Bulk and Surface Wettability Characteristics of Probiotic Powders *in* Their Compressed Disc and Packed-Bed Column Forms

Mohamed A. Ali[1], *Hary L. Razafindralambo*[2,]*, *Giuseppina Conti*[1], *Joël De Coninck*[1]

[1]Physics of surfaces and interfaces Laboratory, University of Mons, 19, Avenue Maistriau, B-7000 Mons, Belgium

[2]Gembloux Agro-Bio-Tech, University of Liege, Avenue de la Faculté 2B, B140 TERRA Teaching and Research Centre, B-5030 Gembloux, Belgium

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ASSOCIATED CONTENT

Supporting Information

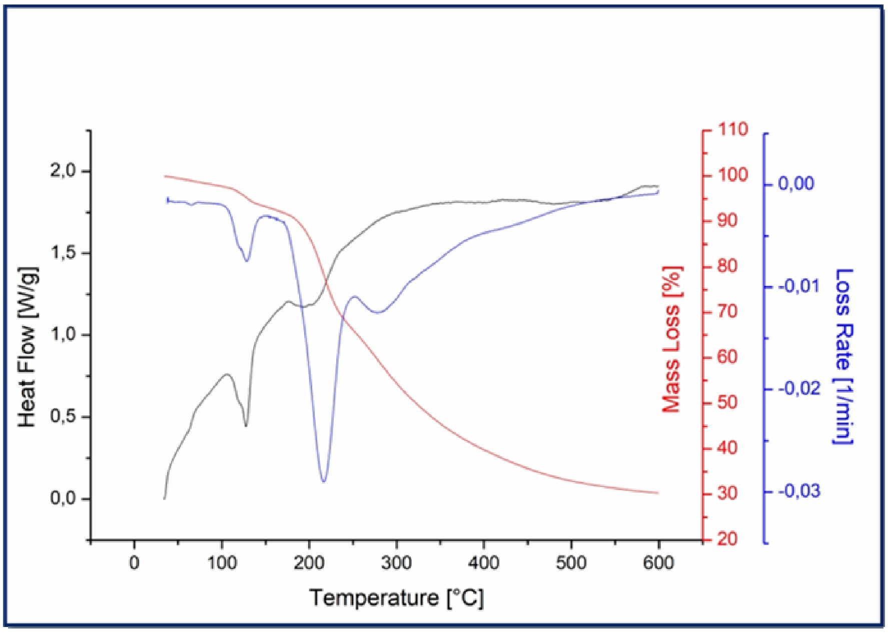


Figure S1: Thermal profile of the multistrain probiotic vivomixx VSM003NM by TGA-DSC: TGA curve (red), DSC curve (black), and DTG curve (blue) obtained by 5°C/min temperature scan

Theoretical aspect of the dynamic capillary rise phenomenon

Capillary rise in a tube is governed by a couple of famous laws. This liquid is itself characterized by a surface tension, γ and a density ρ. Due to the capillary pressure, a liquid penetrates a tube of radius R up to some height H according to the Jurin's law

$$\rho g \pi R^2 H = \gamma cos\theta_e \times 2\pi R = mg$$

Where η the viscosity and θ_e the contact angle, which describes how the liquid/air interface behaves in contact with the tube surface at equilibrium. Often, liquid penetration rates are used to obtain information on effective pore dimensions. One approach is to measure the rate of penetration of a liquid, which is then modeled as a bundle of uniform capillaries.[1–3] The driving force is the difference in pressure between the liquid and the vapor phase due to the curvature of the meniscus within the pore. This is balanced by viscous dissipation and changes in gravitational potential and momentum as the liquid imbibes. Simple expressions may be written to describe each of these terms, yielding an equation which relates the rate of penetration dh/dt to the wetting properties of the tube or the effective tube

$$\frac{2}{R}\gamma.\cos(\theta_e) = \rho g \boldsymbol{h} + \frac{8}{R^2}\eta \boldsymbol{h}.\frac{d\boldsymbol{h}}{dt} + \rho.\left(\boldsymbol{h}\frac{d^2\boldsymbol{h}}{dt^2} + \left(\frac{d\boldsymbol{h}}{dt}\right)^2\right) \qquad \text{(Eq.1)}$$

By neglecting inertia, then this equation can easily be written in the form

$$1 = a.h + b.h.\frac{d\boldsymbol{h}}{dt} \qquad \text{(Eq.2)}$$

Where

$$a = \frac{\rho g \boldsymbol{h}}{\frac{2}{R}\gamma_L.\cos(\theta_e)}$$

and

$$b = \frac{\frac{8}{R^2}\eta}{\frac{2}{R}\gamma_L.\cos(\theta_e)}$$

If we assume that the capillary rise h=0 at zero time, we get:[4]

$$t = -\frac{b}{a}h - \frac{b}{a^2}\log(1 - ah) \qquad \text{(Eq.3)}$$

Leading by Taylor's expansion to

$$t = \frac{b}{2}\boldsymbol{h}^2 \qquad \text{(Eq.4)}$$

Or equivalently

$$h = \sqrt{\frac{2t}{b}} \quad \text{(Eq.5)}$$

which is the well-known approximation for the Lucas-Washburn equation. Now, it is also known that when the liquid will penetrate into the tube, the liquid/air interface will move at a certain speed which will affect the value of the contact angle. The contact angle modification due to this displacement can be described by:[5]

$$\cos(\theta_t) = \cos(\theta_e) - \frac{\zeta}{\gamma}.\frac{dh}{dt} \quad \text{(Eq.6)}$$

where ζ refers to the friction between the moving interface and the solid surface. If we now insert this correction into Eq. 1, we get

$$\frac{2}{R}\gamma.\cos(\theta_e) = \rho g h + \frac{8}{R^2}\eta h.\frac{dh}{dt} + \frac{2}{R}\zeta\frac{dh}{dt} \quad \text{(Eq.7)}$$

which can be written as

$$1 = a.h + b.h.\frac{dh}{dt} + c.\frac{dh}{dt} \quad \text{(Eq.8)}$$

Where

$$c = \frac{\frac{2}{R}\zeta}{\frac{2}{R}\gamma_L.\cos(\theta_e)} = \frac{\zeta}{\gamma_L.\cos(\theta_e)}$$

With the same initial boundary conditions as before, we then get the general solution

$$t = -\frac{b}{a}.h - \frac{b + a.c}{a^2}\log(1 - a.h) \quad \text{(Eq.9)}$$

leading to the expansion

$$t = c.h + \frac{b + a.c}{2}h^2 \quad \text{(Eq.10)}$$

Let us here stress that this modification will affect the behavior of the penetration height h mostly for small time values since it is speed dependent. It will now behave as $h \sim t$. Other dissipation channels have also been considered to describe this additional term[6] but again it only affects the small time behavior of the function h.

For the case of powders or porous media, we usually use Darcy's equation given by

$$h(dh/dt) = k/\eta(\gamma/R_{eff}) \quad \text{(Eq. 11)}$$

where R_{eff} is now an effective radius of imbibition and k is the so-called permeability. Integration of this equation is easy using the previous arguments leading to

$$h = \sqrt{\frac{2.t}{b_{eff}}}$$ (Eq.12)

where

$$b_{eff} = \frac{\eta R_{eff}}{k.\gamma} = \frac{\frac{8}{R_{eff}{}^{2}}\eta}{\frac{2}{R_{eff}}\gamma.\cos(\theta_e)} = \frac{4\eta}{\gamma.R_{eff}.\cos(\theta_e)}$$ (Eq.13)

from which the permeability k can be seen proportional to R_{eff}^2. From the kinematics of the imbibition in a porous media, we can thus extract the effective radius characterizing its permeability or equivalently its porosity. When the porous media is not homogeneous, different scaling behaviors may be observed such as described by Kim et al.[7]

References

(1) Scheidegger, A. *The Physics of Flow through Porous*; University of Toronto Press: Media, Toronto, 1974.

(2) Brakel, J. V. Pore Space Models for Transport Phenomena in Porous Media Review and Evaluation with Special Emphasis on Capillary Liquid Transport,. *Powder Technol.* **1975**, *11* (3), 205–236.

(3) Alim, K.; Parsa, S.; et M. P. Brenner, D. A. W. «Local Pore Size Correlations Determine Flow Distributions in Porous Media,» Physical. *Rev. Lett.* **2017**, *119* (114), 144501.

(4) Terzaghi, K. *Theoretical Soil Mechanics*; Wiley: New York, 1943.

(5) Blake, T. D. Fernandez-Toledano, J.-C.; and J. De Coninck, G. D. Forced Wetting and Hydrodynamic Assist,. *Phys. Fluids* **2015**, *27* (11).

(6) Quéré, D. Inertial Capillarity. *Europhys. Lett. EPL* **1997**, *39* (5), 533–538. https://doi.org/10.1209/epl/i1997-00389-2.

(7) Kim, J.; Ha, J.; Kim, H. Capillary rise of non-aqueous liquids in cellulose sponges,. *J. Fluid Mech.* **2017**, *818*, 2.

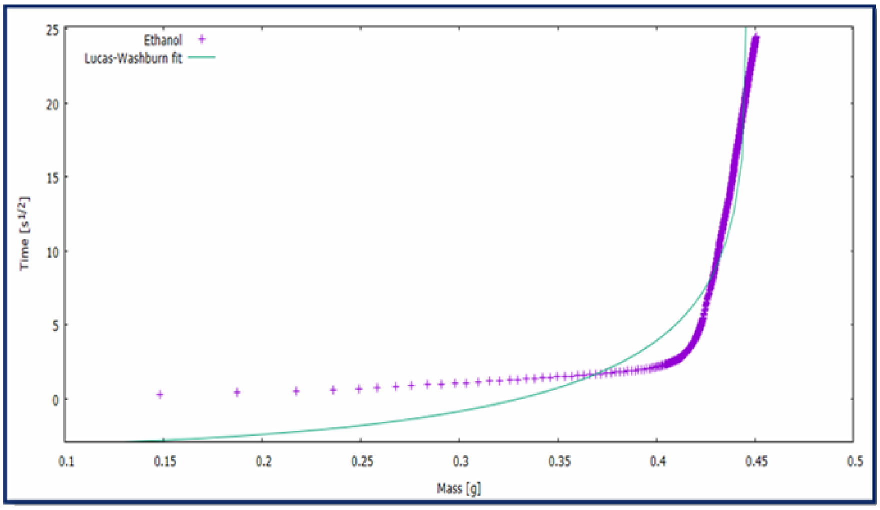
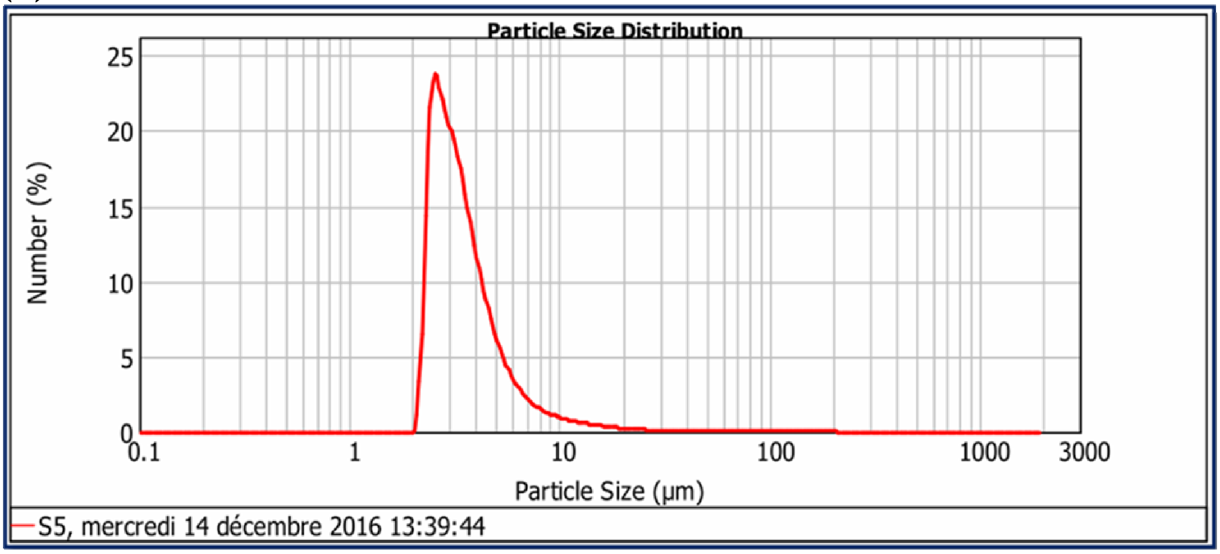


Figure S2: Experimental data (+) and Lucas-Washburn equation best fit (—) of the ethanol capillary rise data into vivomixx VSM003NM packed bed.

(A)



(B)

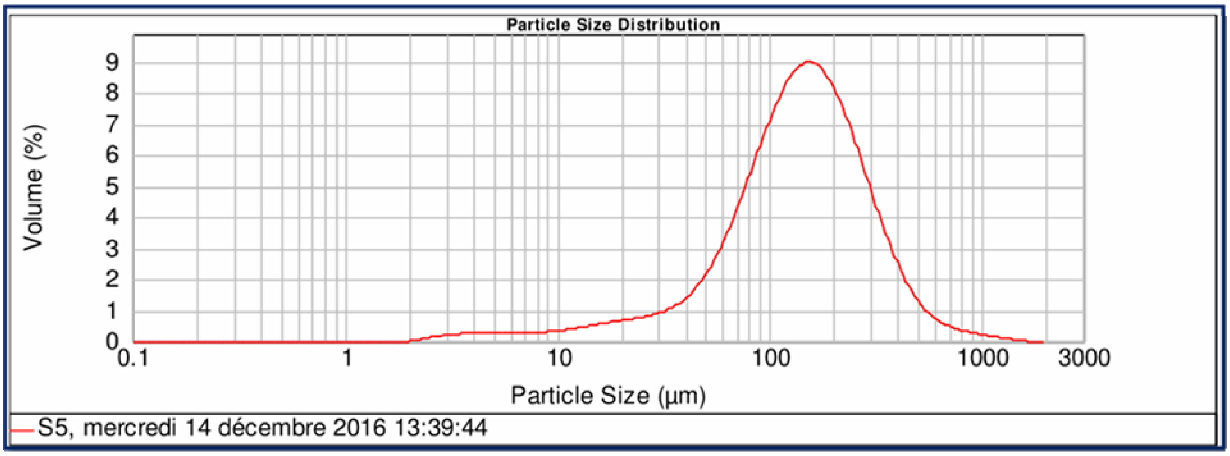


Figure S3: The particle size distribution of vivomixx VSM003NM particles determined by the laser diffraction expressed in number % (A) and in volume % (B)