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Experimental determination of moisture distributions in fired clay brick using a ^{252}Cf source: A neutron transmission study

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HIGHLIGHTS

- ▸ A neutron transmission method was proposed to study liquid transport in porous media.
- ▸ It was used to study water diffusion in two kinds of fired clay bricks.
- ▸ The diffusivities and capillary coefficients were determined.

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ABSTRACT

A neutron transmission method was proposed to study liquid transport in porous media. It was applied to study water penetration into two kinds of fired clay bricks. The results showed that the diffusion processes in the investigated samples are different. Water diffusivities and capillary absorption coefficients characterizing both the flow process and the brick samples were determined and compared. The proposed method is simple, accurate and reliable in studying water diffusion in porous media, in real time.

1. Introduction

Nuclear techniques using a variety of sources such as alpha, beta, gamma, neutron or X-ray radiations are widely used in industry to improve the quality of their intermediate and final products. They are superior in some respects to conventional process monitoring techniques (International Atomic Energy Agency, 2005). Since neutrons have a high scattering cross-section for light nuclides, nucleonic techniques are suitable non-destructive methods to detect hydrogen and/or hydrogen containing materials. This can be achieved by neutron moderations (scattering) and transmission. In neutron moderation methods, incident fast neutrons on a sample containing hydrogenous material such as moisture are moderated (scattered) by the hydrogen atoms (i.e., fast neutrons are thermalized). A suitable neutron detector can be used to count the thermally-scattered neutrons. Spectra and/or neutron counts collected by the neutron detector carry information about moisture (hydrogen) content and distribution in the sample investigated: The higher the moisture content, the higher the count rate of scattered neutrons. The neutron scattering methods has been used by a number of authors in various application see El Abd et al. (2012) and the references cited in. Contrary to the neutron scattering, the neutron transmission method is by far the most widely used technique in radiation applications, because of its simplicity and ease of interpretation. Common neutron radiography and tomography techniques are based on the concept of neutron transmission (El-Abd 2004, El Abd and Milczarek, 2004; El-Abd et al., 2009; Domanus,1992; De Beer et al., 2004; Zhang et al., 2011; Joos et al., 2010). They are based on attenuation of neutrons. Neutrons are attenuated by elements having high absorption and/or scattering cross-sections. Namely, both absorption and scattering of neutrons are removal processes. Thus, an incident neutron beam on a sample containing hydrogen and/or hydrogenous material is mainly attenuated by hydrogen via scattering. The outgoing beam (direct transmitted) can be recorded using a suitable neutron detector. The recorded spectra carry information about moisture distribution in the sample investigated. The higher the hydrogen content, the lower the count rate of the direct transmitted neutrons.

Fantidis and Nicolaou (2011) used fast neutron and dual gamma-rays transmissions for the detection of illicit materials. Cywicka-Jakiel (2003) and Cywicka-Jakiel et al. (2003) optimized

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Nomenclature

I_0	The initial intensity of the incident, well-collimated neutron beam
I_{dry}	The intensity of the neutron beam after passing a dry porous
d	The sample of thickness
μ_m	The linear attenuation coefficient of the porous sample (units cm^{-1})
μ_w	The linear attenuation coefficient of water (units cm^{-1})
d_w	The effective distance the neutrons have interacted with water
θ	The water content ($\theta = d_w/d$)
x	Moisture or water flow direction
x_m	Water front position: maximum distance water moved along flow direction x
t	Absorption time
ϕ	Boltzmann variable ($\phi = x/ t^{1/2}$)
ϕ_m	Boltzmann variable at x_m ($\phi_m = x_m/t^{1/2}$)
$D(\theta)$	Moisture diffusivity
q	Average macroscopic flow velocity of moisture
θ_i	Initial water content of the porous material (for initially dry material $\theta_i \approx 0$)
θ_s	The saturation water content
$\theta(x,t)$	Water content distribution along flow direction x as a function of time (water profiles)
ΔW	Absorbed amount of water in a single capillary
B	Coefficient of capillary suction
ψ	Water capacity of the absorbing material
r_{eff}	The effective radius representing the pore size distribution of a given material
α	Contact angle
η	Dynamic viscosity
γ	Surface tension
ρ	Density of the absorbed liquid
k	Capillary penetration coefficient

and used fast neutron and gamma-ray transmission set-up for the humidity measurement of coke. The optimization focused on maximizing the sensitivity of the neutron flux to humidity changes and on lowering neutron-counting error, both leading to higher accuracy of coke moisture determination. They obtained a good agreement between the moisture content determined from the transmission measurements and the moisture determined from an oven-drying method. Bartle (1999) compared the response of neutron/gamma transmission (Neugat) method with the gamma/gamma transmission (Gamgat) method for characterizing the wool yield of raw wool. Murray Bartle (1996) measured the composition of some liquid mixtures using the simultaneous transmission of neutrons and gamma-rays (Neugat) method. Abdelmonem et al. (2007) have carried out some Monte Carlo simulation to compare the performance transmission from ^{241}Am–Be and 2.8 MeV neutron sources for moisture measurement. It was shown that the 2.8 MeV neutron based moisture measurement setup has a better sensitivity than the ^{241}Am–Be source. Gokhale and Hussein (1997) used a ^{252}Cf neutron transmission technique for bulk detection of explosives. Nordlund et al. (2001) investigated water content in geological samples using transmission of 14 MeV fast neutrons. Granada et al. (1995) used neutron transmission over thermal and sub-thermal energy ranges to determine low hydrogen content in metals. Akaho et al. (2002) used neutron transmission and reflection techniques for the classification of crude oil samples. Sowerby (1989) introduced a method to determine moisture content in substances using sources of fast neutrons and gamma rays. It was shown that fast neutrons transmissions from the samples under investigation are slowed down by a suitable moderator then detected by thermal neutron detector. Neutron gauges based on the moderation have been attractive for the process monitoring of the moisture content in uranium or plutonium dioxide powder used in a nuclear fuel production and in coke used in a blast furnace or a sinter plant for heating and reduction of iron ore (Bulanenko and Frolov, 2003; Bulanenko et al., 2003). The neutron gauges are sometimes used as the reference method in certain area of industry such as soil moisture measurement in agricultural water management (Vicente et al., 2003).

Liquid (moisture) transport and content in building materials is an important topic since deterioration processes in buildings are attributed to the presence of moisture. Salt crystallization may occur due to changes in moisture levels leading to visual damage such as discoloration and/or mechanical damage (Pel et al., 2001, 2003). Additionally, when materials are moist for longer periods growth of micro-organisms, like algae and/or fungi, is often observed (Adan, 1994). Thus, adequate and accurate determination of moisture or humidity conditions is needed.

Transient moisture content profiles can be determined by scanning the sample that contains water via neutron transmission. The intensity I_{dry} of a well-collimated neutron beam after passing a dry porous sample of thickness d is

$$I_{dry} = I_0 \exp(-\mu_m d), \quad (1)$$

and for a sample containing an amount of water or a hydrogenous material, it is

$$I_{wet} = I_0 \exp(-\mu_m d - \mu_w d_w), \quad (2)$$

where I_0 is the initial intensity of the neutron beam, μ_m and μ_w are the linear attenuation coefficients (units cm^{-1}) of the dry porous medium and water (hydrogenous material), respectively; and d and d_w are the sample thickness and the effective distance the neutrons have interacted with water, respectively. From both equations one gets:

$$(1/\mu_w d)\ln(I_{dry}/I_{wet}) = \theta, \quad (3)$$

where $\theta = d_w/d$ is the water content. Since μ_w, is a constant, the water content, θ is proportional with $\ln(I_{dry}/I_{wet})$, namely $\ln(I_{dry}/I_{wet})$ is the water content in arbitrary unites for the scanned position in the sample investigated. It is important to include the sample thickness (d) in case of comparing water contents for samples having different thickness. Thus, $\theta = (1/d)\ln(I_{dry}/I_{wet})$ expresses water contents in units of cm^{-1}.

To the best knowledge of authors, the surveyed methods above except radiography methods are mainly static. Namely they are not used – or rarely used – to study dynamical processes such as moisture transport in porous media. Reliable and accurate results on moisture transport in porous media are rare. In addition, they are not enough in literature to formulate a general theory describing transport in porous media. This can be due to the unavailability and/or the high cost of some well-known methods such as radiography.

Thus, a simple, cheap, portable and dynamical method providing accurate results on moisture transport in porous media in real time is highly needed.