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A new methodology to estimate the steady-state permeability of roast and ground coffee in packed beds

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ABSTRACT

In an espresso-style extraction hot water (90 ± 5 °C) is driven through a coffee packed bed by a pressure gradient to extract soluble material from the coffee matrix. Permeability is a key parameter affecting extraction as it determines the flow rate through the bed and hence brewing and residence time. This may alter bed-to-cup mass transfer and therefore impact brew quality.

In this work a methodology that will allow estimation of the permeability of coffee packed beds in steady-state was developed. Fitting measured flow rate – pressure drop data to Darcy's law resulted in permeability values in the range of 10^{-13}–10^{-14} m^2. Disagreement between the experimental and theoretical permeability, as estimated from dry measurements of particle size distribution and Kozeny–Carman equation, was found. Bed consolidation may have a larger effect on the packing structure than the mere decrease in bed bulk porosity. The Kozeny–Carman equation, corrected with a porosity-dependent tortuosity according to a power law, gave a good fit of the data.

1. Introduction

According to the International Coffee Organisation (2013), approximately 1.6 billions cups of coffee are consumed worldwide everyday, making coffee beans one of the most-traded commodities. The most popular brewing methods require a pressure gradient to drive hot water (90 ± 5 °C) through a packed bed of roasted and ground coffee to extract soluble material from the coffee matrix (Petracco, 2001). This is the case of Italian espresso, novel On-Demand capsule systems (pre-portioned capsules of roast and ground coffee that are brewed using a small automatic brewer) or, at an industrial scale, instant coffee production. In the latter process extraction temperatures as high as 180 °C are used (Clarke, 2001).

Significant effort has been devoted to optimise espresso-style coffee extraction variables to meet consumers' taste. An extraction yield, defined as the mass percentage of roast and ground coffee dissolved in the brew, between 18% and 22% has been proposed as acceptable in terms of brew quality (Navarini et al., 2009). Romani et al. (2004) found in a field study across Italian coffee shops that between 6 and 9 g of ground coffee are typically used in espresso-style extraction; average drink volume and extraction yields were around 22 ml and 24%, respectively. Poor quality in espresso brews is commonly attributed to under and over-extraction. Although the definition of these phenomena may be somewhat subjective, they have been characterised, from a sensory point of view, by low extraction yields with an acid, sweet flavour profiles and high extraction yields with a bitter, astringent flavour profile, respectively (Petracco, 2001).

The influence of product formulation (i.e. botanical kind of the beans, roasting degree, and particle size distribution) and process variables (i.e. extraction time, flow rate, temperature and water pressure) on the physicochemical attributes and sensory profile of espresso brews have been widely studied, such as by Andueza et al. (2002, 2003, 2007), Caprioli et al. (2012), Gloess et al. (2013), Lindinger et al. (2008), Maeztu et al. (2001) and Parenti et al. (2014). Although relevant conclusions may be drawn from these studies (e.g. high temperatures and fine particle size distributions may lead to over-extracted brews) it is also true that the lack of a more engineering approach to the physical mechanism driving the process has promoted some misconceptions and myths surrounding coffee extraction. This is especially true when the role of hydrodynamics process variables is discussed; their dependency on other variables is subtle and is sometimes neglected. For example, Andueza et al. (2002) studied 'water pressure' as a variable that may affect the quality of espresso brews, but they implicitly

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considered it to be independent of particle size distribution, packed bed structure, and flow rate.

In regard to the influence of hydrodynamics in the final quality of espresso coffee, the permeability of the packed beds is a key parameter. For a fixed pressure gradient, the permeability determines the flow rate across the bed and hence brewing time (i.e. time required to produce a given drink volume) and water residence time; the influence of short or long contact times on mass transfer can lead to under or over extracted brews. Therefore there is a genuine motivation to develop predictive models to estimate the permeability of coffee packed beds.

For low Reynolds numbers ($Re_p < 10$) and steady-state, the permeability can be estimated from Darcy's law (Bear, 1988):

$$Q = \frac{KA}{\mu L}\Delta P \quad (1)$$

where Q is the volumetric flow rate, A the cross section area normal to the flow direction, ΔP the pressure drop across the bed, μ the fluid viscosity, L the length of the bed and K the permeability of the medium. In a packed bed the relevant length scale to calculate Reynolds number is an estimation of the equivalent pore size of the bed (Rhodes, 2008).

Petracco and Liverani (1993), based on the following observations, stated that espresso-style extraction takes place during the transient regime of the flow: (i) during the first 2–3 s of extraction, flow rapidly increased and then exponentially decreased by 60–85%; (ii) average flow rate increased as average extraction temperature decreases; (iii) increasing the pressure head above a certain point (~5–7 bar) was found to decrease the average flow rate. The latter observation has also been reported in chromatography studies and was attributed to bed consolidation (Hekmat et al., 2011). Furthermore, in hydration experiments of coffee particles in a beaker, Mateus and Rouvet (2007) reported a dynamic swelling effect due to moisture absorption by the cellulose matrix. Despite the aforementioned non-steady state observations, permeability values have been estimated using Eq. (1). In works concerned with the use of stove-top coffee makers, King (2008) found values of fluid conductance, α, (defined as the proportionality factor between the applied pressure across the bed and the volumetric flow rate) of 1.00×10^{-10} m^3 Pa^{-1} s^{-1}, which is equivalent to a permeability value of 8.98×10^{-13} m^2. This is in good agreement with Navarini et al. (2009), who derived a time-dependent permeability ranging from 7.00×10^{-14} to 4.00×10^{-13} m^2, but is significantly different from Gianino (2007), who reported a value of 2.3×10^{-12} m^2.

Permeability is an exclusive function of particle size distribution of the solids forming the bed and packing structure (i.e. bed bulk porosity). Although this dependency has been thoroughly investigated in many industrial applications, such as chromatography (Hekmat et al., 2011), filtration (Tien and Ramarao, 2013), and oil-containing geological formations (Joseph et al., 2013), to the best of our knowledge, no work has been reported before for coffee packed beds. Therefore the main objectives of this work are to (i) develop a methodology to estimate the permeability of roast and ground coffee packed beds in steady-state and (ii) evaluate and model the effect of particle size distribution and bed bulk porosity (effectively bed bulk density) on permeability.

2. Permeability models

A common modelling approach is to portray the bed as a bundle of parallel capillaries in which the Hagen-Poiseuille equation is applied. The implicit assumption of a homogenous bed (i.e. wall effect can be neglected) remains true for bed-particle diameter ratios $\geqslant 5$ (Di Felice and Gibilaro, 2004). The general expression resulting from this approach (assuming that capillaries are cylindrical) is given in Eq. (2). A detailed derivation can be found elsewhere (Endo et al., 2002; Rhodes, 2008):

$$K = \frac{\varepsilon_{bed}^3}{2\tau^2 S_v^2 (1-\varepsilon_{bed})^2} \quad (2)$$

where ε_{bed} is the average bulk porosity of the packed bed, S_v the surface-to-volume ratio of the packing material and τ the tortuosity of the bed; τ is defined as the ratio of the actual tortuous length travelled by the fluid in the bed to the geometric length of the bed.

The simplest case, where the packing material is formed by mono-sized spheres, implies that $S_v = 6/d_s$ and $\tau = 1.58$; Eq. (2) is then reduced to Eq. (3), known as the Kozeny–Carman equation:

$$K = \frac{\varepsilon_{bed}^3 d_s^2}{180(1-\varepsilon_{bed})^2} \quad (3)$$

where d_s is the diameter of the packing spheres and 180 the Kozeny–Carman pre-factor. If the packing material is non-spherical and exhibits a distribution of sizes, this must be taken into account as $d_s = \Phi d_{[3,2]}$, where Φ is the sphericity of the material and $d_{[3,2]}$ is the average Sauter mean diameter of the distribution. Eq. (3), combined with Eq. (1), has been proved to make reasonable estimates of pressure drops (errors of ±50%) for unconsolidated beds in the range of ε_{bed} from 0.36 to 0.92 (Macdonald et al., 1979). However, as reported in the same work, when the beds strongly deviated from Kozeny–Carman assumptions, (i.e. consolidated beds with ε_{bed} considerably lower than the theoretical 0.36 found by Scott (1960) for random closed packed beds of mono-sized spheres), estimation errors in the pressure drop of up to 300% were found. This suggests that tortuosity, assumed to be constant in Eq. (3), is notably affected by consolidation of the bed. Tortuosity-bed bulk porosity relationships have been thus investigated. For example, Lanfrey et al. (2010) modelled tortuosity of an isotropic packed bed as a decreasing function of bed bulk porosity. However, commercially-available ground coffee has been reported to be characteristically bimodal (Petracco, 2005). A semi-empirical tortuosity-bed bulk porosity correlation for beds formed by a discrete bimodal distribution of spheres has been reported by Dias et al. (2006):

$$\tau = \left(\frac{1}{\varepsilon_{bed}}\right)^n \quad (4)$$

where n is an adjustable parameter which depends on the packing method and varies from 0.4, for loose packed beds, to 0.5, for dense packed beds of spheres.

Two different models will be then considered to estimate the permeability of coffee packed beds: Model 1 (Kozeny–Carman equation, Eq. (5a)) and Model 2 (Kozeny–Carman with a porosity-dependent tortuosity, Eq. (5b)), obtained by substituting Eq. (4) in Eq. (2):

$$K = \frac{\varepsilon_{bed}^3 (\phi d_{[3,2]})^2}{180(1-\varepsilon_{bed})^2} \quad (5a)$$

$$K = \frac{\varepsilon_{bed}^3 (\phi d_{[3,2]})^2}{72\left(\left(\frac{1}{\varepsilon_{bed}}\right)^n\right)^2 (1-\varepsilon_{bed})^2} \quad (5b)$$

3. Materials and methods

3.1. Extraction rig

A rig (Fig. 1) was designed and built to carry out fixed-time brewing cycles. Two main sections are to be distinguished: