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Neutron imaging of textile fibers

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1. Introduction

Tencel Lyocell fibers are used in duvets. The basic requirement of a quilt is thermal insulation. During sleep the human body perspires, therefore moisture management of the duvet is essential for a comfortable sleep. The release of humidity has to be accommodated by the quilt. Hence moisture absorption and humidity transport are very important when designing a coverlet [1, 2].

Neutron imaging is suitable for studying moisture transport processes due to the sensitivity of neutrons for hydrogen [3]. Neutron radiography was used to investigate the moisture distribution in textile fibers under praxis conditions. Real time neutron radiography made it possible to follow the dynamics of the moisture transport without disturbing the ensemble during measurement.

2. Experiments and Results

The experiments were performed at the NR II station at the Atomic Institute. Here we have a collimated thermal beam having a neutron flux of 1.3×10^5 $cm^{-2}s^{-1}$. Digitized neutron imaging with a high dynamic range of 16 bits can be performed. Different detectors may be used. Li based scintillator in combination with a CCD camera, 200 μm resolution and an imaging plate detector, 50 μm resolution. These detectors due to their characteristics have specific applications [4].

At the Atomic Institute we have a long tradition of neutron radiography. Moisture transport is one of the interesting topics we have been working on [5, 6, 7].

2.1 Dynamic neutron radiography

Dynamic neutron radiography or real time neutron radiography means that images can be made continuously after a fixed time interval depending on the exposure time chosen. So the process can be followed in real time without any disturbance to the experimental arrangement.

A humidifier was used to provide moisture at a controlled temperature. On the humidifier, an aluminium box with a partition in the centre was placed. Non-woven fiber samples were placed in the two compartments of the box. Two layers of non-woven were used as half of the first layer could not be seen, it was hidden behind the wall of the humidifier.

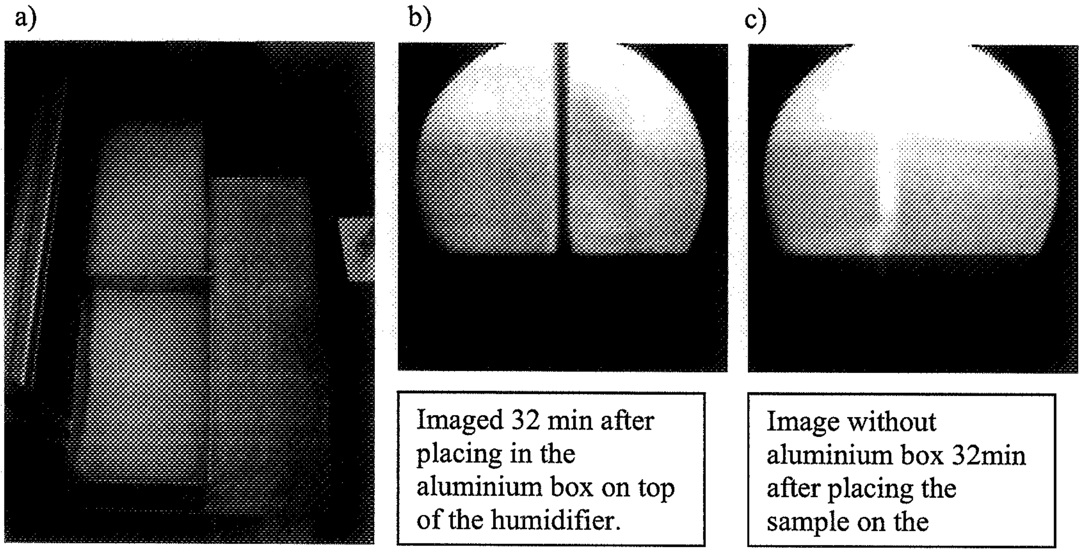


Fig 1: (a) The experimental arrangement showing the aluminium box placed close to the scintillator. (b) NR of the fiber samples inside the aluminium box. (c) NR of the fiber samples without the box. On the lower side the dark region shows the wall of the humidifier.

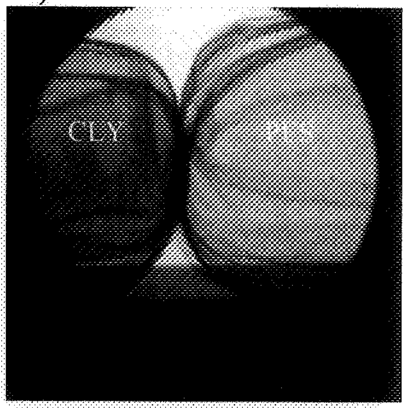
In the middle of the Al-box, there was a double wall of about 6mm thickness. This Al-layer is visible to neutrons and the area covered in the image is quite large. So the experiment was then performed without aluminium box.

2.2 Experiments of fibers enclosed in pillows

The fibers were enclosed in stitched pillow bags, to simulate real conditions and to avoid evaporation. Aluminium wires were placed on the humidifier walls at a height of about 1.5cm in order to see the bottom of the fibers. The purpose was to raise the samples so that the lower part was not hidden behind the walls. The fibers were then placed on top of the wires.

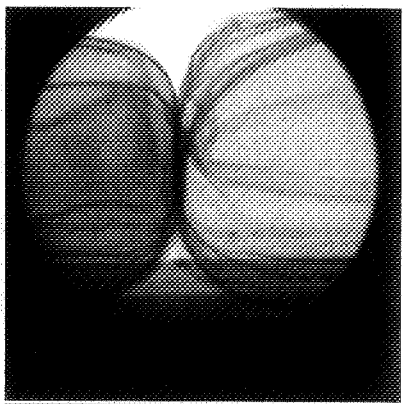
a)

b)



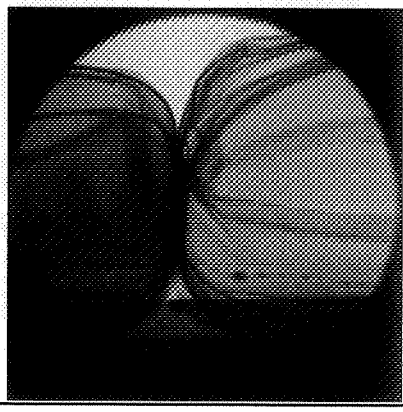
Room temperature, after 53s, first image of the time series.

c)



50°C temperature, after 80min, image number 90 of the time series.

d)



NR with imaging plate detector after two and a half hours. Exposed for 10 min at a temperature of 50°C

Fig 2: a) the experimental arrangement showing the fiber samples in pillows. b) NR showing lyocell on one side and polyester on the other side. c) NR showing condensation along the wires after 80min. d) a high resolution NR made with the neutron imaging detector. CLY represents Lyocell and PES stands for polyester.

These were placed on the humidifier at room temperature of 24°C. A few images were made in these conditions. Then the thermostat was switched to a temperature of 35°C. A series of 90 images was started at room temperature. The temperature became stable at 35°C in about 15 minutes and was maintained for half an hour. After that the temperature was increased to 50°C (which took about 15 min). Again this temperature was maintained for half an hour. During all this time, images were taken at an interval of 53 seconds (the exposure time being 40s with a grabbing time of about 13s).

A time series of neutron radiographs was made with the scintillator and CCD camera. The exposure time for each image was 40s. Then an image was made with the imaging plate detector. The exposure time for the imaging plate detector can be between 10min and 50min. An exposure of 50 minutes yields maximum hydrogen sensitivity and 16 bit image gradation. After exposure, time is required for scanning and erasing the plate before it can be reused. So the repetition interval between two such images would be about one hour.

No considerable difference in the water content in the fibers could be observed. Maybe this was due to the pillows (covers). It was then decided to perform the experiments without pillows.

2.3 Imaging plate neutron radiography measurements

Imaging plate was then used to get a high resolution image in the beginning of the dry sample (sample at room conditions) and after humidifying at 35°C. Then the difference in the gray values can be seen qualitatively and quantitatively.

The fibers were placed without the pillows (covers) directly on the humidifier without using wires.

The condensation of the water is clearly visible at the image in fig.3 where the temperature difference from the surroundings is almost 40 °C. Due to the temperature differences, the water condensation takes place on hydrophobic polyester fibers.

Hygroscopic Lyocell fibers absorb water, the neutron images appear in dark–grey colour.

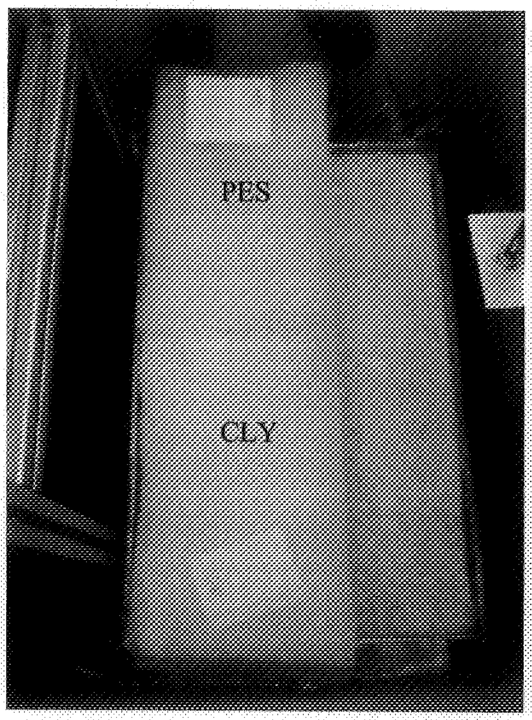


Photo at the beginning of the experiment

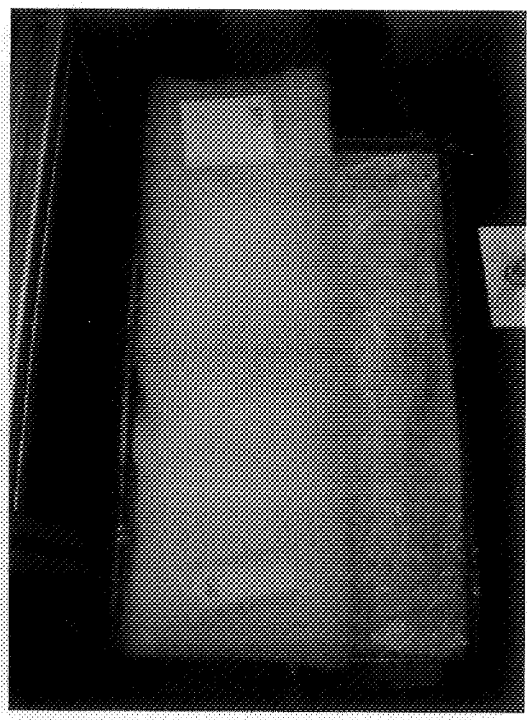


Photo at the end of the experiment. The CLY fibres seem to have collapsed.

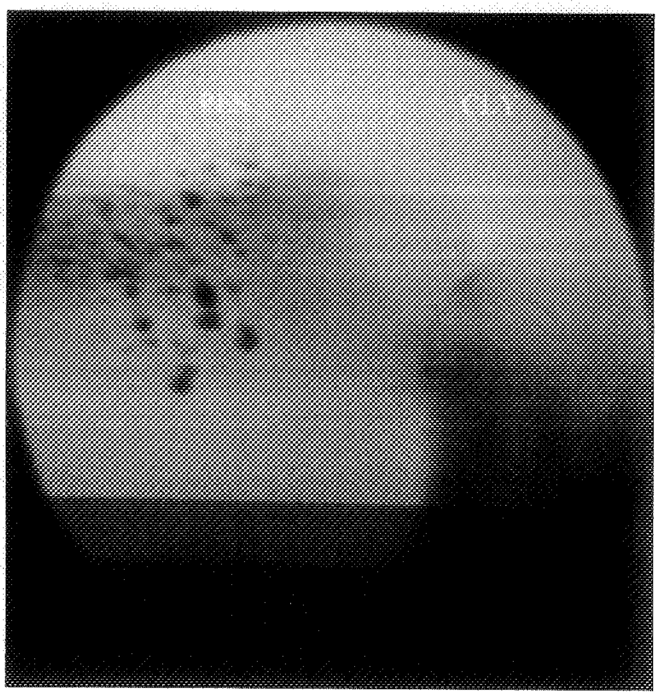


Fig 3. Top: Experimental setup. The humidifier was filled with water (textile was fully wet) and the Lyocell foil was placed on the top of the wet textile. In this setup, the wires weren't used to make a distance between the foil and textiles. Bottom: Imaging plate NR of the filling fibers, exposure time 10 min at 62C. This image shows the condensation near the surface; it seems that the water droplets are placed "above the fiber sample". This phenomenon has to be clarified.

The image in fig. 3 raised the question if the condensation occurs on the polyester fiber, or on the walls of the imaging plate as well. This was checked by imaging without the sample and no condensation was found. So it can be said that the condensation was not on the detector.

Fig. 4 shows the images with the imaging plate at different temperatures. These images were made with an exposure time of 10 minutes. The graphs show the change in moisture with respect to temperature and time.

The analysis was done by measuring the grey values. The lower the value, the higher is the quantity of water absorbed by the sample. In case of small absorption and low scattering, the neutron attenuation can be approximated by the exponential law:

$$I \cong I_o e^{-\Sigma t} \qquad (1)$$

Where I is the intensity of the transmitted neutrons after penetrating a distance t into the target. In our case t is the thickness of the sample. I_o is the intensity of the beam incident on the sample. Σ is the macroscopic cross-section. The measurement of neutron transmission through the sample allows in principle an absolute determination of the sum of cross sections and densities in the sample:

$$T = \frac{I}{I_o} = e^{-\Sigma t} \qquad (2)$$

where,

$$\Sigma = \sum_i \Sigma_i \qquad (3)$$

and

$$\Sigma_i = \frac{N_A \sigma}{A} \rho_i \qquad (4)$$

From the neutron radiograph, the macroscopic cross-section can be calculated. From the macroscopic cross-section, the density of the material may be determined. ρ is the density of the material in gcm^{-3}, A is the atomic weight, N_A the Avogadro's number and σ the microscopic cross-section in cm^2.

In this project we are mainly interested in the water content, therefore one has to normalize the intensities behind the wet sample to the dry sample in order to determine

$$T_{water} = \frac{I_{wet}}{I_{dry}} = \exp(-\Sigma_{water} t) \qquad (5)$$

From Σ_{water} the absolute water density ρ_{water} could be evaluated. This was not possible in this project because dry samples have not been prepared for the measurement of I_{dry}.

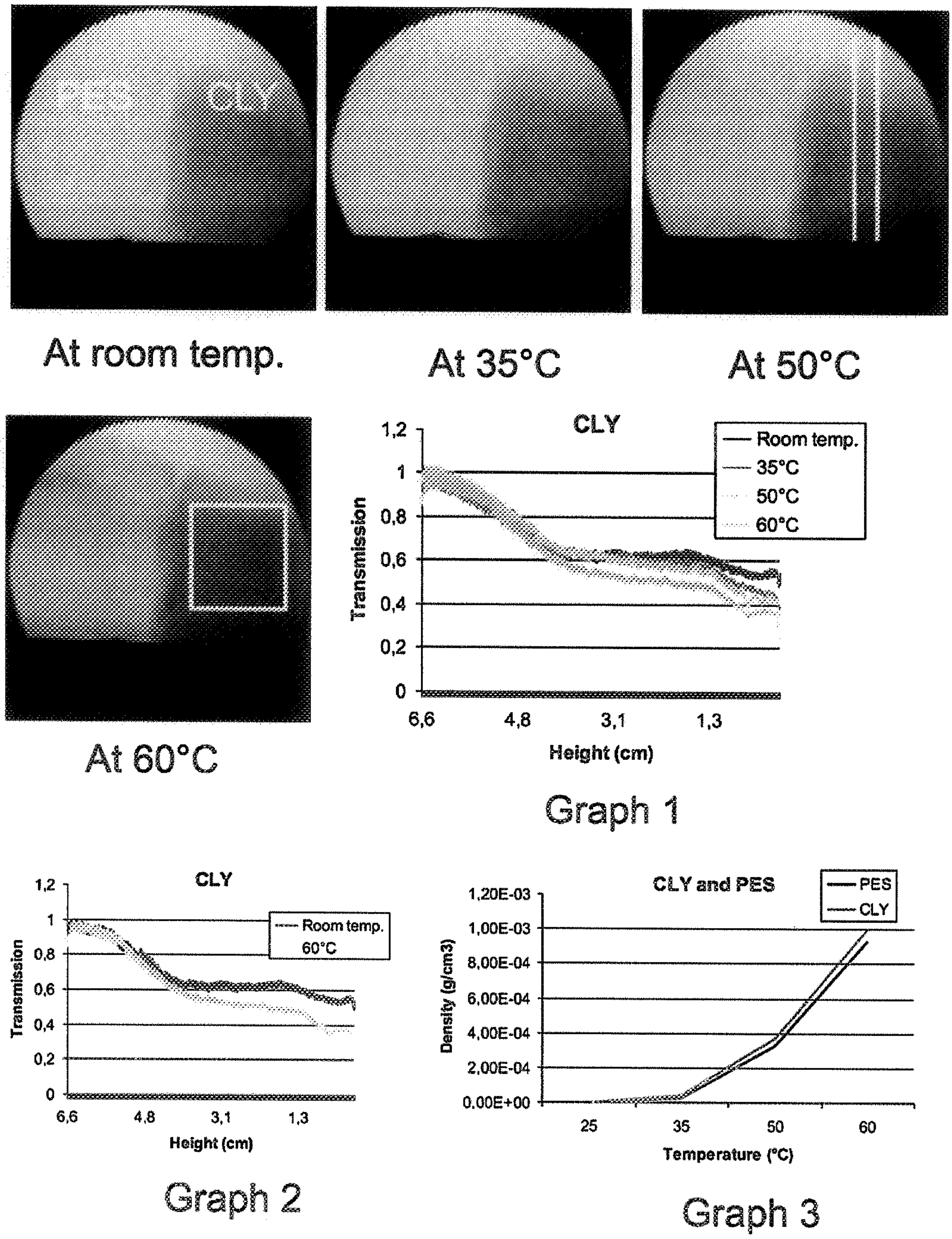


Fig 4: Neutron Radiographs with imaging plate detector, starting with room conditions. Graph 1 and graph 2 show the line profiles taken along the height of the lyocell fiber at different

temperatures. Graph 3 shows the preliminary analysis of the density of water or hydrogen relative to temperature.

From the graphs in fig. 4 it can be seen that the temperature has a detectable influence on the water content. The higher the temperature of humidifier, the higher is the water content and the lower is the neutron transmission. Time of the sample at certain temperature is not a considerable influencing factor because the grey–values do not differ a lot when exposing the sample at 35 °C for a longer time period.

For graph 1 shown in fig 4, a line profile was taken vertically along the height of the sample starting from the bottom to about 2cm above the Lyocell sample. The height of the Lyocell sample was 4,5cm and that of the polyester sample was 6cm. The transmission was calculated and plotted relative to the height. Lower transmission corresponds to higher value of moisture content. So we see that there is higher moisture content on the lower part of the sample which is close to the humidifier. As the temperature increases, the transmission decreases and hence the moisture content increases. Graph 2 shows a significant change with temperature. There is a non linear relationship between the transmission and the water content.

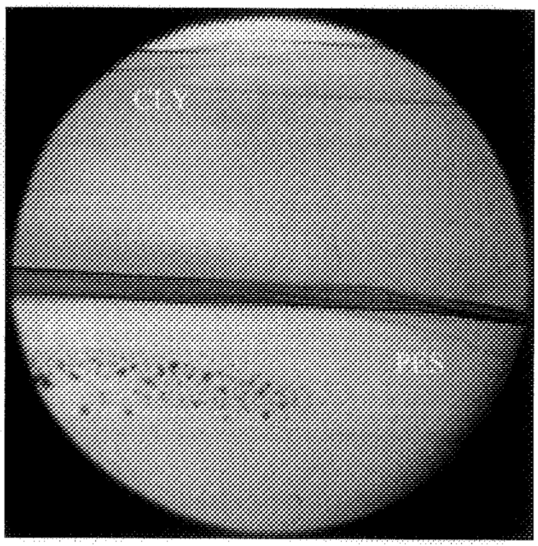
An analysis was done of the density of water in the two kinds of fibers relative to temperature. This density is not an absolute value. I_o is not I_{dry}, so Σ and ρ are not Σ_{water} and ρ_{water} respectively. If I_{water} is known, the value of ρ_{water} can be determined. As we don't know the density of the completely dry samples without any humidity, we have taken a difference between the wet sample and the sample at room conditions which contains a certain amount of moisture. It has been assumed that $I_o = I_{dry}$ for the determination of ρ_{water}. This analysis has been presented in graph 3. The area of interest for this analysis was a square area chosen each on the Lyocell sample and the polyester sample as shown in fig 4.

The sample changes its shape a little bit during the experiment. After the experiment was done, the sample mass was determined gravimetrically.

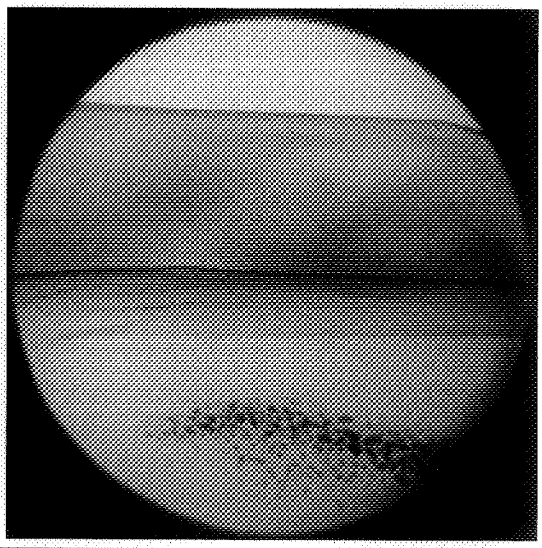
Polyester fibers seem to distribute moisture very homogenously all over the sample while for Lyocell fibers, the water remains more at the bottom of the sample. Lyocell sample was not wet homogenously. Lyocell fibers absorb water into the fiber structure and therefore the water transport is not so quick like for polyester fibers. Polyester fibers have high surface water–conductivity and that's why the water is distributed homogenously all over the non–woven.

2.4 Imaging of fiber samples enclosed in plastic bags

The two types of fibers Lyocell and polyester were humidified to different levels or percentage of humidity and enclosed in plastic bags. Then neutron imaging was done under stable conditions, due to which the exposure time was increased to 50 min to get a higher sensitivity.



Imaging plate NR of the fibers in a plastic bag with 10% humidity.



Imaging plate NR of the fibers in a plastic bag with 30% humidity.

Fig 6: Neutron radiographies made with an imaging plate with an exposure time of 50 minutes. These images clearly show the humidity distribution in the two types of fibers.

3. OUTLOOK

A quantitative analysis of the mass fraction of water is possible. For this purpose the value of the density of the completely dry sample is required. The relation of the humidity content with temperature and time may be studied. A comparison can be made with the gravimetric analysis. Such an investigation can give interesting insight into the diffusion phenomena.

Further experiments can be performed using H2O and D2O. Light water and heavy water give a very good contrast for neutron radiography. This can be useful for investigating moisture transport in moist samples [5]. Neutron tomography under stable conditions can also be performed to get a three dimensional distribution of humidity.

4. REFERENCES

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