NEUTRON RADIOGRAPHY APPLICATIONS IN STUDIES OF DRYING OF CAPILLARY-POREUS SYSTEMS

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Abstract: The application of modern digital neutron radiography in studies of drying processes is demonstrated with two simple examples of cylindrical and rectangular samples made of different materials. The method of revealing the existence of receding drying front from neutron radiographs analysis is shown.

Keywords: neutron radiography, drying phases, receding drying front

INTRODUCTION

Recent application of modern neutron radiography (NR) (Neutron Imaging and Applications 2009; Strobl et al. 2009) in the observations of drying processes of capillary-porous media has created new possibilities of experimental studies. In particular, the drying front and its motion across the sample volume have been visualized and quantified (Shokri et al. 2008, Fijal-Kirejczyk et al 2009, Fijal-Kirejczyk et al. 2011) from the recorded sequences of neutron radiographs. In our previous work (Fijal-Kirejczyk et al. 2011) we have developed the method of analysis based on the study of variations in statistical properties of the registered images of cylindrical samples during drying. The aim of present work was the clear identification of the main phases of drying of capillary-porous samples of different shapes.

The merit of neutron imaging in revealing the presence of water in porous media consists in very strong interaction of thermal neutrons with hydrogen which removes neutrons from the incident beam producing dark regions in the images of water containing samples. Due to small attenuation of neutrons by most materials, the NR provides the possibility of revealing the spatial distribution of water in the sample body (Hassenein et al. 2006, Fijal-Kirejczyk et al. 2009). The NGRS comprises the neutron beam collimators, fluorescent screen, mirror, optical zoom lenses and the high sensitivity CCD camera. The exposure time was 1.6 s. The samples were placed inside a vertical drying tunnel at the distance of ~65 mm from the converter screen. The image analysis was performed with the LUCIA™ 4.60 and ImageJ 1.43u software packages. Before image analysis preprocessing procedures including the correction of pixel brightness for the black current, normalization for neutron beam flux fluctuations as well as the median filtering was applied.

The experiments were performed on cylindrical and rectangular samples prepared from quartz sand and aged mortar, respectively. The cylindrical samples of 27 mm diameter and ~30 mm height were produced by extrusion and immediately placed inside a vertical dryer tunnel at the neutron radiography station. The rectangular samples of 52 mm × 48 mm × 14 mm were made of aged mortar and saturated with water by immersion for 24 hours. The samples were placed on an aluminium support with its lower end attached to electronic balance. The sample support incorporated the K-type steel sheathed thermocouple of 0.5 mm diameter. The thermocouple penetrated the sample vertically from its lower end to the middle. The drying air at temperature of ~60ºC was forced to flow from above at the rate of 0.03 m³s⁻¹. The drying was observed by on-line registration of the sample mass, temperature and sequences of neutron radiographs. The temperature and mass measurements were recorded every 10 s and the neutron radiographs every 2 s.

EXPERIMENT

Experiments were carried out with the NGRS station, at the nuclear research reactor MAREA of IAE (Fijal-Kirejczyk et al 2009, Fijal-Kirejczyk et al. 2011).
EXPERIMENTAL RESULTS

As expected, the variation of the sample’s mass starts from almost linear decrease during the first (constant rate) drying period. (Fig. 1). The sample temperature during that period levelled off at ~32°C after fast initial increase from the room temperature (Fig. 2). At the end of that period the water content was less than 10% of mass. The changes in the sample mass were negligible after ~5000 s of the process (Fig. 1). The second fast increase of the sample temperature to ~50°C was observed close to 3500 s and afterwards the temperature stayed steady for the next ~1200 s until 5000 s of the process have passed. Then the temperature increased to ~58°C, close to the drying air temperature.

The rate of drying for rectangular mortar sample is smaller than that for cylindrical sample (Fig. 3). The constant rate period for the mortar sample is hardly visible and the variation of temperature inside the sample does not show the clear evidence of different periods of drying (Fig. 4).

**IMAGE ANALYSIS**

Despite the qualitative differences in mass and temperature variations of the samples we found the receding drying front visible for both cases. However, it is rather difficult to visualize it in printed pictures of neutron radiographs. In order to demonstrate this assertion we treat the digital images as sets of data relating values of brightness $b$ to each pixel of the sample image. One can build a histogram function $H(b)$ by counting the number of pixels with given brightness value. With determined histograms the moments of brightness are calculated

$$\langle b^n \rangle = \int b^n H(b) db$$

$$\int H(b) db$$

(1)

The average brightness $\langle b \rangle$ and brightness standard deviation $\Delta$, defined as:

$$\Delta = \left( \langle b^2 \rangle - \langle b \rangle^2 \right)^{1/2}$$

(2)

carry most of the information on the processes developing inside the sample. The increase in image average brightness is due to the decreasing amount of water contained in dried sample. This behavior is discernible in the plots of average brightness vs time (Fig. 5 and 6).

The receding drying front is a surface boundary of a wet region in the sample’s volume. This region contains the amount of water detectable by neutrons and is visible as a darker region in the image. The emergence of this pattern increases considerably the standard deviation of brightness. Further on the receding front disappears leaving more or less uniform image. In effect the maximum is observed in time dependence of the standard deviation of image brightness (Fig. 7 and 8). The two maxima observed
in the case of cylindrical geometry (Fig.7) are due to variable path of neutrons penetrating the sample.

![Graph showing time dependence of average brightness for quartz sand cylinder](image)

**Fig. 5.** Time dependence of the average brightness of the quartz sand sample neutron radiographs.

![Graph showing time dependence of average brightness for mortar](image)

**Fig. 6.** Time dependence of the average brightness of the mortar sample neutron radiographs.

![Graph showing time dependence of standard deviation of brightness for quartz sand cylinder](image)

**Fig. 7.** Time dependence of the standard deviation of brightness for the quartz sand cylinder sample neutron radiographs.

![Graph showing time dependence of standard deviation of brightness for mortar](image)

**Fig. 8.** Time dependence of the standard deviation of brightness for the mortar sample neutron radiographs.

**CONCLUSIONS**

We have shown the results of studies on drying of simple objects of two different capillary-porous materials with neutron radiography. The results of neutron image analysis prove to be useful in observations of subtle effects like receding drying front occurrence.

**NOMENCLATURE**

- $b$ pixel brightness
- $t$ time s
- $m_w$ mass of water in the sample g
- $T$ temperature °C

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**REFERENCES**