Applied Radiation and Isotopes 105 (2015) 150–157

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

A method for moisture measurement in porous media based on epithermal neutron scattering

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HIGHLIGHTS

- A new method based on neutron scattering was developed to study liquid transport in porous media.
- An assembly of a Pu–Be neutron source and an array of 4 or 6 He-3 neutron detectors was used.
- Fast as well as slow flow processes in porous media can be investigated.
- Water absorption into clay and silicate bricks, and sand column were carried out.
- The results were discussed in terms of the diffusion theory.

ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form
6 August 2015
Accepted 12 August 2015
Available online 13 August 2015

Keywords:
Neutron scattering
Sand
Bricks
Water absorption
Diffusion

ABSTRACT

A method for moisture measurement in porous media was proposed. A wide beam of epithermal neutrons was obtained from a Pu–Be neutron source immersed in a cylinder made of paraffin wax. ^{3}He detectors (four or six) arranged in the backward direction of the incident beam were used to record scattered neutrons from investigated samples. Experiments of water absorption into clay and silicate bricks, and a sand column were investigated by neutron scattering. While the samples were absorbing water, scattered neutrons were recorded from fixed positions along the water flow direction. It was observed that, at these positions scattered neutrons increase as the water uptake increases. Obtained results are discussed in terms of the theory of macroscopic flow in porous media. It was shown that, the water absorption processes were Fickian and non Fickian in the sand column and brick samples, respectively. The advantages of applying the proposed method to study fast as well as slow flow processes in porous media are discussed.

1. Introduction

Moisture transport in porous media specially building structures is an important issue. Lifetime of building structures is shortened due to the wetting–drying cycle. It is important to develop a suitable non-destructive method to document this issue. Methods based on radiation attenuation (neutron, γ-rays and X-rays), radiography (Roels and Carmeliet, 2006; Pires et al., 2014; Costa et al., 2013; Perfect et al., 2014; Dewanckele et al., 2014; Schröfl et al., 2015; Kang et al., 2013; El Abd and Milczarek, 2004; El Abd et al., 2009) and Nuclear Magnetic Resonance (NMR) (Marica et al., 2011; Koptyug, 2012) are often used. Gamma ray scattering studies are used in medical, agricultural, industrial and archeological fields (Harding and Harding, 2010; Hussein and Waller, 1998; Stokes et al., 1982; Holt et al., 1984; Cesareo et al., 1992). In addition, they have been used for determining water content in soil and building materials (Cruvinel and Balogun, 2006; Bucurescu and Bucurescu, 2011; Shivaramu et al., 2002; Raghunath et al., 1983; Priyada et al., 2014).

Neutron back scattering (NS) is an effective method for investigation of materials containing elements having high scattering cross-sections such as hydrogen and carbon. The method is based on irradiating samples under investigation with neutrons. Usually, the incident neutrons have different energies. Namely, they are characterized with a spectrum of fractions of thermal, epithermal and fast neutrons. Thermal neutrons are reflected by the scattering elements in the sample. While epithermal and fast neutrons – shortly epithermal neutrons – are moderated "neutrons lose energy by the scattering nuclei in the sample" and become thermal after a number of collisions. These neutrons (reflected and moderated) can be detected by a proper thermal-neutron detector such as ^{3}He detector. Methods based on neutron scattering are widely

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http://dx.doi.org/10.1016/j.apradiso.2015.08.013
0969-8043/

used in some applications. These were surveyed in (El Abd et al., 2012, 2013).

The traditional method of neutron scattering for investigating water uptake (absorption) by a porous sample can be described as follow: a sample absorbing water is irradiated by an incident fine beam of neutrons. Scattered neutrons from different wetted regions (obtained by scanning the sample) are recorded by ^{3}He or BF-3 neutron detector. This work was carried out in (El Abd et al., 2012). If water flow is slow through the investigated sample, scanning the sample is not a problem. However, it takes a long time that makes the investigation process tedious. In addition, if the absorption process is fast such as in soil and sand columns, scanning the sample will be impractical and no reliable and accurate data can be obtained.

Unsaturated water flow in porous media is a process occurring as a function of space and time. According to the author's knowledge, NS is rarely used in studies of water content determination in unsaturated flow in porous media.

The aim of the present work was the development of a method to determine water content distribution in unsaturated flow in porous media based on epithermal neutron scattering. A wide epithermal neutron beam was obtained from a Pu–Be neutron source. An array of slow neutron detectors was used to record scattered neutrons instead of using a single detector. The method was used to study slow as well as fast liquid transport in porous media. Water content distribution in the unsaturated flow regime was determined dynamically "as a function of space and time".

2. Theoretical background

Moisture (water) transport in unsaturated porous media is commonly described at the macroscopic scale by the macroscopic theory of flow in porous media (diffusion theory). The theory is based on Fick's law (Darcy's law) of diffusion. It can be written in one dimension (Philip, 1969; Hall, 1977), x (neglecting gravity) as

$$q(\theta) = -D(\theta)\frac{\partial\theta}{\partial x}, \tag{1}$$

where $q(\theta)$ is the water flux (a function of the water content, θ) and $D(\theta)$ is the water content dependent diffusivity. By combining Eq. (1) with the continuity equation, $\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial x}$, where t is the time, the moisture transport in unsaturated porous media can be described by the non-linear partial differential diffusion (Philip, 1969; Hall, 1977):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}(D(\theta)\frac{\partial\theta}{\partial x}), \tag{2}$$

Eq. (2) can be transformed to an ordinary differential equation using the Boltzmann variable, $\varphi = \frac{x}{\sqrt{t}}$ and the water diffusivity can be derived from it using the well-known boundary conditions and it is given by

$$D(\theta) = -\frac{1}{2}\frac{d\varphi}{d\theta}\int_0^{\theta}\varphi\, d\theta, \tag{3}$$

According to Fick's hypothesis as well as the Boltzmann transformation, all points along the flow direction x at the same water content, scale with $\sqrt{t}$. This means that the $(\theta - \varphi)$ profiles should be a single master curve.

Anomalous diffusion is used to account for the deviation from $t^{1/2}$-scalling (Kuntz and Lavalle´, 2001; Lockington and Parlange, 2003; Aarão Reis and di Caprio, 2014; Kumar and Roy, 2015; Ninghu, 2014; Sun et al., 2014; Deseri and Zingales, 2015; Alaimo and Zingales, 2015; Babak and Azaiez, 2014; Moghaddam et al., 2015; Straka and Fedotov, 2015). In anomalous diffusion, it was assumed that the water flux, q can be given by:

$$q(\theta) = -D(\theta)\left|\frac{\partial\theta}{\partial x}\right|^{\alpha}, \tag{4}$$

where α is a real number (α=1 corresponds to the Darcy or Fick's law). Combining (4) with the continuity equation, one gets a non-linear diffusion equation which is given by

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}(D(\theta)\left|\frac{\partial\theta}{\partial x}\right|^{\alpha}) \tag{5}$$

Assuming that θ depends on the single variable γ (Generalized Boltzmann variable) given by

$$\gamma = X/t^{n} \tag{6}$$

This assumption is reasonable at least when the water front position x_m is proportional to the imbibition time, t to the power n (with the index n being a real number). One finally obtains the following form of the diffusivity

$$D(\theta) = -nt^{(1+\alpha)n-1}\left|\frac{d\gamma}{d\theta}\right|^{\alpha}\int_0^{\theta}\varphi\, d\theta \tag{7}$$

Two special cases discussed in the literature are: (1) (Kuntz and Lavalle´, 2001) assuming $\alpha = 1/n - 1$ to get rid of the time variable in the diffusivity (Eq. (7)) to obtain the anomalous diffusivity $D_a(\theta)$, which is only a function of the water content θ

$$D_a(\theta) = -\frac{1}{1+\alpha}\left|\frac{d\gamma}{d\theta}\right|\int_0^{\theta}\varphi\, d\theta, \tag{8}$$

and (2) the Darcy (Fick) case (Lockington and Parlange, 2003), corresponding to α=1

$$D(\theta) = -nt^{2n-1}\left|\frac{d\gamma}{d\theta}\right|^{\alpha}\int_0^{\theta}\varphi\, d\theta \tag{9}$$

3. Experimental arrangements

The experimental set-up used in this work is shown in Fig. 1. It consists of cylinder made of pure paraffin wax (40 cm diameter and 50 cm length). Along the central axis of the paraffin wax, there is an empty polyethylene tube (5 cm diameter and 46 cm length). A Pu–Be neutron source (1Ci) was inserted in the paraffin cylinder through the central tube, such that a wax layer of 4 cm thick is in front of the source – exit face of neutrons. After inserting the source, the tube is blocked by a rod made of paraffin wax. The paraffin wax, surrounding the source from all sides, moderates and reflects fast neutrons emitted from the neutron source. The paraffin cylinder was surrounded by blocks of graphite ($17 \times 17 \times 50$ cm^3) from all sides except the exit face of neutrons – left side in Fig. 1. Graphite (a reflector) minimizes fast neutrons leakage. It was further surrounded by blocks made of borated paraffin wax. The borated paraffin wax minimizes thermal neutron leakage. The irradiation system (the paraffin wax cylinder, graphite and borated paraffin wax) was fixed on a wooden table (1.5 m height above the ground). In addition, sheets of Cd were used to cover the irradiation system including the exit face of neutrons. It (Cd) prevents the leakage of thermal neutrons specially from the exit face of neutrons, such that energies of outgoing neutrons were above the Cd-cut off energy of 0.55 eV. Additionally, the incident neutrons were in the form of a wide beam that irradiated a large area of the samples investigated.

Four ^{3}He neutron detectors (LND-252172) – the detector array – were used to record scattered neutrons from samples investigated. These detectors were wrapped (shielded) with Cd