Experimental report

29/07/2024

Proposal: **1-07-12**

Council: 10/2022

Title: Quantitative measurement of water vapor condensation in homogeneous and heterogeneous porous media

Research area: Engineering

This proposal is a new proposal

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Samples: porous samples

Instrument	Requested days	Allocated days	From	To
NEXT	4	3	18/06/2023 06/09/2023	19/06/2023 08/09/2023

Abstract:

The focus of this study is to measure and analyze the complex condensation process of vapor in cracked heterogeneous porous media, in-situ, using quantitative time-resolved neutron tomography. The experiment is performed by injecting well-characterized vapor at pre-established flow rates into porous samples with a known macroscopic heterogeneity (cracks and fracture network) superposed to the inherent heterogeneities (such as grains, pores, and capillary network). Based on the results from previous campaigns at ILL, we will improve the quantitative accuracy of the vapor content. This will be achieved by adopting several calibration methods to extract the precise density field of water saturation as well as improvements on the previous experiment setup. The evolution of the 3D saturation fields obtained by the in-situ neutron imaging accompanied by the microstructural characterization of the sample obtained by X-ray tomography will be used to highlight the contribution of the mechanisms that affects the propagation of water accumulation in the specimen, and to calibrate physical parameters of an already developed multi-phase multi-component numerical flow model.

Numerical modeling of vapor condensation in fractured porous media based on *in-situ* rapid neutron tomography

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This study focuses on phase change phenomena in porous media with two-phase flow, a domain often underexplored due to the intricate coupling of heat and mass transfer and medium heterogeneity. However, understanding condensation in porous media is vital for various applications like concrete durability, geothermal energy and oil recovery, soil remediation, CO_2 storage, to name a few. We employed rapid neutron tomography during vapor injection experiments and introduced a novel numerical approach for this aim.

The experiments consist of 3D rapid neutron imaging, facilitated by neutron beam at Institute Laue Langevin Grenoble (ILL) using the imaging instrument NeXT (Neutron and X-ray Tomograph). Additional X-ray and synchrotron microtomography provide further insights into sample microstructure and crack morphology, which significantly influences water accumulation and migration. The experiments were preceded by a calibration and correction campaign where the quantification of water content was fitted to empirical correlation and the spurious deviations arising from the scattering of neutrons are accounted for.

In the calibration experiments, we attempted to identify the deviations from ideal conditions, such as scattering contributions that affect the accuracy of water concentration measurements. Consequently, the direct application of the Beer-Lambert law is limited, especially for samples with significant scattering components, necessitating correction methods. The black-body (BB) grid correction method [1] is evaluated and found to be highly effective. This method corrects for scattering contributions by using an ordered array of black bodies to measure and compensate for biases, proving effective even for transmissions below 1% [2]. The experimental setup and configuration for BB correction are shown in Figure 1, and the improvements compared to non-corrected measurement from a wedge thickness phantom are depicted in Figure 2

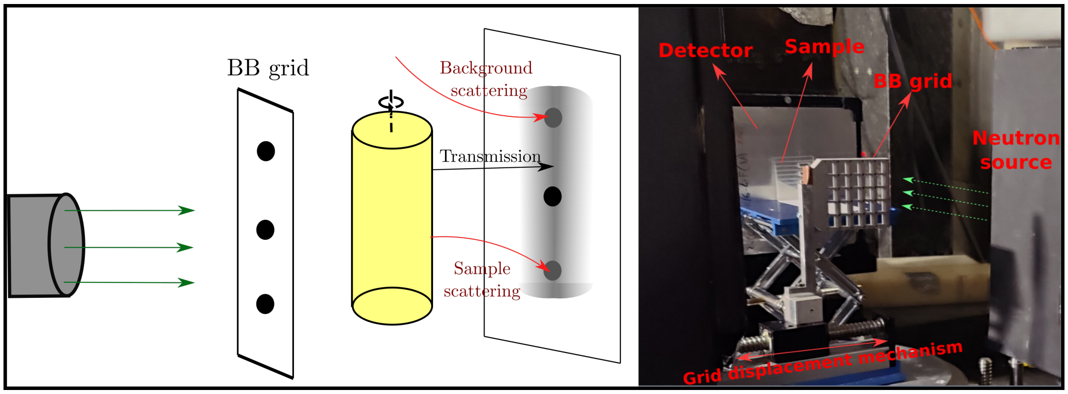

Figure 1: The experimental setup and configuration for BB correction

In the vapor injection experiments [3,4], the measurements were conducted using rapid in situ neutron tomography, capturing time-resolved images every 30 seconds. This non-destructive imaging technique allowed for detailed visualization and quantification of water within the samples using the performed calibration experiments. The vapor was injected using a controlled vapor injection system, ensuring consistent conditions across experiments. The samples were collected from Fontainebleau sandstone, some of which were artificially

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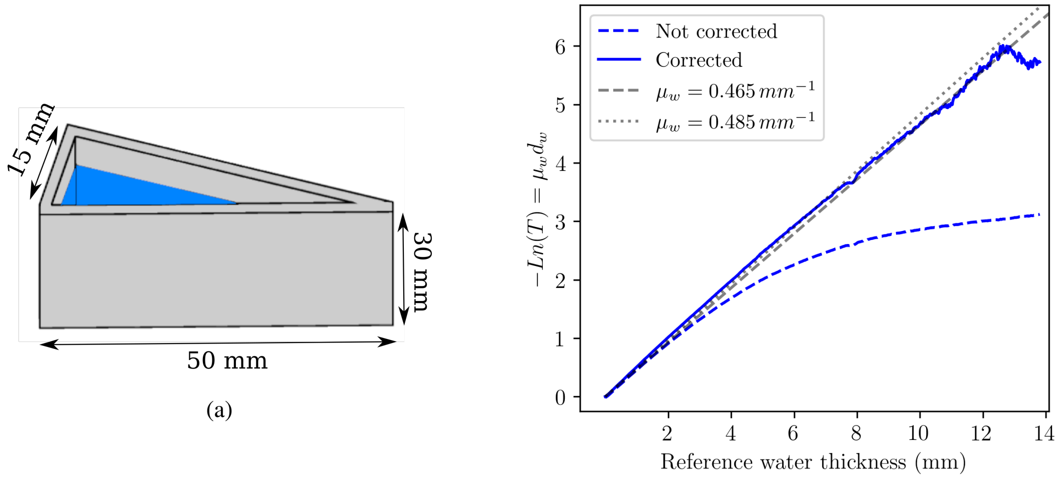

(a)

(b)

Figure 2: Logarithm of the transmission as a function of reference water thickness for the water in the wedge thickness phantom without and with BB correction. The grey dotted lines correspond to linear attenuation coefficients based on the Beer-Lambert law for the whole spectrum and spectrum peak.

cracked to simulate natural fractures. The experimental setup and an example of the condensed water field inside the samples are shown in Figure 3.

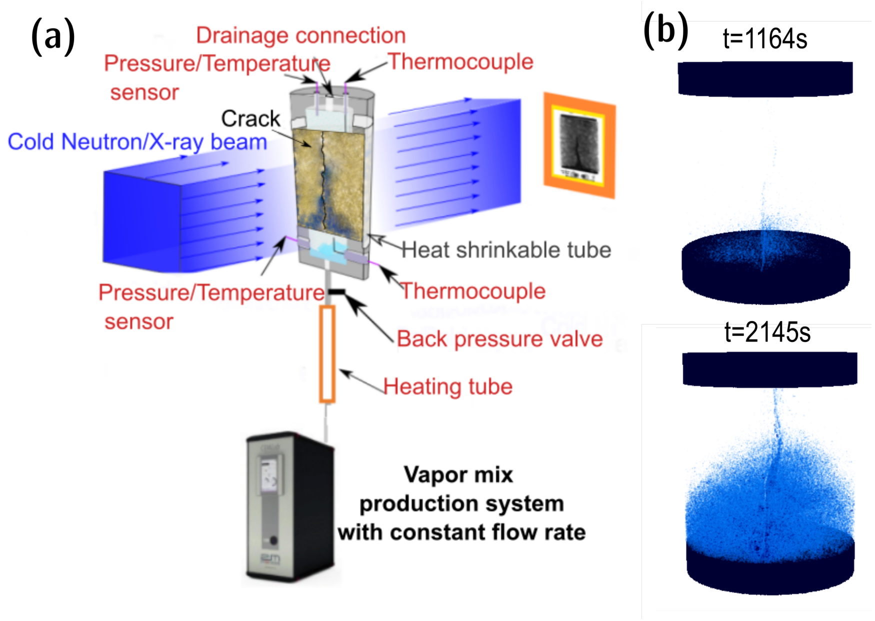

Figure 3: (a) vapor injection experimental setup at ILL, (b) 3D field of condensed water at two times during injection

The use of neutron tomography proved to be a valuable tool in capturing the complex dynamics of condensation and water migration, offering insights for future research and practical applications. The measurement of water content was found to be reliable when compared to the boundary condition in terms of total water content in the samples. As seen from Figure 4, the presence of cracks significantly influences the condensation process by providing preferential pathways for vapor migration and initial condensation sites. In cracked samples, condensation begins within the crack, leading to higher overall water content in the matrix due to pressure buildup and subsequent capillary action. Matrix porosity affects the distribution and accumulation of condensed water. Lower porosity samples exhibit quicker water saturation and higher water content within the crack due to limited absorption capacity of the matrix, whereas higher porosity samples demonstrate a more gradual and widespread water distribution, indicating greater water absorption capacity. Increasing the vapor flow rate results in higher water condensation and faster propagation of the wetting front. Higher flow rates cause higher pressure buildup, which pushes the condensed water further, leading to a broader spread but lower local water content compared to lower flow rates.

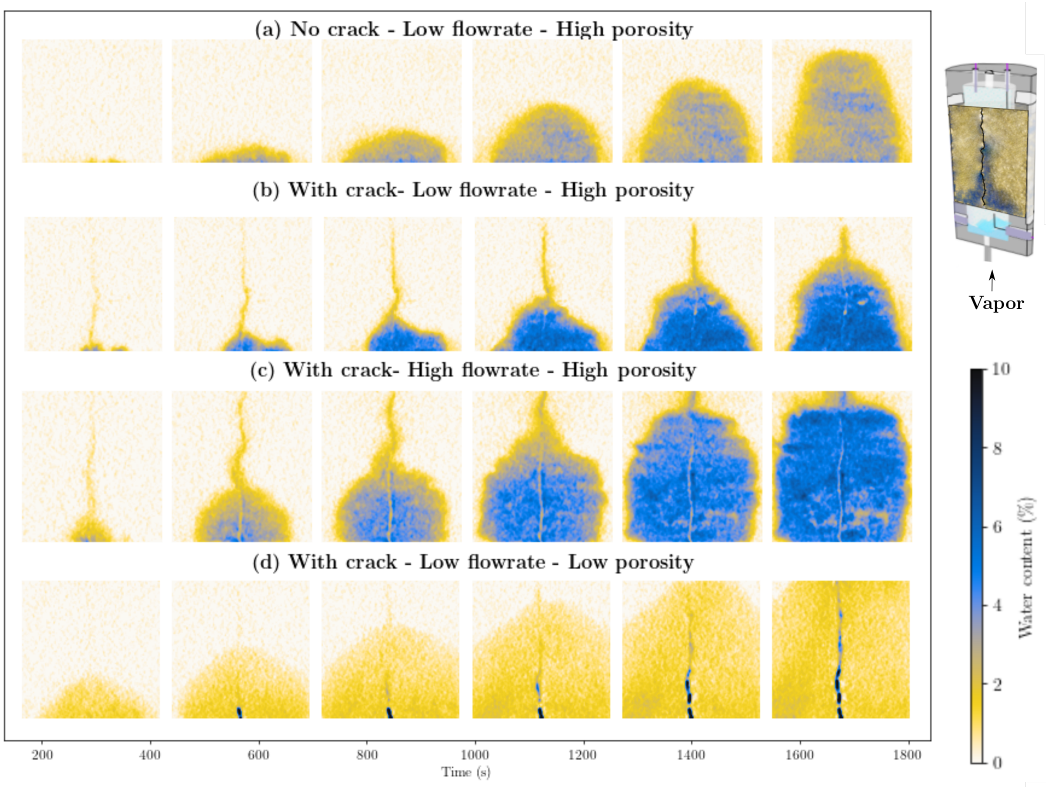

Figure 4: Effects of fracture, porosity, and flow rate revealed by neutron imaging

References

[1] Boillat, P., et al. (2018). ”Chasing quantitative biases in neutron imaging with scintillator-camera detectors: a practical method with black body grids” Optics Express, 26, 15769.

[2] Nemati, A., et al. (2024). ”Towards in-situ water quantification via neutron imaging: insights from NeXT-Grenoble.” Measurement Science and Technology, 35, 075405.

[3] Gupta, R., et al. (2022). ‘Experimental characterisation of transient condensed water vapour migration through cracked concrete as revealed by neutron and x-ray imaging: Effect of initial saturation’. Cement and Concrete Research 162 106987.

[4] Nemati, A., et al. (2024). ”Rapid In Situ Neutron Tomography and X-ray Imaging of Vapor Condensation in Fractured Sandstone.” Transport Porous Media, 150 327–57.