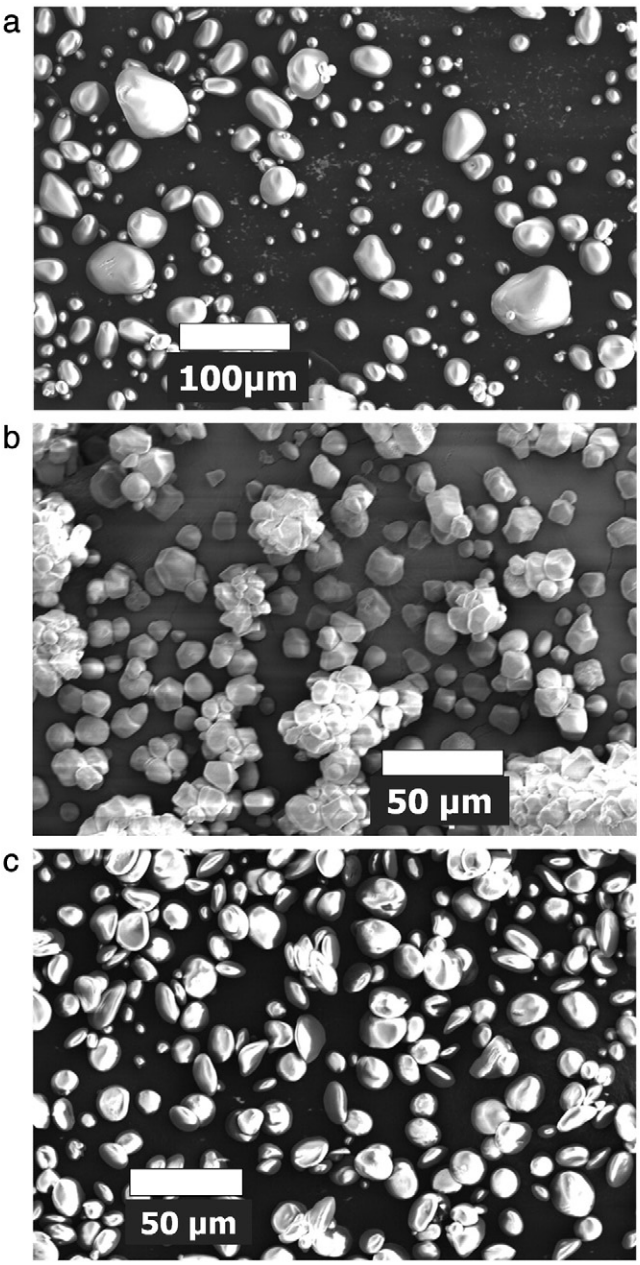

Fig. 2. SEM image of (a) potato (b) corn (c) wheat starch.

2. Materials & methods

2.1. Material characterization

Three types of starches, derived from corn, potato and wheat are used. Furthermore, glass beads are used as reference material.

Moisture content of as-received corn starch is determined by a Mettler–Toledo infrared balance. One batch of corn starch (160 g) is dried to assess the effect of moisture. The powder was placed in an oven at 45 °C for 2 h, after which temperature was increased to 95 °C for another two hours. Temperature was raised stepwise in order to remove water without causing gelatinization. Weight of corn starch after drying is recorded.

Laser diffraction measurements of the dry powder in air are performed using the Coulter LS 230. Scanning electron microscopy (SEM) images are recorded using the JEOL JSM6010 SEM apparatus. Obtained images are shown in Fig. 2. Shape factors (aspect ratio) for potato, corn, and wheat starch are determined by Qicpic apparatus. Image analysis and thresholding are performed using WINDOX.

2.2. DPT measurements

Powder beds of corn, potato and wheat starch are prepared over a range of porosities. A known mass of powder is placed into a cylindrical container (internal diameter 9.5 cm) and pressed down with a piston. Additional weights (ranging from 1.5 to 19.5 kg) are used to compress the powder. The height of each bed after pressing is determined and associated porosities are calculated, assuming a starch density of 1.479 g/cm^3 [8]. Eq. (5) gives overall porosity ε.

$$\varepsilon = 1 - \frac{V_{powder}}{V_{bed}}. \tag{5}$$

Experimental values of the DPT are obtained using a Celestron digital microscope camera. 20 μL droplets of distilled water ($\gamma_{LV} = 72.1$ mPa · s, $\mu = 0.0011$ N/m [9]) are placed on the bed with a needle. Impact height is kept to a minimum to avoid splashing. Short videos are recorded for 15 consecutive droplets and time for complete depletion of the droplet is recorded manually. Droplets are spaced regularly over the bed, and edges of the bed are avoided.

Table 1
Powder properties.

	θ (°)	εtap (−)	φ (−)	$d_{3,2}$
Corn starch	70 ± 8	0.27	0.81	13.22
Potato starch	57 ± 9	0.21	0.84	34.57
Wheat starch	62 ± 7	0.51	0.83	18.52
Glass beads	58 ± 1[a]	0.41	1	72.36
Porous silica	60 ± 2	0.87	1	90.0[b]

[a] Data from [5].

[b] Data from supplier Sichma Aldrich.