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Moisture Diffusivity of Building Materials from Water Absorption Measurements

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ABSTRACT: Moisture diffusivity is a transport property that is frequently used in the hygrothermal analysis of building envelope components. This property is dependent on the local moisture content. The experiments that lead to the detailed information on the dependence of diffusivity on moisture content are often very sophisticated. However, two recent exercises, as a part of the activities of an International Energy Agency Annex, have shown that a correct estimate of the magnitude of the moisture diffusivity can provide useful information with regard to its application in hygrothermal analysis. This technical note presents results from a simple moisture absorption measurement that led to a good estimate of the moisture diffusivity of building materials. Results from measurements on a sample of spruce are presented.

INTRODUCTION

Moisture diffusivity, D_w, is one of the moisture transport properties of building materials frequently used in hygrothermal analysis. It appears in the moisture transport equation:

$$\dot{m}_m = -\rho_0 D_w \text{ grad } u \tag{1}$$

where

$\dot{m}_m$ = density of moisture flow rate
ρ_0 = dry density of the material
u = moisture content (mass of water/mass of dry material)

The moisture diffusivity, which is dependent on the local moisture content of the building material, is usually determined by conducting a free water intake experiment [1-5]. The experiment is designed to determine

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the moisture distribution in a test specimen at various intervals. Either a gamma-ray attenuation method [6,7] or a nuclear magnetic resonance method [5] is used to determine the moisture distribution, in situ. The results are analyzed, to derive the moisture diffusivity as a function of moisture content, either using a Boltzmann transformation procedure [2,3] or by calculating directly the ratio between the moisture flow and moisture gradient [4,5] at various locations in the test specimen.

Two common exercises were undertaken by the participants of the International Energy Agency Annex XXIV on Heat, Air, and Moisture Transfer in New and Retro-fitted Insulated Envelope Parts to assess the reliability of the experimental and analytical procedures currently used to determine the moisture diffusivity of building materials. In one exercise, test specimens were cut from a carefully chosen sample of eastern white pine and distributed to four participants to determine the moisture diffusivity that will quantify moisture transport in the longitudinal direction. Three participants used the gamma-ray attenuation procedure, and the fourth used the nuclear magnetic resonance method to determine the spatial and temporal distribution of moisture in test specimens. The results from this exercise, summarized in a report [8], are shown in Figure 1.

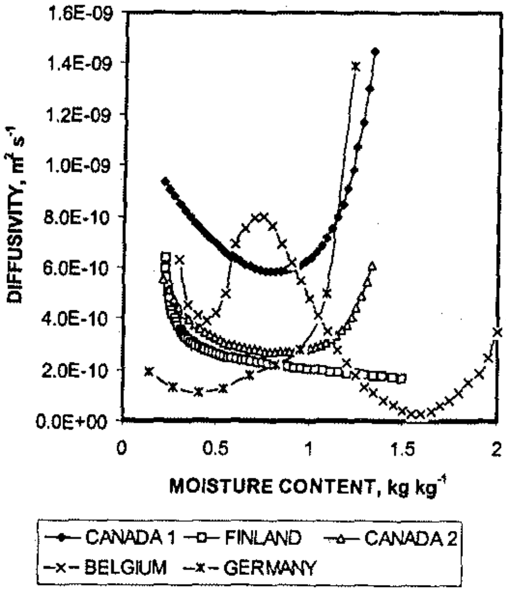

FIGURE 1. Results from the first common exercise of the IEA Annex XXIV; four participating countries were given test specimens according to their specifications from a carefully chosen sample of eastern white pine. The results show rather large differences.

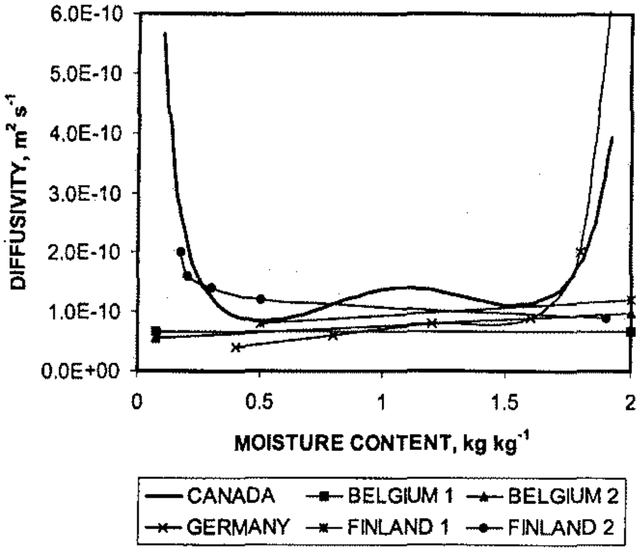

FIGURE 2. Results from the second common exercise of the IEA Annex XXIV; four participating countries were given the same set of experimental data on spatial and temporal moisture distribution from a water intake experiment in which the gamma-ray method was used. Each derived the moisture diffusivity using a different analytical procedure. Results show some differences in the derived values for diffusivity. The material was spruce.

In the second exercise, one set of data from a series of gamma-ray attenuation measurements were distributed to four participants to derive the corresponding moisture diffusivity. The results from that exercise, summarized in a second report [9], are shown in Figure 2.

The results from the first exercise showed that, even for a carefully chosen test sample, the property referred to as "moisture diffusivity" was not uniquely determined by the participants. The shapes of the curves that show the dependence of diffusivity on moisture content obtained by different participants were very different. However, the order of magnitude is shown to be approximately 10^{-10} $m^2 s^{-1}$. Minor differences were to be expected because of some inhomogeneity among the various test specimens. However, the results from the second exercise shown in Figure 2 were surprising. The moisture diffusivity derived by each participant reproduced the experimental moisture distribution with reasonable accuracy. In one analysis (Canada), all data were simultaneously used to solve the conservation equation that corresponded to the transport equation (1) by optimizing the functional dependence of D_w on u using a least-squares method [10]. The complex function so derived as well as a constant moisture diffusivity (Belgium 1) are, from a practical point of view, equally acceptable! If this is true, no sophisticated equipment such as gamma-ray equipment or NMR equipment may be necessary to "estimate" the magnitude of moisture diffusivity. Indeed, water absorption coefficients together with capillary saturation moisture content can be used to calculate an average value for the moisture diffusivity [11,12] for substitution in the transport equation (1). The results reported in this technical note confirm the usefulness of this rather simple approach.

MATERIAL AND METHOD

The material used in the experiment was spruce. The same test specimen used for the second common exercise referred to above was used in the experiment reported here. It was a 32.7 cm × 29.9 mm × 50.0 mm rectangular specimen coated with a water vapour resistant epoxy resin on all four of its longitudinal surfaces. The two end surfaces (29.9 mm × 50.0 mm) were exposed. The density of the specimen was 394 kg m^{-3}.

The moisture intake process used for the experiment is schematically shown in Figure 3. This is identical to the process selected for the second common exercise. From time to time, the test specimen was taken out, the wet surface was gently pressed against a layer of absorbent paper to remove droplets clinging to the surface, weighed and put back. This was continued for several days.

RESULTS

The increase in weight of the test specimen is linearly dependent on the square root of time, as shown in Figure 4. The area of the surface in contact

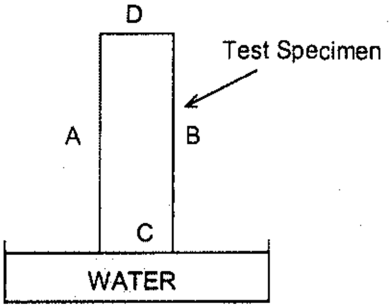

FIGURE 3. Schematic drawing of the moisture intake process. All four longitudinal surfaces, such as A and B, of the test specimen are coated with epoxy resin. The surface C is in contact with water and open. The surface D is open to the ambient air.

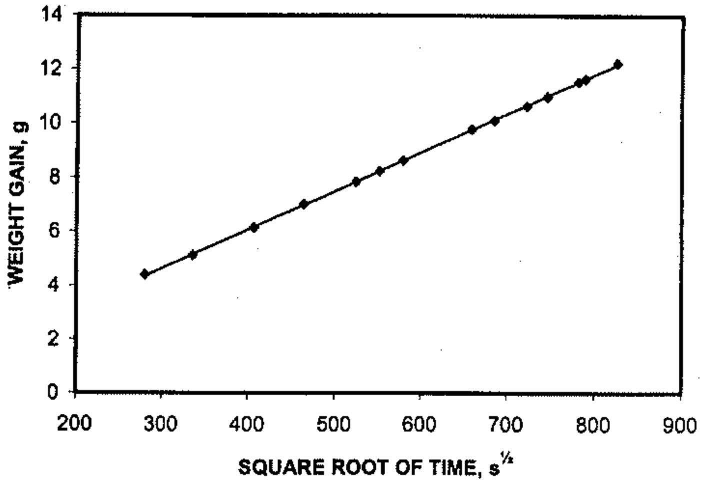

FIGURE 4. Results from the water absorption measurements; the change in weight is linearly dependent on the square root of time.

with water being 29.9 mm × 50.0 mm, the water absorption coefficient [13], A, is calculated from the slope of the straight line in Figure 4 to be 0.0096 kg m^{-2} $s^{-1/2}$. The capillary saturation of spruce is known to be ≈200% by weight. Gamma-ray measurements in our laboratory have confirmed this value, where the highest volumetric moisture content, w_c, measured was ≈785 kg m^{-3} (the density of the dry material being 400 kg m^{-3}). Gravimetric measurements conducted on small test specimens soaked in water also yielded $w_c \approx 785$ kg m^{-3}.

Direct use of the transport Equation (1) will give the following equation for an average value for the moisture diffusivity:

$$D_w \approx \left(\frac{A}{w_c}\right)^2 \tag{2}$$

Substituting for A and w_c in Equation (2) gives $D_w \approx 1.5\text{E}{-10}\ \text{m}^2\ \text{s}^{-1}$.

Krus and Künzel [11], taking the shape of the advancing moisture front into consideration, has given the following equation for the average value of D_w:

$$D_w = \frac{\pi}{4}\left(\frac{A}{w_c}\right)^2 \tag{3}$$

Substituting for A and w_c in Equation (3) gives $D_w = 1.2\text{E}{-10}\ \text{m}^2\ \text{s}^{-1}$.

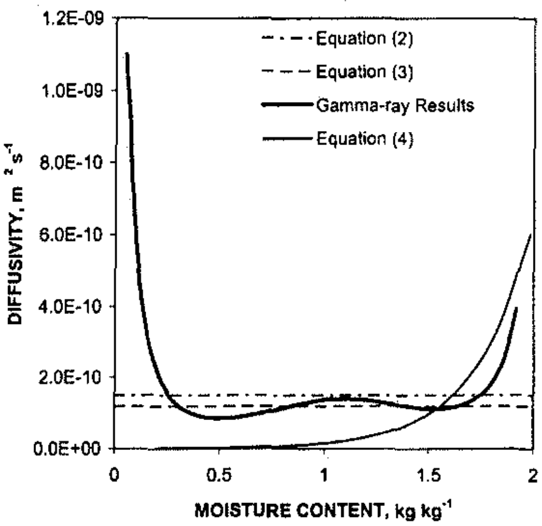

FIGURE 5. Comparison of the moisture diffusivities calculated using four different procedures. For the most part, the average value calculated from a simple experiment is not very different from that derived using a sophisticated gamma-ray method.

de Wit and van Schindel [12] derived an exponential function to calculate the dependence of D_w on the volumetric moisture content, w, as follows:

$$D_w = \left(\frac{A}{w_c}\right)^2 \frac{b^2}{2b-1} \exp b\left(\frac{w}{w_c} - 1\right) \tag{4}$$

with $5 < b < 10$. Once again, the shape of the moisture front that advances in the test specimen is considered in the derivation of Equation (4). The values for moisture diffusivity calculated according to Equation (4) for spruce (b assumed to be 7.5 for wood) from the present measurements are shown in Figure 5. For comparison, the value obtained from the optimization method in the second common exercise and the average diffusivities calculated using Equations (2) and (3) are also shown in Figure 5.

CONCLUDING REMARKS

The moisture diffusivity calculated from simple water absorption measurements, clearly establishes the order of magnitude of the transport property. The average values calculated using Equations (2) and (3) are surprisingly close to the values determined using very sophisticated equipment and analytical procedures. The values calculated from the exponential Equation (4) match well at the higher moisture content range, but results at the lower range seem to depart considerably. The effect of this on the calculated moisture distributions is to be investigated and compared with other calculations.

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