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Drop impact on natural porous stones

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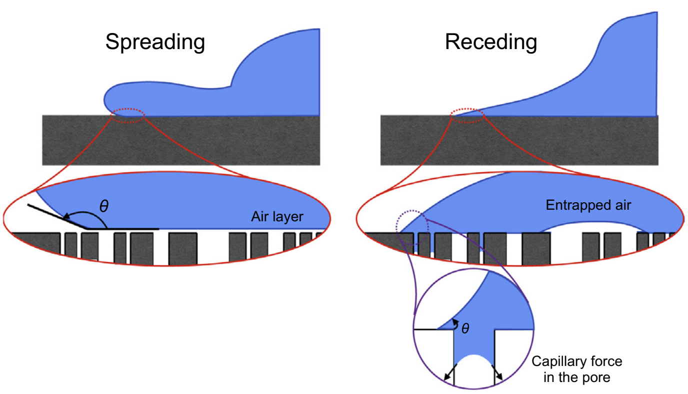
GRAPHICAL ABSTRACT



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ABSTRACT

Drop impact and spreading on three natural porous stones are experimentally determined using high-speed imaging and compared with spreading over an impermeable steel surface. The dynamic non-wetting behavior during spreading and the hydrophobic contact angle >90° is attributed to the presence of an air layer between the droplet and the porous substrate. As the contact line pins at maximum spreading on the porous stone, the maximum spreading determines the liquid contact area on such substrate. The droplet gets pinned when the air layer is broken at the contact line and capillary forces develop in fines pores at the droplet edge, pinning the droplet. Maximum spreading on porous stones increases with impact velocity but does not scale with Weber number at low impact velocity. It is demonstrated that dynamic wetting plays an important role in the spreading at low velocity and that the dynamic wetting as characterized by the dynamic contact angle θ_D has to be taken into account for predicting the maximum spreading. Correcting the maximum spreading ratio with the dynamic wetting behavior, all data for porous stones and non-porous substrate collapse onto a single curve.

1. Introduction

The study of impacting drops spreading over porous media has received little attention compared to similar studies on impermeable surfaces, although such event is more commonplace and often plays an important role in several processes [1]. One of the first studies for drop impact on permeable surface was performed by Wallace and Yoshida [2]. They investigated the spread factor defined as the ratio of the diameter of a stain to the initial drop diameter on paper, as a function of impact energy for pesticide spray application. Chandra and Avedisian [3] compared drop

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impact on impermeable stainless steel surfaces and porous ceramic surfaces. They used the difference of volume before and after impact to estimate the volume absorbed into the ceramic substrate. Although such difference was measured to be between 12% and 15%, considering the time scale of maximum spreading (under 5 ms), the absorbed volume was finally neglected in their maximum spreading prediction. Previous work focused mainly on the depletion of the droplet from the surface and on the influence of properties of porous media (porosity, pore size) and liquids on the impact and depletion processes.

Less information is available about liquid (re)distribution inside the porous media after drop impact. In terms of computational work, Yu et al. [4] and Reis et al. [5,6] performed numerical simulations of drop impact on porous media with volume-of-fluid method. Yu et al. [4] compared the experimental results of drop impact on heated porous media with simulation results. They did not consider absorption given the presence of a vapor layer on the porous substrate. Reis et al. [5,6] developed a numerical model to resolve both the shape of the impacting drop on the surface and the liquid content distribution in the porous medium. They performed a parametric study varying impact conditions, permeability, porosity, pore size and wettability and found the simulated droplet shape to agree with what is seen in experiments. The predicted liquid content in the porous medium compared well with magnetic resonance imaging results after full absorption. The shape of the droplet in the porous medium is similar to a half-spheroid, which aspect ratio depends on the porous medium and liquid droplet characteristics [5].

More recently, drop impact on granular media has been quite investigated. Marston et al. [7] studied the maximum droplet spreading diameter on packed glass beads for different liquids, i.e. 50% ethanol–50% water, ethanol, water and acetone, and reported that maximum spreading scales with $We^{1/5}$. Katsuragi [8] studied the size of craters in granular layers resulting from water drop impact. He assumed that the crater size is determined by the maximum spreading diameter of the droplet and reported that crater size scales with $We^{1/4}$, the same scaling proposed by Clanet et al. [9] for smooth impermeable (no deformable) substrates. Delon et al. [10] also reported a $D_{max}/D_0 \sim We^{1/4}$ scaling when studying water drop impact on sand substrates of different grain sizes. Nefzaoui and Skurtys [11] reported that maximum droplet spreading on dry glass bead substrate scales with $We^{1/5}$ for water droplet and with $We^{1/4}$ for liquids with higher surface tension. Zhao et al. [12] showed that crater size scales with impact energy on substrates of different grain sizes. Going further, Zhao et al. [13] showed that maximum spreading for water drop impacting dry glass beads granular media scales with the effective Weber number defined by the maximum crater depth.

For drop impact on porous media, the influence of the porous medium on spreading is still insufficiently understood due to the presence of simultaneous behaviors, spreading and absorption, and due to the lack of knowledge of the contact line behavior on porous and rough surfaces. There is a clear need to quantify properly droplet spreading on porous media. In this paper, we determine experimentally the drop impact and spreading on three natural porous stones using high-speed imaging and compare it with the behavior on an impermeable surface. Especially we analyze maximum spreading at low impact velocity in view of the dynamic wetting behavior as characterized by the dynamic contact angle. We finally propose a method to scale all data into a single curve taking into account the dynamic contact angle.

2. Methods and material

Three natural stones are selected for droplet impact experiments on porous media: Savonnières, Meule and Pietra Serena. Savonnières is a highly porous quasi-pure calcitic stone (99.8% $CaCO_3$), and is used as a building material on facades of historical buildings (e.g. railway station Gare de l'Est in Paris), as a stone for sculptures (e.g. the sculptures on the facade of the cathedrals in Aachen and Cologne), and is applied for restoration purposes [14,15]. The sandstone Meule (grès à meules) is composed of quartz grain (74%), with clay and other secondary mineralization, and is used as a building material (e.g. tower of the cathedral of Strasbourg) [16]. Pietra Serena is a fine-grained and compact sandstone, and is used widely as a building material for columns, cornices and arches and as a stone for sculptures (e.g. Pazzi and Medici chapels in Florence). Fig. 1 shows light microscope images of the porous stones. The porous stone samples are prepared by cutting cubes ($20 \times 20 \times 20\ \mathrm{mm}^3$). The bulk density ρ_{bulk} defined as the ratio of the dry mass to the total volume, the open porosity Φ defined as the ratio of the volume of open pores to the total volume and the saturated water content w_{sat} defined as the mass of water filling the open pores per total volume are measured. The water absorption coefficient A_{cap} is determined by measuring the absorption mass rate per unit surface in a free water uptake experiment. The capillary water content w_{cap} equals the water content when the water front reaches the top of the sample during capillary absorption. The impervious surface is steel, with an arithmetic average roughness of 0.42 μm and an equilibrium contact angle of $\theta_{eq} = 61°$.

In Table 1, the measured properties of the three stones are summarized. The stones are selected mainly for their range of open porosity in order to understand the influence of surface pore structure on the dynamics of droplet spreading. Elaborate studies on the pore structure, moisture and mechanical properties of Savonnières and Meule can be found in [14,16,17]. Savonnières shows the highest porosity, a faster water absorption rate and the largest capillary water content of the three stones. The capillary water content is smaller than the saturated water content due to air entrapment during imbibition from a free water surface. Pietra Serena shows the lowest porosity, water uptake coefficient and capillary water content. The portion of the pore space filled by water at capillary moisture content in Savonnières, Meule and Pietra Serena is respectively 56%, 72% and 80%.

The arithmetic average roughness R_a for Savonnières, Meule and Pietra serena is respectively 10, 9 and 4 μm, showing the porous materials are quite rough due to the sawing process, compared to the smooth steel surface. The equivalent pore radius R_{eq}, defined from pore size distribution measurement using mercury intrusion porosimetry (MIP) [14,16] and scanning electron microscope (SEM) image [18], for Savonnières, Meule and Pietra Serena equals respectively 100, 10 and 0.04 μm. It was not possible to measure the equilibrium contact angle on stones due to the immediate spreading of the droplet and capillary uptake by the substrate, so no equilibrium could be found. The main components of the stones display very low contact angles (calcite $\sim 0°$ and quartz $\sim$ 11–19°) showing they are almost perfectly wetting [19–21].

Water drop impact on porous stone is recorded in shadowgraphy using a high-speed camera (10,000 frame per second, 7.38 μm spatial resolution and 5 μs exposure time). The properties of water and the impact conditions are given in Table 2. The drop impact test is repeated more than 10 times with 3 different samples at arbitrary surface locations for each measuring condition in order to obtain sufficient reproducibility. Experimental results are reported by their average value (symbol) and standard deviation (error bar). Drop impact on porous stones is compared with the drop impact on impermeable steel surface. Images captured from high-speed camera are analyzed with a custom-made image analysis MATLAB code for determination of: the initial droplet diameter D_0, the impact velocity V_i, the spreading diameter at the rim $D(t)$, the spreading diameter at the contact line $D_{CL}(t)$, the dynamic contact angle θ_D, the maximum spreading ratio