A new model for wetting and drying of wood end-grain – with implications for durability and service-life

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ABSTRACT

New experimental data for wetting and drying of wood end-grain, Sandberg (2009), imply that traditional models for moisture transport are not at all applicable. A new model is developed to consider the phenomenological behaviour of water transport in and out of end-grain, using the pore water pressure and sorption scanning properties. Modelling results are compared to experimental results and the consequences for durability are discussed.

Keywords: durability, wetting, drying, end-grain, model

1. INTRODUCTION

For durability and service-life of wooden outdoor structures, above ground, moisture accumulation due to absorption of water from the end-grain is decisive. Prediction of the service-life in a natural climate requires a correct description of the moisture balance close to the end-grain. Traditional models for moisture transport are based on Fick’s 2nd law and moisture transport descriptions using the moisture content as the transport potential. Recent experimental studies show, however, that the traditional models do not describe the absorption and drying processes in a correct way. A new approach is needed.

2. TRADITIONAL MOISTURE TRANSPORT MODELS FOR WOOD

Moisture flow \( g \) in wood, and in many other materials, usually [2] is described with Eq. (1)

\[
g = -D_w \cdot \rho \cdot \frac{\partial u}{\partial x} \text{ [Pa]}
\]

where \( D_w \) is the moisture diffusivity, \( \rho \) is the density, \( u \) is the moisture content and \( x \) is the position. The diffusivity is certainly not a constant but very moisture-dependent. An analysis of literature data [2] showed a moisture-dependency as in Fig. 1. This moisture dependency was derived from drying experiments [3] and verified against experiments for steady-state moisture flow [2].

Using the diffusivity Eq. (1) for predicting water absorption into and drying out of wood gives results as in Fig. 2.
Figure 1: Moisture dependency of the diffusivity according to literature data [2]

Figure 2: Predicted moisture content profiles during wetting and drying with a traditional model

The moisture profiles after wetting show an MC decreasing with depth from the surface. After drying starts, the MC drops close to the surface but moisture continues to penetrate further, deeper into the material.
3. NEW EXPERIMENTAL OBSERVATIONS OF WETTING AND DRYING OF END-GRAIN

Most studies of moisture transport in wood above the fibre saturation point (FSP) are done for the drying process of timber. Studies for describing the behaviour of wood in the building envelope are mostly done within the hygroscopic range, i.e. well below FSP.

Sandberg (2009), however, measured moisture profiles during wetting and drying from the end-grain of wood conditioned to $u = 12\%$. The measurements were done with CT-scans. Some of her results are shown in Fig. 3.

![Figure 3: Moisture content profiles during drying, after wetting for 14 days, sapwood of Norway spruce [5]](image)

In Fig. 3 it is obvious that the traditional moisture transport equation does not hold. Moisture is transported towards the surface, to the left in the figure, during drying, but that is against the moisture content gradient, contrary to what Eq. (1) says. These conditions prevail all the time up till MC drops below FSP close to the surface, where the MC-gradient turns. There is neither any sign of further penetration of water during the drying period, as in Fig. 2.

The results are also remarkable when the drying time is compared to the time of wetting. The wetting time in Fig. 3 is 14 days. The water absorbed during these 14 days is dried out in less than seven days. Wood end-grain is very special in this respect. Most other materials absorb water quickly but dry out very much slower.

Because of these differences between traditional modelling and experiments a new approach is needed. A better model should be able to describe the moisture flow above FSP against the MC-gradient and the large difference between wetting and drying times.
4. PHENOMENOLOGICAL DESCRIPTION OF WETTING AND DRYING OF END-GRAIN

4.1 Wetting

The experimental observations may be explained in the following way. Capillary absorption of water will follow paths like a series of “straws”, cf. Fig. 4, where the water movement is due to the capillary suction beneath the meniscus in the lumen. Water will penetrate through that small portion of the ring pores that remained open after the previous drying, Sandberg & Salin (2010). This is of course a simplified way to describe the flow paths.

The capillary suction, the pore water pressure $P_w$, will depend on the size of the meniscus in lumen

$$P_w = -\frac{2\sigma \cdot \cos \theta}{R} \text{ [Pa]}$$  \hspace{1cm} (2)

where $R$ is the radius of lumen, $\sigma$ is the surface tension and $\theta$ is the contact angle between the meniscus and the surface of lumen. $\theta$ is here assumed to be zero, for simplicity.

The flux of water $g$ depends on this pore water pressure difference $\Delta P_w$ and the resistance $\Omega$ to water flow

$$g_{abs} = \frac{\Delta P_w}{\Omega} \text{ [kg/(m}^2\text{s)]}$$ \hspace{1cm} (3)

The resistance $\Omega$ to water flow should mainly be the resistance of the narrow openings in the ring pores. The lumen will of course have a certain, but small, resistance as well. Assuming that a unit length of the tracheids, with a certain number of ring-pore openings and lumens in-between, has a resistance of $\Omega_0$, the resistance to water flow of a unit area of flow path with a certain thickness $x \text{ [m]}$ will be
Now, the capillary absorption may be calculated by setting the volume of water that penetrated during a certain time step $\Delta t$ equal to the amount of water needed to fill the available pore volume in an infinitesimal thickness $\Delta x$

$$g_{abs}(x) \cdot \Delta t = \frac{2\sigma}{R \cdot \Omega_0 \cdot x} \cdot \Delta t = \rho \cdot p \cdot \Delta x \quad [\text{kg/m}^2]$$

where $p$ is the available porosity and $\rho$ is the density of water. Rearrangement and integration gives the penetration depth after a certain time $t$

$$x = \sqrt[4]{\frac{4\sigma}{R \cdot \Omega_0 \cdot \rho \cdot p}} \cdot \sqrt{t} \quad [\text{m}]$$

and the time to reach a certain penetration depth $x$

$$t_{wet} = \frac{R \cdot \Omega_0 \cdot \rho \cdot p}{4\sigma} \cdot \frac{x^2}{[\text{s}]}$$

### 4.2 Drying

When drying starts the lumen next to the drying surface will rapidly be emptied. Then drying occurs through water vapour diffusion from the small meniscus formed in the openings of the ring pores, with a radius of $r$, and the drying surface and liquid flow in the rest of the flow path, cf. Fig. 5. The resistance $Z$ to vapour diffusion is small since it does not include moisture transport through the ring pores and cannot be derived from moisture transport properties of wood in the fibre direction; it is much smaller.

The pore water pressure on the other side of the first ring pores is given by Eq. (2) with the radius being $r$. The flux of water is, however, given by the difference in pore water pressure between the meniscus at the ring pores and the meniscus in the lumen at the depth of penetration

$$\Delta P_w = \frac{2\sigma}{R} - \frac{2\sigma}{r} \quad [\text{Pa}]$$

which is a suction towards the drying surface.
Since the size of the meniscus in the ring pores corresponds to an RH close to 100 \%, the moisture flux up to the drying surface, that empties the “straw”, will initially be pure vapour diffusion

\[ g_{\text{dry}} = \frac{\Delta \nu}{Z} = \frac{v_s (1 - RH)}{Z} \text{ [kg/(m}^2\text{s)]]} \tag{9} \]

where \( RH \) is the relative humidity in the surrounding air and \( v_s \) is the vapour content at saturation at the current temperature. To maintain this flux the liquid flux beyond the first ring pores must be of the same magnitude. If not, the meniscus in the ring pores will be broken and the lumen emptied in the next tracheids. This will of course happen if the depth of penetration is very large, which gives a large resistance \( \Omega \) to liquid flow, and when the “straw is emptied, i.e. the local moisture content reaches FSP.

### 4.3 Wetting vs. drying times

The time \( t_{\text{dry}} \) required to empty the capillaries after wetting, as long as the evaporation is “supplied” with water being sucked in the “straw”, can be found from the amount of water to dry out, expressed as the flux in Eq. (9) during the drying time or as the available amount of water above FSP

\[ g_{\text{dry}} \cdot t_{\text{dry}} = \frac{v_s (1 - RH)}{Z} \cdot t_{\text{dry}} = \rho \cdot p \cdot x \text{ [kg/(m}^2\text{)]} \tag{10} \]

where \( p \) is the porosity above FSP and \( x \) is the original depth of penetration. From this equation the drying time can be derived

\[ t_{\text{dry}} = \frac{\rho \cdot p \cdot x \cdot Z}{v_s (1 - RH)} \text{ [s]} \tag{11} \]
The drying time will be shorter than the time for wetting if $t_{\text{dry}}$ in Eq. (11) is smaller than $t_{\text{wet}}$ in Eq. (7)

$$\frac{\rho \cdot p \cdot x \cdot Z}{\nu_s(1-RH)} < \frac{R \cdot \Omega_o \cdot \rho \cdot p}{4\sigma} \cdot x^2 \ \text{[s]}$$  \hspace{1cm} (12)

or

$$x > \frac{4\sigma \cdot Z}{R \cdot \Omega_o \cdot \nu_s(1-RH)} \ \text{[m]}$$  \hspace{1cm} (13)

Here $\sigma$, $Z$, $\nu_s$, and $RH$ are constants for a given drying climate. Consequently, whether the requirement is fulfilled or not will depend on the depth of water penetration, the cross-section of the lumen and the number of open ring-pores.

4.4 Moisture profiles
The model will predict a sharp penetration front in each “straw”. This is, however, not what was measured, cf. Fig. 3. Sandberg (2009) made an important observation to explain this. The water penetration looked like “fingers”, with “straws” having very different penetration depths. From a moisture distribution with a series of sharp penetration front in “fingers”, the average moisture content profile could look like the distribution in Fig. 3, cf. Fig. 6.

![Figure 6: A moisture content profile as an average of penetration depths in a series of “fingers”.](image)

The moisture profile during drying will follow a similar pattern, with the “front” in each “finger” moving to the left when drying proceeds.
5. A MATHEMATICAL MODEL FOR END-GRAIN WATER ABSORPTION AND DRYING

A mathematical model capable of describing end-grain wetting and drying must contain two parts that differ from traditional models. The flux equation in Eq. (1) must be replaced by a flux equation according to Eq. (3), with the pore water pressure as the transport potential. The “resistance” to water flow in a “straw” should be replaced by a water permeability $k_P$. The flux equation above FSP will then be

$$g = -k_P \frac{\partial P_w}{\partial x} \text{ [kg/(m}^2\text{s)]}$$

(14)

The viscosity may be included in the permeability, as in Eq. (14) or included separately in the flux equation. Below FSP a flux equation similar to Eq. (9) should be suitable.

The next part that is important is the relationship between the moisture content and the pore water pressure. This relationship is called the suction curve. An example is shown in Fig. 7.

![Figure 7: A suction curve for spruce with a large hysteresis between desorption and absorption above FSP; after Adamson et al (1970) and Penner (1965). A scanning curve (in red) is added for an MC around 120 %.

The suction has a very large hysteresis. The scanning curves between the desorption and absorption curves are largely unknown, but from the observations in this paper it is obvious that the must be almost horizontal. This means that when the process changes from wetting to drying, the pore water pressure can drop a lot, without the moisture content having to change.
6. DISCUSSION AND CONCLUSIONS

The observations by Sandberg (2009) that heartwood end-grain of spruce dries much faster than it is wetted, are extremely important especially for understanding the effect of various parameters on durability and service-life of wooden structures. Controlling wetting of end-grain is regarded as the key parameter to delay deterioration but the observation implies that controlling drying is equally important, if not more important. For wood species and drying conditions where the described model will be applicable, it is obvious that any wetting of end-grain can be balanced by drying during a much shorter period. This knowledge may be used to improve durability and prolong service-lives by designing joints considering the drying possibilities.

The model is fairly simple but seems to be able to explain and quantify the observations. Decisive wood parameters are the cross-section of lumen, the portion of the ring-pores being open and the size of the openings. Decisive drying parameters are the temperature and humidity of the surrounding air and the air movement close to the end-grain.

The model seems to be applicable under certain circumstances that could be expressed in the decisive wood and drying parameters as a penetration depth of water. This requirement could imply that the model does not hold for wood where the penetration depth is very large. This could also be expressed in terms of wood properties. This must be further explored.

It is not common knowledge to include a model like this in traditional software for moisture balance calculations. Also very advanced models do not include hysteresis or scanning curves in the sorption or suction curves. For this application this is of extreme importance.

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