Absorption of a water droplet impacting on porous media

Jae Bong Lee [a,b], Dominique Derome [c], Peter Vontobel [d], Jan Carmeliet [b]
[a]*Korea Atomic Energy Research Institute (KAERI), 989-111 Daedeok-daero, Youseong-Gu, Daejeon 305-353, Republic of Korea*
[b]*Chair of building physics, ETH Zürich, Stefano-Franscini-Platz 5, CH-8093 Zürich, Switzerland*
[c]*Laboratory for Multiscale Studies in Building Physics, Swiss Federal Laboratories for Materials Science and Technology (EMPA), Überlandstrasse 129, CH-8600 Dübendorf, Switzerland*
[d]*Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut (PSI), Villigen, Switzerland*
[*]*Corresponding author: jaebonglee@kaeri.re.kr*

1. Introduction

The phenomenon of wetting by impinging droplet on porous media is ubiquitous in nature and is associated with mechanisms found in various industrial applications [1-3]. Understanding the wetting of porous media by drop impact is also relevant for the environmental fate of toxic materials. In case of a severe accident in a nuclear power plant, aerosol or droplets might get in the environment and be re-deposited to the ground or the built environment by precipitation. Understanding the absorption of drop impacting porous materials is a first step towards developing methods to prevent or mitigate toxic substance absorption and improve cleaning techniques.

In general wetting behavior of the impinging droplet on surface is known to depend on the properties of the liquid (density, viscosity, surface tension), impact conditions (drop size, impact velocity), and the surface properties (wettability, roughness) [1]. Absorption is governed by the properties of the liquid and of the porous media (porosity, pore size, wettability) [3]. Once the deposited droplet is completely depleted from the surface, the liquid further redistributes within the porous media due to capillary forces and evaporation occurs at the surface [4].

In the present paper, the wetting and absorption behavior are observed by optical high-speed imaging and neutron radiography and analyzed as the liquid-solid contact diameter, moisture content and absorbed moisture mass.

2. Method and Results

2.1 Experimental setup

The wetting and absorption process are captured by high-speed imaging and neutron radiography for higher temporal resolution in different time scales. Neutrons are attenuated by the hydrogen of water, but penetrate the porous media made of silicon. The experiment for the absorption of drop impact is performed at the NEUtron Transmission Radiography (NEUTRA) beamline of the Paul Scherrer Institut, Villigen, Switzerland. The NEUTRA beamline is operated with neutrons within a thermal spectrum [5]. Figure 1 shows

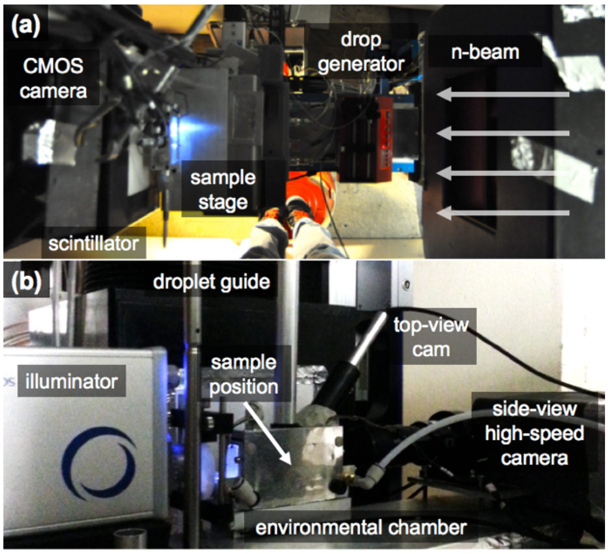

Fig. 1. (a) Beamline configuration for neutron radiography at NEUTRA. (b) Experimental setup for drop impact test.

configuration of beamline for neutron radiography (Fig. 1a) and the synchronized high-speed imaging setup for drop impact (Fig. 1b). The droplet is generated 3, 20 and 60 cm of height from top of sample and deposited on the top of 2 x 2 x 2 cm (width x height x thickness) dimensions of porous Savonnières limestone (porosity 27%, effective pore radius 100 μm). After impact of a droplet on the surface, the hydrodynamics of drop impact on the surface is captured with 1000 f.p.s temporal resolution and 7.38 μm spatial resolution and the water mass transfer into porous media is recorded every 3 seconds with 45.5 μm spatial resolution [4].

2.2 Quantification for water mass inside porous media

The water mass distribution inside porous media is quantified by neutron radiography. The transmission value T on each pixel is obtained with the monochromatic exponential attenuation law (Beer-Lambert), expressed as:

$$\mathrm{T}(t) = \frac{\mathrm{I}}{\mathrm{I_0}} = \exp\left(-\Sigma \cdot d(t)\right) \qquad (1)$$

where $\mathrm{T}(t)$ is the change of the transmission based on the time t, $\mathrm{I_0}$ is the intensity of the incident beam, I is the intensity of the transmitted beam, $d(t)$ is the total thickness of the object in the beam direction and Σ is the linear attenuation coefficient. The absolute water mass excluding porous media is extracted from substitution between wet and dry images:

$$M(t) = \frac{\rho \cdot \text{pixelsize}^2}{\Sigma_{\text{water}}} \ln\left(\frac{T_{\text{dry}}}{T_{\text{wet}}(t)}\right) \quad (2)$$

where the water attenuation coefficient is $\Sigma_{water} = 3.63$ (1/cm), T_{dry} and T_{wet} are transmission values for dry porous media image and porous media image after drop impact. The water mass calculated from neutron radiography is compared with the water mass given by drop injection system, and less than 6.5% difference is found. The absorbed water mass is also estimated with high-speed imaging method using a spherical cap shape assumption [4].

2.3 Water mass distribution

Figure 2 shows water mass distribution in Savonnières limestone after drop impact (initial water droplet mass M_0 = 4.3 mg, impact velocity V_i = 0.5 m/s) and the profiles of average moisture content at the center of drop impact over time. After impact, drop spreads over porous media driven by kinetic energy and recedes by capillary energy [1]. The liquid-solid contact diameter on surface reaches a maximum during the spreading phase, following it is staying pinned at maximum [3]. The pinned droplet becomes a reservoir for water uptake and its contact area with the porous media thus determines the entry path of water (Fig. 2 t = 3 s). The droplet is depleted and redistribution within the porous media and evaporation at the surface occur (Fig. 2 t = 18 and 30 s). It is found that the width of the wetted area inside porous media, being much wider than the liquid-solid contact diameter on the surface, indicates that the droplet becomes a point source for 3-dimensional uptake also along the surface.

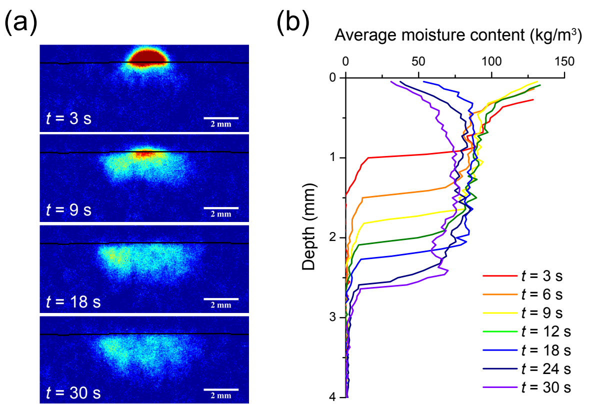

Fig. 2. (a) Time evolution of water mass distribution in porous media for a droplet impact on Savonnières limestone (initial water droplet mass M_0 = 4.3 mg, impact velocity V_i = 0.5 m/s). (b) Profiles of average moisture content at the center of drop impact for various times during absorption.

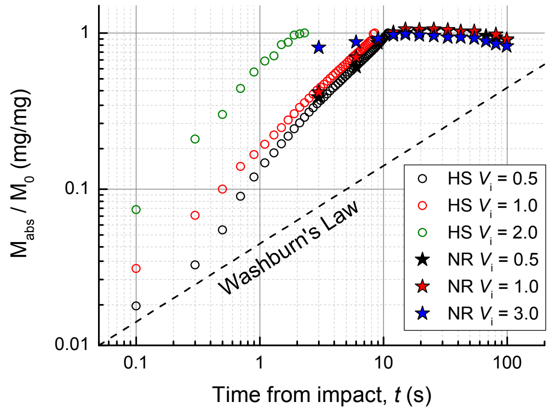

Fig. 3. Normalized absorption mass versus time for different impact velocities on Savonnières limestone in log-log plot. Data extracted from the HS: high-speed images, NR: neutron radiography.

2.4 Absorbed water mass

Figure 3 shows the normalized absorbed water mass in porous media by initial water droplet mass. The results show good agreement between the two measurement method at V_i = 0.5 and 1.0 m/s. The absorption phase where the absorbed mass increase and the evaporation phase where the mass decreases can clearly be distinguished. The dash line presents the 0.5 slope as predicted by the Washburn equation. It is shown again that the absorption process of impinging droplet is not unidimensinoal from an infinite water source, but 3-dimensionally into the porous media.

Figure 4 illustrates the fate of a droplet after impact on a porous media for different time scales. At short time after drop impact, the droplet spreads over porous media [3]. The liquid-solid contact diameter then gets pinned at maximum during absorption [4]. Once the water-porous media contact is established, absorption of the liquid within the porous media is initiated. The water mass absorbed increases until the droplet is depleted. Once the droplet is depleted, water evaporation at the surface and further redistribution of moisture within the porous media are observed.

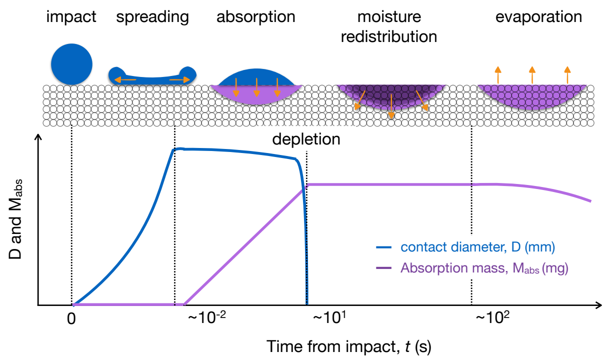

Fig. 4. Schematic representation of the fate of a droplet after impact on a porous media over different time scale: spreading, absorption, drop depletion, moisture redistribution and evaporation. Graphical representation of time evolution of droplet contact diameter D and absorbed mass in the porous media M_{abs}.

3. Conclusions

This paper presents an experimental investigation of the absorption of liquid droplets impacting on porous media. High-speed imaging and neutron radiography are used to quantify moisture absorption. The life of a droplet after impact on porous media continues over different time scales and is summarized. The results of this study are relevant for applications where mass transfer between the impacting droplet and the porous media has to be understood.

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