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Permeability of powder beds formed from spray dried dairy powders in relation to morphology data

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ABSTRACT

The formation of lumps during industrial recombination of powder is a common problem in many industries. An important step in the recombination process is the wetting of the dry material. Only with an efficient wetting the individual powder particles will disperse and a complete dissolution will occur. In difference, a slow or incomplete wetting will not supply liquid to all portions of the powder, resulting in the formation of lumps.

The resistance to wetting can be described by a material's permeability. This parameter is often estimated using the Kozeny-Carman equation, which models the permeability of a porous medium (such as a bed of powder) based on the porosity and specific surface area of the medium. This model has proven valid for a bed of packed spheres, but due to the model assumptions the accuracy of the model when utilized on beds formed from more complex, spray dried powders can be questioned.

In this study, the permeability of powder beds consisting of spray-dried diary powders when exposed to an air flux has been characterized, using a method based on air permeametry. The results show that the Kozeny-Carman model is insufficient to estimate the permeability of such beds. Furthermore, the measured porosity of the bed had no influence on the permeability constant.

Based on the results of this study a correlation between morphological powder parameters and permeability was developed. This correlation indicates that a small surface weighted average diameter of the particles as well as a narrow width of the particle size distribution have a positive effect on the permeability of a bed. In addition, incorporation of the structural parameter “BedRatio”, defining the basis of the bed to consist of agglomerates or primary particles (fines), indicates that a bed consisting of mainly agglomerates has a slightly larger permeability.

1. Introduction

The wetting of packed powder media, a so called powder bed, is a crucial step if a successful recombination of powders is to be achieved [1,2]. During industrial recombination, an efficient wetting results in a complete dispersion of the individual powder particles and thereby allows for a satisfactory dissolution of the dry powder media [3,4]. An incomplete wetting of the powder bed on the other hand, may result in gelling preventing further dissolution and resulting in the formation of lumps. Lumps formed during industrial recombination can affect consumer perceived quality aspects such as flavor and visual appearance of a food product or the flow properties and color of a paint. The presence of lumps is therefore highly undesirable in industrial processes. The current industrial solution to this problem is to use heavy and energy demanding mixing operations. However, despite these techniques some powders are considered impossible to recombine without the formation of lumps. If the unit operation of mixing could be optimized significant energy savings could be achieved for the industry. In addition, powders earlier considered almost impossible to recombine could become easier to use.

The rate of wetting of a powder bed is, among other things, determined by the permeability of the bed, which describes the ease of fluid transport through the medium [5]. A highly permeable bed will be wetted quickly while a bed with a low permeability may not be wetted at all. The resistance to wetting is determined by the pressure drop caused by the frictional forces between the flowing fluid and the surfaces of the particles forming the bed. The amount of free volume in the bed, i.e. the porosity, is also expected to affect the permeability.

A crucial step in the optimization of a recombination process is, therefore, to understand the wetting kinetics of powder beds and how it is affected by the morphological parameters of different powders. This means that the relation between the permeability constant of the porous medium and powder morphology needs to be defined. The purpose of this study was to establish such a relation for agglomerated spray dried dairy powders.

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2. Background

The flow through porous media behaves differently depending on the flow regime, described by Reynolds number, for which the flow occurs. This is described by Fand et al., [6]. Fand, and many others [5,7–9], divides the flow into four different regimes which, from low to high Reynolds numbers, are: The pre-Darcy regime, the Darcy regime, the Forchheimer flow regime and the turbulent flow regime. The exact transitions between these regimes is differing within literature [6,8], but it could be stated that among them the pre-Darcy and the Darcy regime describe laminar flow while the flow is considered fully turbulent in the turbulent flow regime. Between these, is the Forchheimer regime where the development of boundary layers means that inertia must be taken into account in the description of the flow, as in the commonly used Ergun Equation [10].

In the Darcy regime the Reynolds numbers are low, and the flow is laminar. Here, mainly viscous forces are responsible for the pressure drop of the flow, as described by Darcy's law:

$$Q = k \cdot \frac{A \cdot \Delta P}{\mu \cdot L} \tag{1}$$

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

Many attempts to estimate the correlation between the structural parameters of a porous medium and the permeability constant in Eq. (1) are available within the literature. One of the most common is the Kozeny-Carman equation, [11]:

$$k = c_0 \cdot T_0 \cdot \frac{\varepsilon^3}{M^2} \tag{2}$$

where ε is the porosity of the medium, M [m^2/m^3] is the specific surface area of the powder bed bulk and c_0 and T_0 are constants. The basis of the Kozeny-Carman equation is a model stating that the void space of porous media can be considered as small capillaries perforating it. Depending on the assumed shape of the capillaries the value of the c_0 constant changes, with a value of 0.5 corresponding to cylindrical capillaries [5]. The alignment of these assumed capillaries in the direction of flow determines the value of the tortuosity constant T_0, which is defined as:

$$T_0 = \left(\frac{l}{l_{tortuous}}\right)^2 \tag{3}$$

where l_{tortuous} is the actual length of the tortuous capillary, and l is the shortest distance between its ends. This ratio has been determined by Carman, to be $1/\sqrt{2}$ for porous media consisting of packed spheres, [12]. This yields a value of the constant T_0 as 1/2. Carman also empirically determined a value of the constant c_0 to 1/2.5 as valid for the case of flow through packed spheres. The product $c_0 \cdot T_0$ then becomes 1/5, and is often noted as the so called Kozeny-Carman constant (c) which together with the common rewriting of the specific surface area (M) to correspond to the specific surface area of only the solid part of the bed, $M = (1-\varepsilon)M_{\text{solid}}$, gives Eq. (2) as:

$$k = c \cdot \frac{\varepsilon^3}{\left((1-\varepsilon) \cdot M_{solid}\right)^2} \tag{4}$$

where M_{solid} [m^2/m^3] is the specific surface area of only the solid part of a porous media (i.e. the particle structure) and c has a stated value of 1/5. For the specific case of flow through a packed bed of perfect spheres, M_{solid} can be written as:

$$M_S = \frac{\pi \cdot d_p^2}{\left(\frac{\pi \cdot d_p^3}{6}\right)} = \frac{6}{d_p} \tag{5}$$

where d_p[m] denotes the diameter of the particles.

The estimate of the permeability constant resulting from Eqs. (4) and (5) has been proven to correspond well to experimental results for the flow through packed beds of monodisperse spheres [6,12,13], and the relation has also been validated by simulations [14].

However, it should be emphasized that Eq. (4) is based on the assumptions that all the void space of a porous media is available to the flow and occur as cylindrical capillaries with constant tortuosity. This would generally be the case for homogeneous beds such as beds formed from particles without any aggregation (randomly packed spheres). However, random packing of more complex powders often results in more heterogeneous beds. Irregular particle shapes prevent close packing of the particles. This effect is further enhanced if large agglomerates exist in the sample, which could have a very porous nature within themselves in addition to taking random shapes. The adhesion of smaller cohesive particles to larger ones as well as to agglomerates, also increases the heterogeneity of the bed. This means that a significant portion of the free volume in the bed may be unavailable to the flow. Alternatively regions could be formed where the porosity is significantly higher than in the bulk of the bed [15–17]. Usage of the specific surface area of the solid phase $M_{s.}$, Eq. (5), for spheres excludes any increase in surface to volume ratio due to more varying particle shapes as well as any fine irregularities occurring at the particle surface. Many authors therefore slightly vary the expression for the relation, a summary is presented by Xu et al. [18], or the value of the Kozeny-Carman constant (c), in order to achieve a better fit with experimental results [18,19].

In an extensive study, Wasan et al. [20] evaluated the validity of the Kozeny-Carman model for more complex samples and considered the Kozeny-Carman constant (c) to be a function of both bed porosity and particle shape. Some authors, [21–22] use correction factors based on particle sphericity to adapt expressions for the estimation of the permeability to beds consisting of non-spherical particles. However, in order for such an adaption to yield accurate results all particles of the bed should have the same sphericity. In a previous study [3], we found that this is never the case for the agglomerated structure of spray dried powders which could vary considerably in shape.

It is clear from the literature that many of the assumptions on which the Kozeny-Carman model is based make it unsuitable if the permeability of powder beds consisting of agglomerated spray dried powders is sought. Therefore, there is a need to adequately measure the permeability of such media and, based on the results, determine whether the Kozeny-Carman model can accurately predict the permeability of such beds. In addition, a study on the influence of particle morphology on bed permeability should be conducted in order to identify the particle properties that have the largest effect. This has been the aim of this study.

3. Materials

The spray dried dairy powders included in the study are presented in Table 1. The powders were selected for having differing morphological parameters. Both skim milk powders (SMPs) and whole milk powders (WMPs) were used. Some powders were commercial products bought for this project, while others were collected directly from the spray drier during either commercial or pilot plant production, (see Table 1). The particle size distributions of all powders were measured using a