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Entrapment of air during imbibition of agglomerated powder beds

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ABSTRACT

Complete wetting is crucial for efficient recombination of powders. On the powder bed scale, wetting is governed solely by capillary forces and the resistance to flow, i.e. spontaneous imbibition. Slow or incomplete imbibition of the powder bed may lead to gelling of the liquid front, which will stop the recombination process and cause the formation of lumps, which is usually undesirable.

In this study, the spontaneous imbibition of powder beds consisting of spray-dried dairy powders with diverse morphologies has been investigated. Uniform radial spreading of the imbibition front was seen in all the beds, but a large amount of air was trapped in the inter-particle free space in the imbibed volume. A positive correlation was found between bed porosity and the fraction of air trapped in the bed after imbibition. Since the amount of trapped air was calculated as a fraction of the porosity of the dry bed, this relation was unexpected.

The large fraction of air trapped in the bed and the uniform radial spreading of the imbibition front indicate considerable heterogeneity of bed on the microscopic scale, but a homogenous structure on the macroscopic scale. Possible explanations of the large fraction of trapped air are the presence of local dead-end structures in the bed and film flow of the imbibing liquid.

1. Background

The formation of lumps during the dissolution of dry powders is a common problem in many industrial processes. For example, lumps in food products affect consumer-perceived aspects such as mouth feel and appearance, as well as the nutritional value of the product, while lumps in paint and fillers affect the color and behavior of the product. When mixing powders and liquids, large amounts of the powder are often added to the surface of the liquid, forming a dry powder layer. This powder layer is called a powder bed. In an earlier study, we defined the powder bed scale as the scale at which a portion of the powder (O mm), consisting of individual powder particles, could be regarded as one separate porous medium (Börjesson et al., 2014), This portion may be located on the surface of the liquid or submerged beneath the liquid surface due to mixing, as illustrated in Fig. 1.

On the powder bed scale, the wetting of the powder bed is governed solely by capillary forces and the resistance to flow, where the latter is given by the permeability of the bed. As long as no external forces are applied, this is defined as spontaneous imbibition, and is governed by Darcy's law used with the capillary pressure:

$$Q = k \cdot \frac{A \cdot \Delta P_{Cap}}{\mu \cdot L} \qquad (1)$$

where Q is the volume flow rate [m^3/s], k is the permeability constant of the powder bed [m^2], A is the cross sectional area of the porous medium [m^2], ΔP_{Cap} is the capillary pressure [Pa], μ is the dynamic viscosity of the fluid [Pas] and L is the length of the porous medium [m].

During all imbibition processes, the imbibing fluid replaces a non-wetting fluid; in the case of a powder bed, usually air. Ideally, rapid and complete imbibition are desirable since this will result in complete dispersion of the individual particles of the powder which, in time, will lead to complete dissolution (Hellborg et al., 2010). Slow or incomplete wetting, will prevent the dispersion of the particles, which could result in gelling at the powder liquid interface leading to encapsulation of air and unwetted dry matter.

Unfortunately, it is difficult to obtain values of the capillary

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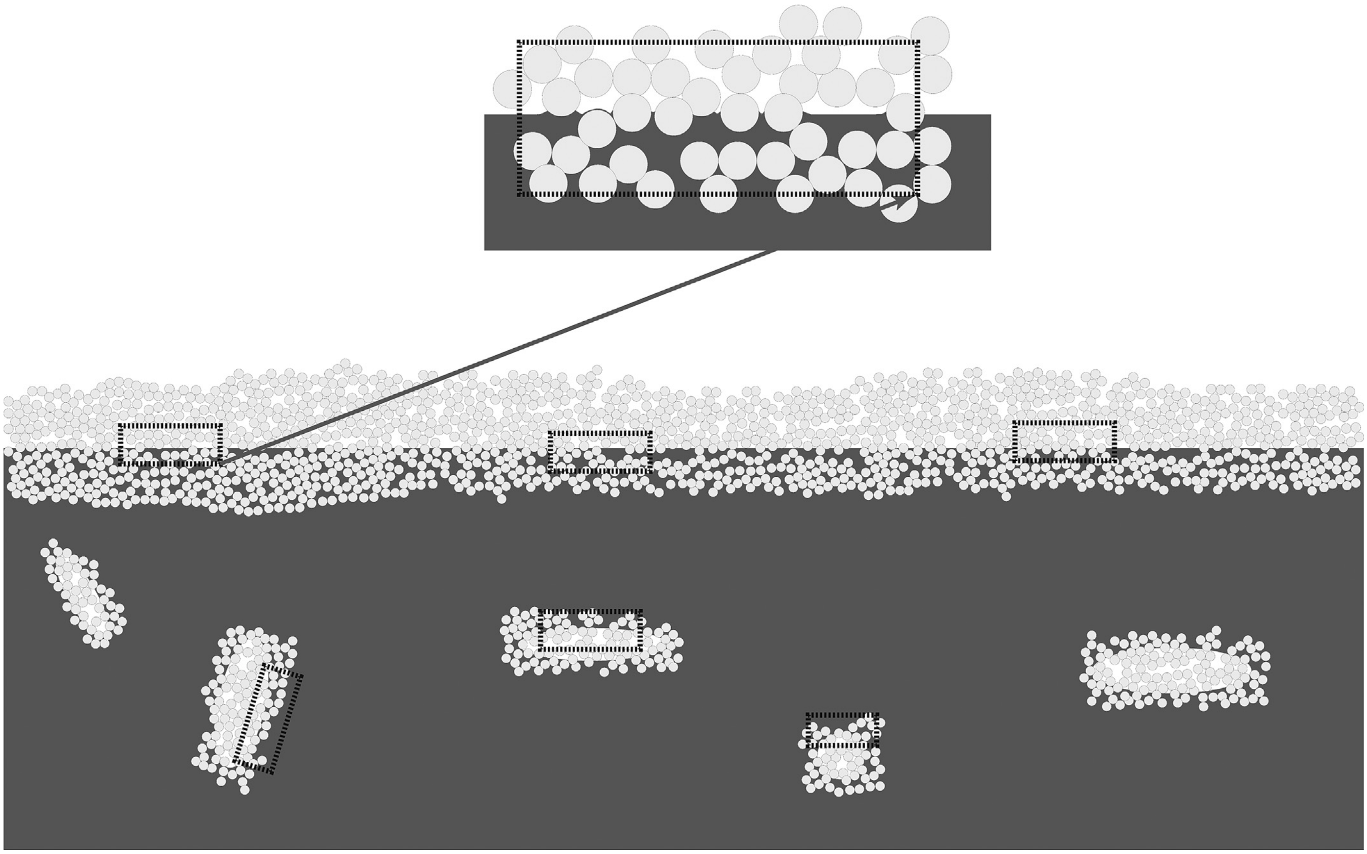

Fig. 1. Examples of powder bed segments on the powder bed scale illustrated as dotted boxes. Portions of powder on or below the liquid surface as a result of mixing, can be regarded as porous media, in which imbibition is driven by capillary forces.

pressure and permeability of powder beds consisting of agglomerated, spray-dried powders, since most models are based on either well-defined capillaries, or beds in which the particles are perfectly spherical. The Kozeny-Carman model can be used in such cases (Bear, 1972; Carman, 1937).

$$k = \frac{1}{5} \cdot \frac{\varepsilon^3}{M^2} \tag{2}$$

where ε is the porosity of the powder bed and M [m^2/m^3] is the specific surface area of the bed bulk. The constant 1/5 was determined by Carman to be valid for a porous bed of packed spheres (Carman, 1937, 1956).

However, in a recent study we found that Eq. (2) was insufficient to predict the permeability of powder beds consisting of spray-dried dairy powders (Börjesson et al., 2016). In that study, the permeability of the powder beds was measured using air permeametry. The results showed that the permeability of the investigated powder beds was independent of the measured porosity of the bed. This was explained by dividing the free volume of the bed into large spaces that had a limited effect on the pressure drop but significant effect on porosity, called the void space, and narrow channels connecting the larger spaces believed to have a substantial effect on the pressure drop but only a limited effect on the porosity, called the pore space, see Fig. 2.

How will this heterogeneity in bed structure affect the imbibition of such a porous media?

A fundament in the research of imbibition is the Washburn equation (Washburn, 1921). It can be derived from the pressure balance between the driving capillary pressure and the pressure drop resulting from viscous stresses.

$$\Delta P_{Cap} - \Delta P_{Vis} = 0 \tag{3}$$

In the case of flow in a cylindrical capillary, Poiseuille flow can be applied, which together with Young's equation for capillary pressure in a cylindrical channel yields the Washburn equation in the form below:

$$\frac{dL}{dt} = \frac{1}{4} \cdot \frac{r \cdot \gamma \cdot \cos\theta}{\mu \cdot L} \tag{4}$$

where L is the penetrated, fully wetted length in the capillary [m], γ is the surface tension between the imbibing liquid and the non-wetting fluid [mN/m], t is the wetting time, and r is the radius of the capillary [m]. For a porous medium, an average "corresponding radius" is commonly used in Eq. (4) to predict the rate of imbibition. This may be based on the concept of hydraulic radius, (ε/M) (Bear, 1972), or a more complex estimation (Staples and Shaffer, 2002; Young, 2004).

Eq. (4) gives the wetting rate in a fully wetted capillary (contact angle 0, no-slip condition). It is clear from the equation that higher wetting rates can be expected in larger capillaries, since the ΔP_{Cap} scales with the diameter of the capillary while the ΔP_{Vis} scales with the square of the capillary diameter. However, Ridgway et al. (2002), Alava et al. (2004) and Schoelkopf et al. (2002, 2000) showed that imbibition was not always faster in larger channels. Based on the original work by Bosanquets (Bosanquet, 1923), these authors found that during the first few moments of imbibition, the smallest capillaries could be favored by the liquid due to the pressure drop resulting from inertia. Eq. (3) can thus be rewritten.