Water vapour permeability of wood – remarks on cup method procedure and measured data of spruce wood

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Abstract. Although the water vapour permeability of wood has been determined many times, there can be found a wide spread of values even related to only one wood specie and its single anatomical direction. This spread can possibly be attributed to the measurement method itself, since the cup method often shows high inter-laboratory error. However, even if the measurement and evaluation processes are well performed and under control, there were found several factors that can still highly affect the resulting value – up to ca. 70 %. These factors are neither mentioned in standards, nor were found in other sources. This paper theoretically describes those factors and their possible impact to the final value of water vapour permeability. Paper also presents one particular measurement scheme and obtained data from four cup tests performed on spruce wood in transverse direction.

1. Introduction
Water vapour permeability of wood has been studied many times [e.g. 1-4]. However, the data shows high spread, even related to only single wood specie and its single anatomical direction (see Figure 8). Most of the data were determined using the cup method [5,6]. Although the method is simple in principle, the measurement and evaluation processes contain lot of steps that provide a room for possible errors. This is likely the reason why the method often shows high inter-laboratory error [7-10]. On the other hand, when the processes are precisely defined and controlled, also a good agreement among different measurements can be achieved [10,11]. Nevertheless, regarding wood, there were found several factors that can lead to significant different values even the measurement is very under control. These factors are neither presented in standards nor were found in other sources. They are mostly associated with the specific properties of wood which combines strong dependency of the vapour permeability on moisture content and high hygric capacity with, moreover, significant hysteresis.

2. Theory
To be more specific in this section, a several numerical calculations were performed. For such purpose was used a function of water vapour resistance factor of spruce wood in transverse direction that is presented later in this paper (see section “4. Results”).

2.1. Hygro-thermal history of the sample
Value of water vapour permeability depends on the moisture content present within the material [3]. However, in many cases it is described as a function of relative humidity. Although this approach can be reliable for many materials and calculations, it is questionable if so for wood. Due to its strong hysteresis between the adsorption and desorption processes, there is a wide range of possible moisture contents (MC) corresponding to a single value of relative humidity (RH), (see Figure 1-right). Thus, there is also a wide range of water vapour permeability values corresponding to a single RH-value. In Figure 1-left can be seen two functions of water vapour resistance factor (µ-value). One is plotted as

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corresponding to the relative humidity on adsorption isotherm and the second to the 97%-desorption isotherm (i.e. desorption isotherm measured descending after adsorption at 97 %RH). It can be seen that in range of 20 – 80 %RH the difference between the μ-values corresponding to the two isotherms is ca. 20 – 50 %. For instance, at 50 %RH the μ-value of spruce in transverse direction can be ca. 75 or almost twice more (ca. 130) or anywhere between, depending on actual moisture content present within the material. It means, that the hygric or hygro-thermal history of the sample can play an important role in resulting measured μ-value. It can also be beneficial to use proper hysteresis model in numerical simulations to achieve more precise results.

In terms of the cup-test measurement, it is beneficial to be well familiar with the moisture content distribution across the samples before the test and also after reaching equilibrium vapour flux at the end of the test. This can be achieved by, for instance, following any known sorption isotherm curve (e.g. boundary adsorption or desorption curve). If the adsorption isotherm is chosen, the samples have to be, before the test, conditioned at first at 0 %RH, then at the lower of the two humidity levels of the upcoming cup test and even after exposed to the cup-test boundary conditions. It is needed for the samples to experience only adsorption within their whole thickness. If the samples would be exposed to the cup-test boundary conditions directly after conditioning at 0 %RH, in the first stages of the test, there will be a moisture intake on both exposed surfaces of the sample. This will consequently shuffle the final moisture content distribution across it, which that will no longer correspond purely to the adsorption isotherm.

![Figure 1](image)

**Figure 1.** left – difference between adsorption- and desorption-RH-related μ-value of spruce wood in TR direction; right – difference of moisture content of spruce wood at 50 %RH.

### 2.2 Mean relative humidity within the sample

In Figure 1-left can be seen that vapour resistance of wood is highly dependent on relative humidity within it. Therefore, when the equilibrium moisture flux through the sample is reached, during the cup test, the distribution of relative humidity (and so of moisture content) across the sample is nonlinear (see Figure 2-left). Therefore, the mean relative humidity within the sample (hereafter RH_mean) is neither the arithmetical average of the RH levels on its surfaces (hereafter RH_avg_surf), and indeed not the average of the boundary RH conditions of the cup test (hereafter RH_avg_BC). However, it is usually needed to assign the measured vapour permeability to its corresponding relative humidity or moisture content value, especially when trying to define moisture-dependent function for purposes of numerical modelling. In Figure 2-left can be seen that after performing the two most common cup tests - conditions “A” (23°C; 0/50 %RH) and “C” (23 °C; 50/93 %RH) according to the ISO 12572 [5], the difference between the RH_mean and RH_avg_surf can be around 9 and 7 %RH, respectively. As can be seen in Figure 2-right, the choice of the relative humidity corresponding to the measured μ-value can cause ca. 35 – 40 % difference of the μ-value. Therefore, the choice of this relative humidity should not be underestimated. On the other hand, when performing the cup test under a narrower difference of boundary RH levels, the difference between the RH_mean and RH_avg_surf diminishes, which leads
also to lower error using any of the two values (see Figure 7). To determine the RH_mean in the sample, it is possible to measure the moisture content of the samples directly after finishing the cup test (i.e. with the equilibrium MC distribution across the samples) and compare it with the chosen corresponding sorption isotherm.

Figure 2. left – distribution of RH in the sample after reaching equilibrium moisture flux during the “A-“ and “C-conditions” cup tests; right – difference of µ-values related to RH_mean and RH_avg_surf.

2.3. Measurement time and weighing periods

Measurement time and weighing periods should not be underestimated. Since the wood has high hygric capacity and relatively high vapour resistance, especially in radial and tangential directions, it can take months to reach an equilibrium moisture flux (considering samples thicker than 10 mm), (see Figure 3). Regarding duration of the weighing periods, ISO 12572 presents an equation for their determination based on the expected sample permeability, balance precision, etc. However, there are several other factors that can affect the weighed mass of the sample and thus prolong the weighing period. It is the adsorption or desorption on the exposed sample surface during the weighing outside the climatic chamber, adsorption and desorption caused by the differences of temperature of the sample and finally differences of atmospheric pressure between the periodical weighings which cause differences in buoyancy force acting on the cup setup. Correction for the buoyancy has to be applied carefully in terms of wood since by experience it seems that the total pressures outside and inside the cup are quickly equalized via the wooden sample and thus the air within the cup should be excluded in the calculations. All mentioned effects cause some limited error to the weighed mass, however when observing very small changes of mass, these effects can play important role and should be eliminated or diminished by e.g. enlarging sample area, lowering the sample thickness or prolonging the weighing period.

Figure 3. Weight change of 5 samples of spruce wood in transverse direction during the cup tests in conditions 96.8/75.0 %RH (left) and 11.2/0.2 %RH (right).
2.4. Dimension changes

Wood differs from mineral-based materials, among others, in the mechanism of adsorption of water molecules. Those do not form adsorbate on the walls of the pore system (until very high humidity levels are present – ca. > 99 %RH) [12], but are adsorbed into the cellular structure of the wood (into its matrix). This causes swelling and shrinking of wood. Therefore, the area and thickness of the samples change depending on the particular cup test conditions applied. In terms of measurement process the used sealant has to adapt to those volumetric changes while still keeping the sample tightly imbedded on the cup. Volumetric changes affect the final µ-value also during the evaluation process. The value can be calculated using the real thickness of the sample measured directly after the cup test, which may seem to be the correct approach. However, in numerical modelling the thicknesses of material layers are usually considered to be constant in time. Therefore, to obtain reliable results of the numerical simulation, all permeability values should be determined using only one uniform thickness (e.g. the dry value). On the other hand, the area of the sample used for the calculation of the µ-value should be the real area measured directly after each particular cup test (average from top and bottom area).

2.5. Density dependency

The vapour permeability of wood is also dependent on its density. Density of spruce can vary of approx. 30 % and more. It seems, that the difference of mu-value is in the same order as the density difference. Thus, even respecting all previously mentioned recommendations, the results can still differ quite widely, depending on the particular piece of wood tested.

3. Methods

3.1. Samples

For the experiment were used 5 circular samples made out of one board of spruce wood. The direction of the vapour diffusion across the samples was the combination of tangential and radial direction in the ratio of ca. 1.7:1. Average dry density of the samples was measured as 432 kg/m³, the average dry thickness was 12.8 mm, and the dry diameter 81.7 mm.

3.2. Preconditioning

Before the first cup test, the spruce board was dried to ca 12 %MC and stored for several months in 22±2 °C and 55±5 %RH. Then the samples were cut out and conditioned in 96.8 %RH. For the conditioning was used saturated salt solution of K₂SO₄. Since the conditioning took 2 months, both sides of the samples were periodically exposed to UV-C light to prevent mould growth.

3.3. Preparing the cup setup

Samples were imbedded in circular openings of the plastic lids. For the tight and elastic contact was used butyl rubber tape (see Figure 4). Lids with imbedded samples were placed on glass cups. The vapour-tight contact between the lid and the cup was provided by the silicone ring casted from all sides by petroleum jelly. Without the casting the contact was found to not be sufficiently tight. Inside each cup was placed 100 ml of saturated salt solution which provided the distance between the surfaces of solution and the sample quite thick (ca. 40 mm). Although this thickness is out of the range stated in ISO 12572, it was analysed that the friction on the walls inside the cup should eliminate the air movement caused by maximum possible temperature differences during the experiment – therefore the air in the cup was considered as still, only allowing vapour diffusion.

3.4. Procedure

The whole procedure included four consecutive cup tests using the set of 5 samples. Cup tests were performed in ca. 22.5 °C and humidity conditions specified in Table 1. Average airflow speed above the samples was measured as 0.2 m/s. This flow was analysed to provide resistance for moisture transport equal to ca. 12 mm of still air. The tests were performed in the “desorption mode” which means that the equilibrium moisture content across the whole thickness of the sample corresponded in each of the cup tests to the values on 97%-desorption isotherm. In all tests the salt solution imposing higher relative humidity was placed inside the cup. This was performed to minimize the error caused by possible
dilution of the solution by incoming water molecules leading to possible increase of relative humidity inside the cup. For imposing 0 %RH was used molecular sieve 3Å instead of the often-used silica gel, because of its better performance. Measured relative humidity during the fourth test was around 0.2 – 0.3 %RH. Weighing periods were periodically 3 and 4 days, which for the dryer conditions were found to be still too short (see Figure 3-right). The whole procedure took 7 months.

**Table 1. Boundary conditions in four consecutive cup tests and used salts**

| Test no. | RH\_cup [%] | RH\_chamber [%] | Salt solution in cup | Salt solution in chamber |
|----------|-------------|----------------|----------------------|--------------------------|
| 1        | 96.8        | 75.0           | K\_2SO\_4            | NaCl                     |
| 2        | 75.0        | 43.2           | NaCl                 | K\_2CO\_3                |
| 3        | 53.0        | 11.2           | Mg(NO\_3)\_2         | LiCl                     |
| 4        | 11.2        | 0.2            | LiCl                 | molecular sieve 3Å       |

**3.5. Drying**

After the fourth cup test, the samples were dried and their dry dimensions and densities evaluated. Also, an equilibrium moisture contents after each of the previous cup tests were calculated.

**3.6. Evaluation**

Evaluation was performed according to the standard ISO 12572 [5], based on the first Fick’s law. The evaluation process included corrections to the equivalent air layer thicknesses below and above the samples and the correction to the buoyancy force during weighing caused by atmospheric pressure. Correction for masked edges of the samples was not relevant since the sealant was applied only on the side face of the samples. μ-values were determined using the dry thickness of the samples. Expanded uncertainty was estimated for 95% confidence, according to [13]. Based on the measured moisture contents after each of the cup tests and known shape of the 97%-desorption isotherm, the mean relative humidity within the samples (RH\_mean) was determined. By mistake it was not possible to determine the MC-value of the samples after the fourth cup test, and thus the μ-value of this final test was plotted against RH\_avg\_BC (see Table 1 and Figure 6).

**3.7. Permeability function**

Based on the measured μ-values and their corresponding RH\_mean (for the fourth test RH\_avg\_BC) was generated a μ-function that can be seen in Figure 6. Its mathematical form is presented directly in the chart in Figure 6. By offsetting the function by the RH difference between the adsorption and desorption isotherm also the adsorption-RH-related μ-function was found (see Figure 6).

**3.8. Numerical simulations**

By using the desorption μ-function, the whole measurement procedure of the four cup tests was simulated. An equilibrium RH distribution across the samples was determined (see Figure 7). The desorption μ-function was also used for the brief simulations presented in section “2. Theory”.

**4. Results**

Table 2 summarizes the results of four cup tests performed on spruce wood with dry density 432 kg/m\(^3\) in its transverse direction. The MC-value of the samples after the final fourth test is not present within the table as by a mistake it was forgotten to be evaluated. In Figure 6 can be seen two μ-functions – one related to RH levels on adsorption and second on 97%-desorption isotherm. In Figure 7 can be seen results from numerical simulations of all four cup tests – the distribution of relative humidity across the samples after reaching equilibrium vapour flux.
## Table 2. Summary of test conditions and measured values

| Test no. | T [°C] chamber | RH [%] cup / chamber | mean water vapour resistance factor (based on dry thickness) \( \mu \) [–] | measured mean moisture content MC [%] | corresponding RH on 97%-des. isotherm RH_avg BC [%] | average RH of boundary conditions RH_avg BC [%] | difference between RH_mean and RH_avg_BC [%] |
|----------|----------------|----------------------|-------------------------------------------------|-------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1        | 22.4           | 96.8 / 75.0          | 5.3 ± 1.7                                       | 21.6                                | 88.1                                          | 85.9                                          | + 2.2                                         |
| 2        | 22.1           | 75.0 / 43.2          | 29.7 ± 3.4                                      | 14.1                                | 66.2                                          | 59.1                                          | + 7.1                                         |
| 3        | 23.1           | 53.0 / 11.2          | 125.9 ± 9.3                                     | 9.5                                 | 40.5                                          | 32.1                                          | + 8.4                                         |
| 4        | 22.6           | 11.2 / 0.2           | 806.5 ± 143.9                                   | -                                   | -                                             | 5.7                                           | -                                             |

### Figure 5. Adsorption- and desorption-isotherms-related \( \mu \)-functions of spruce wood (432 kg/m\(^3\)) in transverse direction; left – RH range 0 to 100 %; right – RH range 30 to 100 %.

### Figure 6. Simulated relative humidity distribution across the sample in the four cup tests and depicted RH_mean, RH_avg_surf and RH_avg_BC values.
5. Discussion

In Table 2 can be seen that range of measured μ-values is wide. Under the dry conditions (22.6 °C; 0.2/11.2 %RH) the μ-value was found to be 806.5, while under the humid conditions (22.4 °C; 96.8/75.0 %RH) the obtained value was 5.7. Therefore, and based on the generated μ-function, can be stated that μ-value of spruce wood in transverse direction can vary from order of 1 to order of 1000 within the hygroscopic range.

The shape of the desorption μ-function presented in Figure 6 was adjusted based on numerical simulation of all the four cup tests. Otherwise, it could be possible to find more shapes of the function that fit the four measured values. In any case, especially the data between 0 and ca. 10 %RH are still bonded with high uncertainty. The MC-value and so the RH_mean of the samples after the final fourth cup test were not evaluated by a mistake and therefore the driest measured μ-value was plotted in Figure 6 against its RH_avg_BC.

The RH_avg_BC values of all four tests are also shown in Figure 6 to be possible to imagine how different would be the shape of the μ-function if it was plotted against them. Although this paper suggests to plot the measured μ-values against the RH_mean, by further analysis it was found, that even this RH-value is not the true corresponding one. To find this corresponding value a few numerical calculation steps are needed, however these are not presented in this paper.

By comparing the generated μ-functions with the data found in other sources [2,4,14-16], it was found, that although there is a wide spread of values, all of them can be valid. In Figure 7 can be seen that most of the data lay inside the two presented boundary μ-functions while the deviation of the rest of the datapoints can be attributed to, for instance, the differences of the wood density (see also section “2.5.”). It should be emphasized, that only spruce wood in transverse direction was considered for this comparison. Best agreement of our measurement (the desorption μ-function) was found with the data in Kumaran (2002), [16], while the data found in Kumaran (1996), [4] corresponds well with our adsorption-RH-related function (see Figure 8).

![Figure 7. Comparison of μ-values from different sources with established adsorption- and desorption-RH-related μ-functions; left – RH range 0 to 100 %; right – RH range 20 to 100 %.

6. Conclusions

It was presented, that when performing the cup test measurement on wood a significantly different results can be obtained even dealing with only one wood specie and its single anatomical direction. The difference of measured μ-value up to ca. 50 % can be attributed to the hygro-thermal history of the samples (see section “2.1.”) and another ca. 30 % difference to the differences of wood density (see section “2.3.”). Thus, the total difference of measured μ-value of wood under the same test conditions, can be up to ca. 60-70 %, while all such values are valid (see section “5.”). Therefore, in terms of wood, it can be beneficial to use a proper hysteresis model in numerical simulation tools, at least to achieve precise results.

In addition, when trying to define the μ-function as function of relative humidity, another ca. 40 % difference of the μ-value can be caused by the choice of the corresponding relative humidity (see section
Therefore, the measured vapour permeability of wood should always be provided with all important context information of the measurement, especially the hygro-thermal history and density. Based on measured data it was found that the vapour permeability of spruce wood in transverse direction can vary from order of 1 to order of 1000 within the hygroscopic range.

For comprehensible measurement and evaluation of the water vapour permeability of wood is beneficial to (1) be familiar with the hygro-thermal history of the samples, (2) be sure about the tightness of used sealant and its adaptability to the volumetric changes of the samples during the measurement, (3) keep the moisture content distribution across the samples during the whole cup test procedure well under control (e.g. corresponding to any well-known sorption isotherm), (4) after the test determine equilibrium moisture content of the samples, thickness and diameter, (5) do not underestimate total measurement time and duration of the weighing periods.

For purposes of numerical modelling the vapour permeability values measured on wood have to be all evaluated using only single thickness of the sample (if the numerical model do not include volumetric changes of material layers), while the area should be used the one measured directly after performing the particular cup test.

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