Numerical investigation of droplet spreading on porous and non-porous surfaces

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Introduction

The spreading of liquid drops on solid surfaces is a widespread phenomenon of both fundamental and industrial interest. In many applications though, surfaces are porous or covered with a thin porous layer. These applications include ink jet printing, fuel droplets hitting on combustors porous walls, painting, oil recovery and drug delivery on human skin. The presence of a porous layer modifies the wettability of the substrate and, hence, the spreading patterns are very complex in comparison to the case of smooth surfaces. When a droplet hits a porous surface with relatively low velocity two dominant processes take place: droplet spreading and droplet penetration into the porous medium (PM). The balance of these processes depends on various parameters such as the droplet impact velocity, material porosity and surface tension. Understanding the underlying mechanisms of drop spreading on a porous surface remains limited, in particular with respect to spreading on a non-porous surface. Earlier investigations were mainly devoted to viscous wetting, and most modeling approaches were performed within the framework of a continuous porous material [1] while pore-scale approaches being quite rare [2]. In the current work an attempt in made to analyze numerically the characteristics of a droplet interacting with a surface, using as a basis test cases of liquid droplets with varying viscosities and surface tensions (n-heptane, isopropanol and water) impacting both onto porous and non-porous media (stainless steel, ceramic, glass) [3,4,5]. The primary aim is to compare the simulations with literature available experimental data and to explore the time evolution of the impinging droplet shape as well as the velocity and pressure fields within the droplet using both a macroscopic and a pore scale analysis. Moreover, the effect of different parameters on the process is examined by performing a parametric study based on the variation of: a) the Darcy (Da) number by varying the medium porosity in order to represent the effect of droplet impingement on surfaces ranging from concrete to very coarse sand, (b) the Weber (We) and Reynolds (Re) numbers by varying the impact velocity to assess the importance of inertia in relation to surface tension and viscosity. For higher velocities, the predictive capabilities of the literature suggested framework at the splashing threshold are also investigated [5].

Numerical set-up and experimental parameters

The case of a droplet (water and heptane) hitting a flat non-porous (stainless steel) surface from [3] is first modelled.and then results are compared with experiments in terms of time evolution of the spreading factor. Following, in order to study the collision and deformation dynamics of droplets hitting on porous surfaces and the effect of the surface porosity on the spreading, the experimental results of [4] are reproduced numerically using two different methodologies; one treating the porous media explicitly (resolved porosity) and one implicitly (black box approach). The liquid presented in the present abstract is n-heptane (C_7H_{16}), however, results of a water and isopropanol droplet will be also included. For this initial comparison demonstrated here, the droplet diameter was 1.50 mm and the droplet velocity at the time of impact was 0.93 m/s (impact Re number 2300 and We number of 43). The porous surface studied in the present abstract was constructed by machinable alumina particles with a nominal size approximately 5 to 10 μm and an average porosity of 25%. Following, additional numerical simulations will be performed to provide a sensitivity analysis of the droplet impact and splashing based on the variation of the Da, Re and the We number. The overall numerical algorithm is developed within an open source CFD code (OpenFOAM). The numerical set up can be seen in Fig.1. In the implicit model the PM area is treated as a “black box” (see Fig. 1a) where the permeability due to the porous area is represented by an additional sink term in the momentum equation based on the Darcy-Forchheimer equation for the pressure gradient. The PM is considered as homogeneous. In the explicit model a more realistic PM is geometrically reconstructed based on spheres with various diameters extracted from a Gaussian distribution within the range of 5-30 μm (depending on the material) which are arranged such as the overall porosity is consistent with the experimental one (see Fig 1b), which is resolved by the numerical grid. A novel interface tracking algorithm based on VOF that dampens spurious/non-physical velocities in the vicinity of the liquid/air interface (currently an issue with the generic InterFOAM solver) is implemented in OpenFOAM.

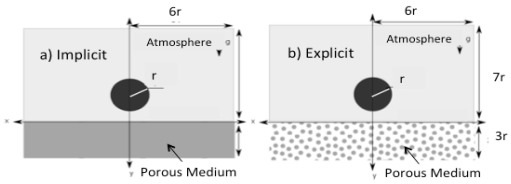

Figure 1: Schematic representation of the numerical set-up

Results and Discussion

Figure 2 and 3 show the impact of the droplet on the porous surface when the implicit model is used. Four snapshots of the collision covering a total time period of 0.4ms are shown for the volume fraction, velocity (Fig 2, middle, right column) and pressure (Fig. 3) and compared with experiments (Fig.2 left). The experimental photographs present the image of the portion of the liquid droplet outside the porous substrate, while the numerical simulations display the liquid both inside and outside the porous region. It should be noticed that in the experiments the camera was positioned at a small angle in relation to the surface and thus the photographs represent a perspective view of the droplet. The mechanism driving this flow is mainly related to the pressure difference between the impact region outside the substrate and the capillary pressure acting in the fluid interface inside the porous medium. During the initial stages of impact the stagnation pressure in the drop, which drives the outward jetting of the liquid, is much larger than the restraining forces due to surface tension and viscosity (i.e. shear stress). As the droplet spreads out into a thin film the kinetic energy is, however, dissipated stopping further spreading of the liquid. In the first few instants of the impact, liquid projects radially from beneath the droplet away from the impact point. The numerical simulation accurately predicts this phenomenon although the simulated droplet seems having larger height implying that potentially the penetration is under predicted. Figure 4 compares enlarged views of a droplet impacting on a stainless steel surface with a droplet on the ceramic surface, taken 0.2 ms after impact in both cases. The visible diameter of the wetted area on the ceramic surface is smaller than on the stainless steel surface and the droplet maintains an almost spherical shape without any radial ligaments. The difference could be due to the fact that the pressure in the liquid at the point of impact can drive some of the liquid into the porous surface, rather than just sideways, as is the case when the surface is impermeable implying the importance of the accurate numerical representation of the liquid penetration through the porous surface.

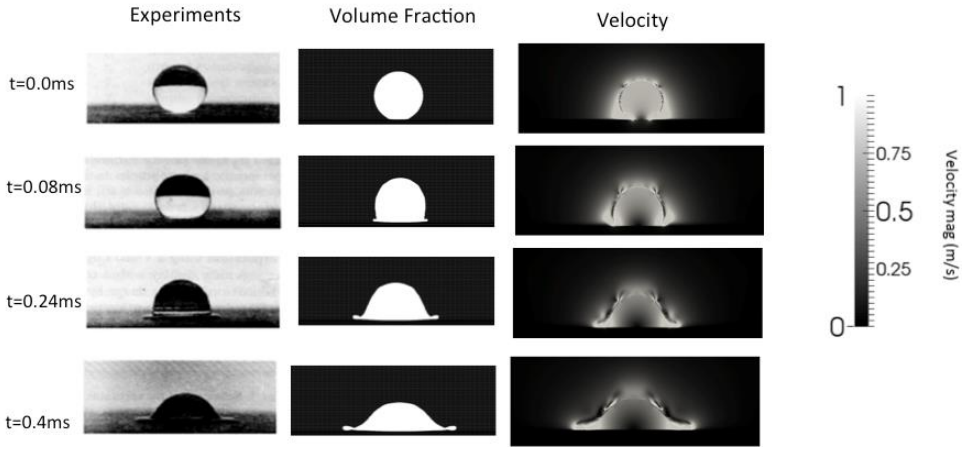

Figure 2: Time evolution during droplet impact. For the simulations (middle and right column) the implicit model is used.

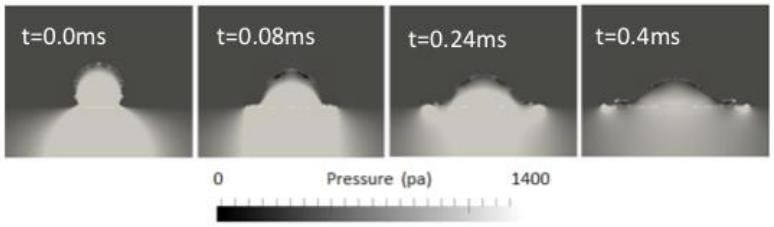

Figure 3: Time evolution of pressure.

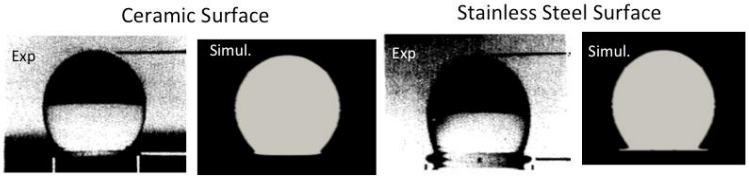

Figure 4: Droplet impact on ceramic (left), stainless steel (right).

References

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