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Dear Editor,

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Sincerely,

Dejan Brkić

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The discussers would like to express their appreciation to the authors Neupauer and Dennis (2010) for representing classroom activities that are used to illustrate basic concepts of groundwater flow using a simple apparatus called Darcy bottle. In technical paper by Neupauer and Dennis (2010), although the used apparatus is simple and the tests are largely understandable, some points are unclear and need to be clarified. In discussed paper Darcy’s law is introduced to students in a way to calculate the rate of change of one variable in relation to another (Carlton and Nicholls 2001). The discussers are also involved in teaching of underground flow to the students of petroleum engineering, but they use different approach; i.e. students have to measure some quantities in the laboratory and then to calculate others. Pet um department at University of Belgrade had very simple professional permeameter, but few parts are now broken and since the spare parts are not available, the discussers have to manage to made exercises with student using hand-made apparatus. Experience shows that student cannot understand concept of hydraulic conductivity and permeability before few introductive examples. These exercises will be used also to illustrate problem which can arise with use of corn syrup as working fluid. Simple system of sphere packing is used to calculate porosity, permeability and specific surface of porous systems (Figure 1). Most models of flow through porous media are first constructed with perfect spheres in mind. Note that system is spatial (where granular beads are spheres and not circles). Also, different colors of spheres used in Figure 1 do not necessary mean that particles have different mineralogical structure. Color is used only to differentiate particles by their size (or precisely by diameter).

Figure 1. System of sphere packing used to calculate porosity, permeability and specific surface

Porosity of systems made by uniform spherical particles depends only on packing. In figure 1, disposition of particles shown in examples A) and B) are typical for water and air filters, cooling towers, scrubbers, absorber columns, adsorption contactors, ion exchange columns, and air driers, while disposition shown in C) and D) are typical for underground aquifers and oil and gas reservoirs where pressure overburden is significant (Trussell and Chang 1999). First task for student is to calculate porosity using knowledge from geometry (answers: $\Phi_{A)}=\Phi_{B)}\approx0.477$ and $\Phi_{C)}=\Phi_{D)}\approx0.26$). For Darcy's bottle more possible pattern is A), i.e. B). Example E) is introduced to examine mixture of small and large beads packed similar as in example A) or B). It is not always obvious at first sight for students that $\Phi_{A)}=\Phi_{B)}$, but $\Phi_{E)}<\Phi_{A)}$ and consequently $\Phi_{E)}<\Phi_{B)}$. Next task is to calculate permeability. This can be done using Kozeny-Carman model (Reyssat et al 2009) for spherical systems (1):

$$k=\frac{d^2}{180}\cdot\frac{\Phi^3}{(1-\Phi)^2} \qquad (1)$$

Fixing value of porosity, it is obvious that larger diameter of beads produces increased permeability ($k_{A)}>k_{B)}$ and $k_{C)}>k_{D)}$). Third task is to calculate specific surface which is for a media made of uniform spheres well defined (2):

$$s = \frac{6\cdot(1-\Phi)}{d} \qquad (2)$$

Here, specific surface is defined as the surface area of the media divided by its bulk volume where $s_{A)}<s_{B)}$ and $s_{C)}<s_{D)}$. Definitions of other types of specific surfaces are available from paper of Trussell and Chang (1999). Porosity, permeability and specific surface are defined only using properties of sample matrix, but the value of hydraulic conductivity in Darcy's equation (Eq. 1 of the original paper) incorporates the characteristics of the porous media as well as the fluid. It has unit of length/time (m/s). In correcting Darcy's coefficient for the viscosity and the density of the fluid, permeability eliminates the influence of the type of fluid on the permeability which are constant for the model, making the model more robust. Permeability has units of lengthsquared (m^2). Correlation of Darcy's hydraulic conductivity and permeability can be calculated using kinematic viscosity of fluid as $k=K\cdot(\nu/g)$. Here lies first problem in experiment proposed with Darcy's bottle. Darcy's conducted experiments with water and not with other type of fluids. Corn syrup is not adequate fluid because then concept of wettability (adsorption effect) has to be introduced in this case. The surface wettability of porous system is the result of complex interactions between fluids and the surface of sand or gravel grains. Measurements of contact angles (Figure 2) provide a convenient and conceptually simple approach to quantification of the wettability given by liquid pairs at a smooth mineral surface.

Figure 2. Contact angles caused by different wettability cause changes in effective porosity

It is clear that water and corn syrup has different wetability capacities. Can one prove that permeability does not depend on fluid properties only knowing hydraulic conductivity for water and corn syrup (can be measured using Darcy's bottle), and knowing water and corn syrup kinematic viscosity (3):

$$k = K_w \cdot \left(\frac{\nu_w}{g}\right) = K_{CS} \cdot \left(\frac{\nu_{CS}}{g}\right) = K_{air} \cdot \left(\frac{\nu_{air}}{g}\right) \qquad (3)$$

Previous equation is valid only in absence of wetting effect (thus can be accomplished using air as working fluid or in theory even mercury). According to Benner and Bartell (1941), even water on same mineral surfaces can produce different wetting angles in presence of different fluids (Figure 3). Mineral surface in examples 1) and 2) is quartz and in 3) and 4) is calcite. Water is surrounded with i-octane in example 1) and 3) and with naphthenic acid in example 2) and 4).

Figure 3. Different water wetting angles on same mineral surfaces in presence of different fluids

Fixing the specific surface, residual of fluid in sample is caused only by different wetting capacity (Figure 4). Residual of corn syrup in sample is greater than water residual. This means that increased amount of non-movable corn syrup in comparison with non-movable water cause effect of decreased effective porosity and consequently not only decreased value of Darcy's conductivity but equally of permeability (similar e.g. one can conclude from eq. y=A/B=3/4 that A=3 and B=4, but if A=sin(x) and B=cos(x) previous conclusion fails). This amount of non-movable water can be extracted entirety from the sand sample by drying, but with corn syrup this cannot be done. For example, air permeability in presence of water varied from $8.5 \cdot 10^{-12}$ m^2 for volumetric water content of 2.03% to $2.3 \cdot 10^{-12}$ m^2 for water content of 20.0% (Springer et al

1998). It is important to note that Darcy's experiments actually provide no information about any properties within a packed column (Gray and Miller 2004).

Figure 4. Process of filling and empting a Darcy's bottle

For measure of Darcy's conductivity for teaching purpose, we can recommend apparatus (Figure 5) developed at the University of Washington (Massmann and Johnson 2001). Using air as working fluid, sand remains dry (but for very accurate results Klinkenberg's effect has to be resolved). For minor pressure drop air can be treated as incompressible fluid.

Figure 5. Simple hand-made permeameter

The conductivity of the sample (Figure 5) is measured by submerging the lower section of the tube in water and measuring how quickly the water forces the air through the soil sample. First, the top of the tube is sealed and then cork is removed. Because the air pressure in the lower section of the tube is greater than atmospheric pressure water level in the tube will arise. Time in which water level is changed from H_0 to H_1 also has to be measured (4).

$$K_{air} = \left(\frac{\rho_{air}}{\rho_w}\right) \cdot \frac{L}{\Delta t} \cdot \ln\left(\frac{H_0}{H_1}\right) \tag{4}$$

Further, permeability and Darcy's conductivity for water and corn syrup can be calculated using Eq. (3).

Carlton and Lisgarten (2006) also proposed simple way to make Darcy's bottle. Permeameter can be made also using instructions in the paper of Noll (2003).

Nomenclature:

The following symbols are used in this discussion:

k	permeability (m^2)
K	Darcy's conductivity (m/s)
d	diameter of spherical beads (m)
s	specific surface (m^2/m^3)
L	sample length (m)
H	water level (m)
Δt	time (s)
g	gravitational constant (m/s^2)
Φ	porosity (-)
ν	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)

Index

w	water
cs	corn syrup
air	air

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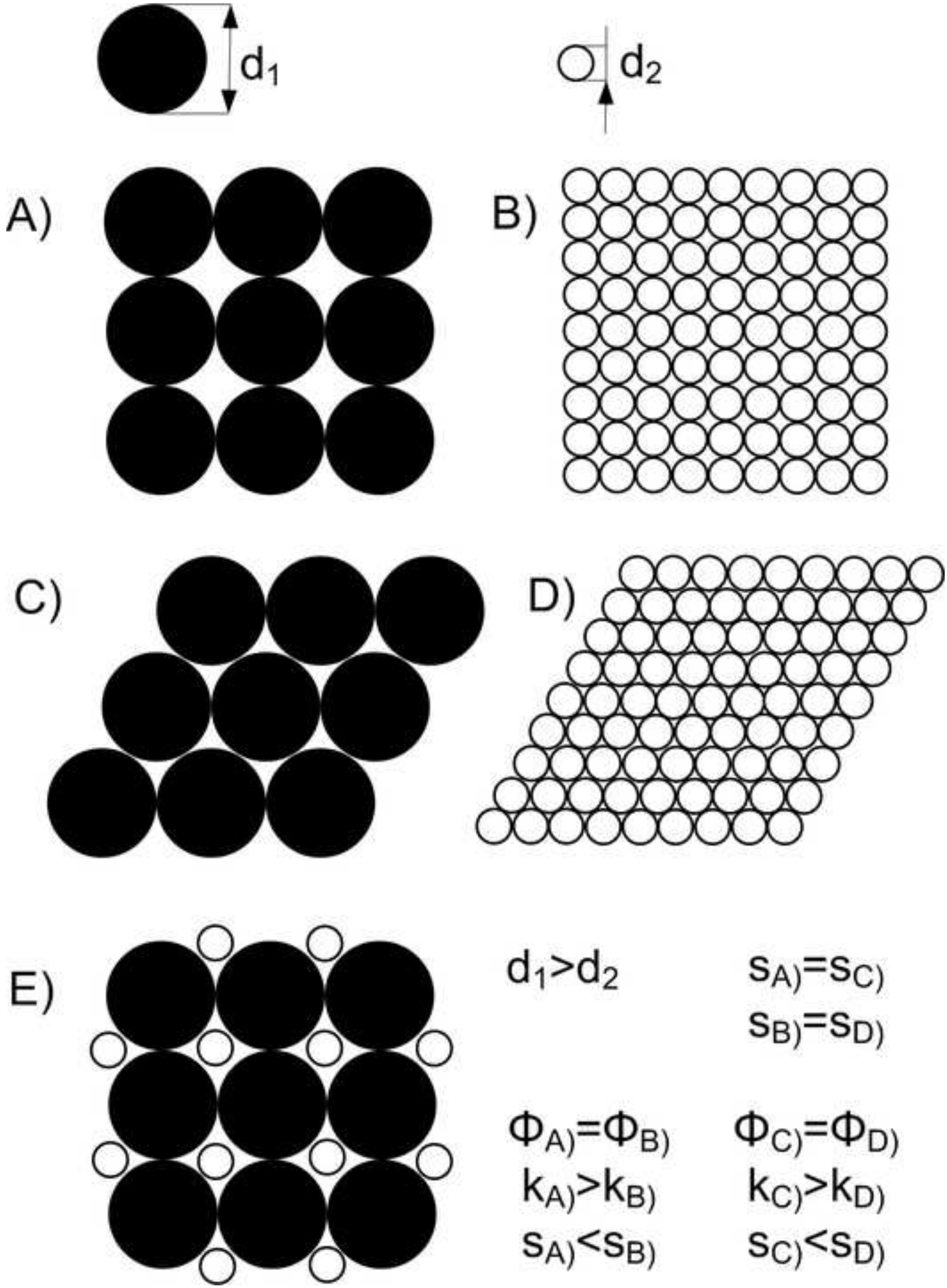

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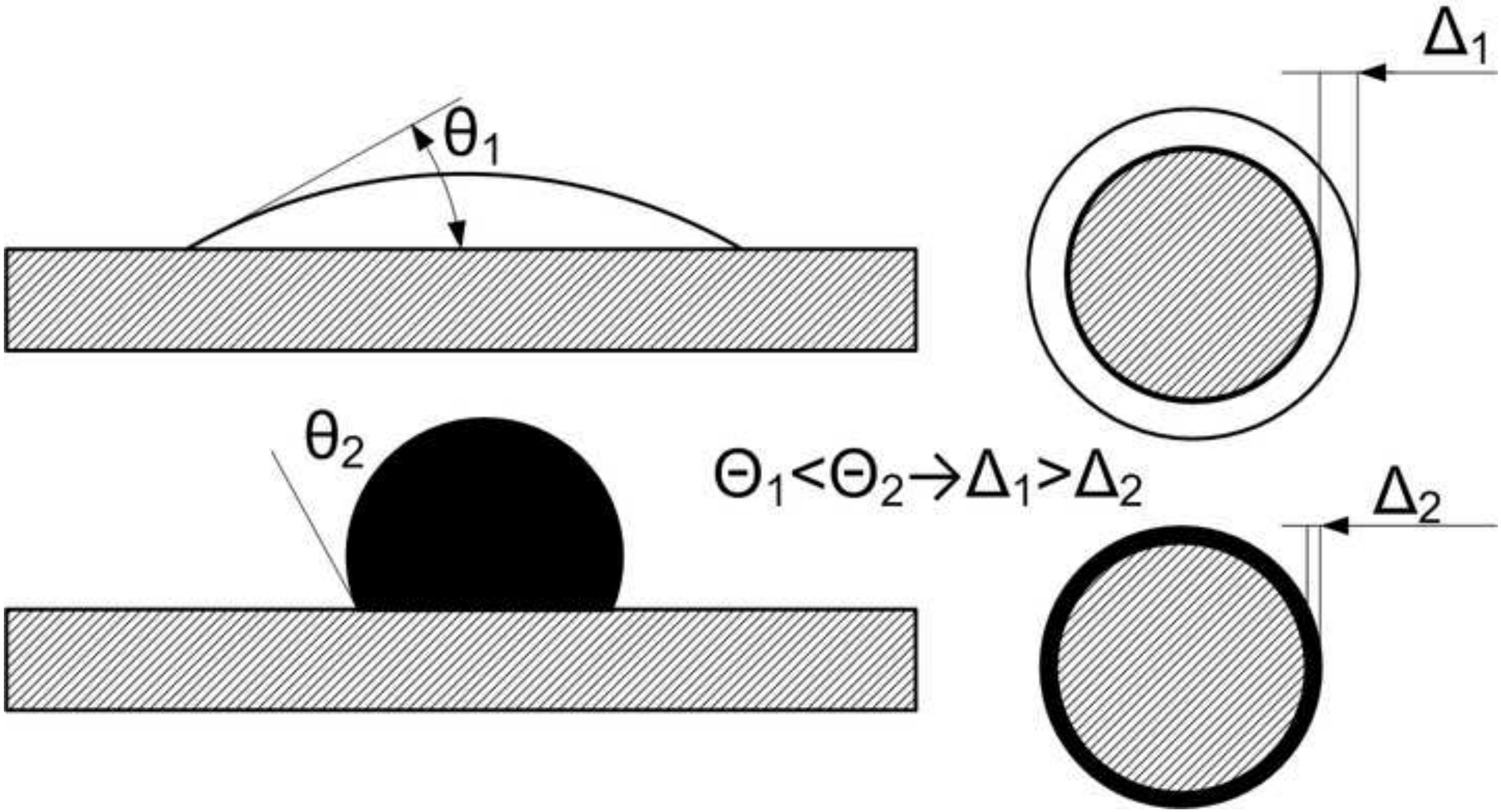

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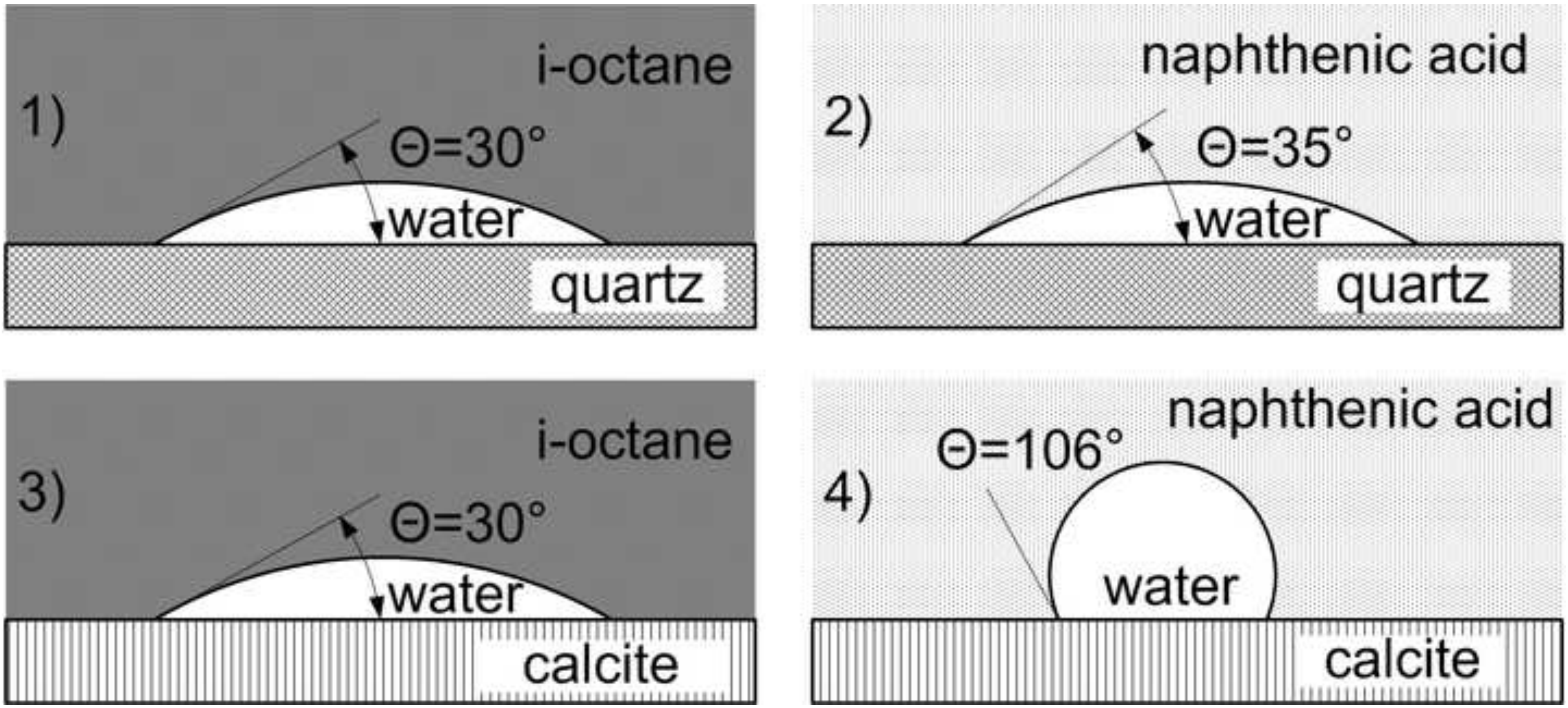

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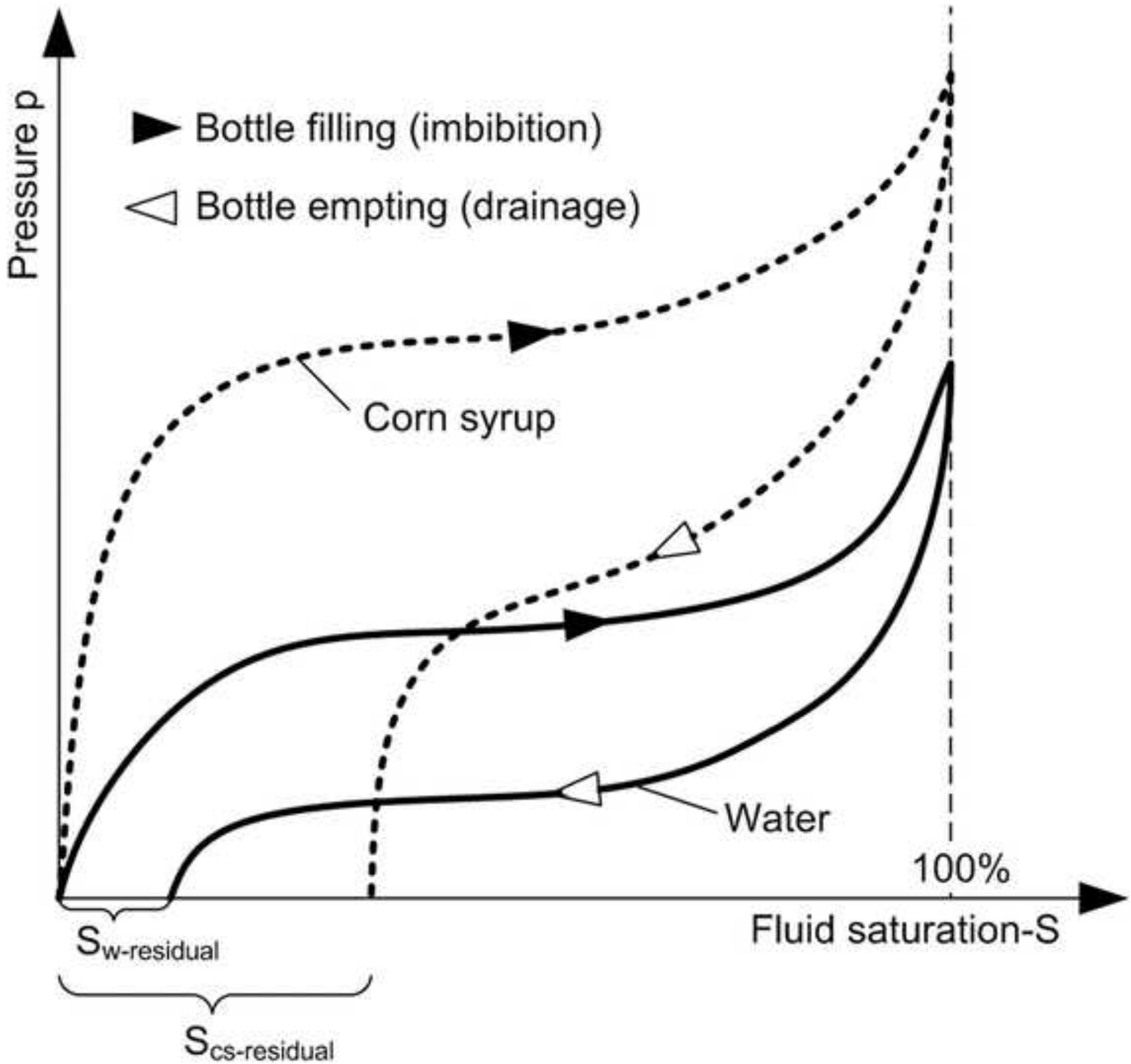

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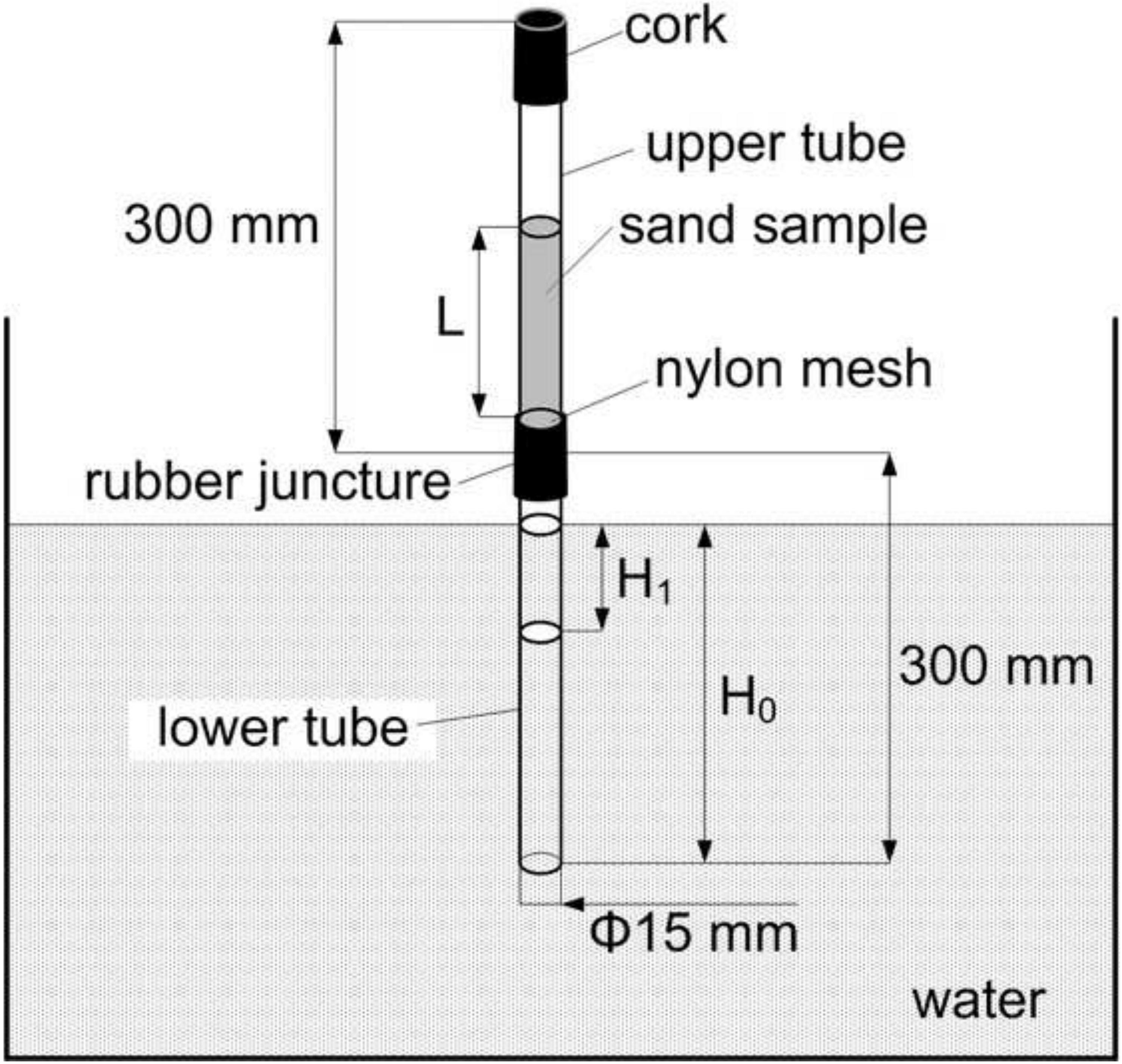

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