A DISCUSSION OF “CHARACTERIZATION OF HYGROTHERMAL PROPERTIES OF WOOD-BASED PRODUCTS – IMPACT OF MOISTURE CONTENT AND TEMPERATURE”

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ABSTRACT

In 2014, this journal published the paper “Characterization of hygrothermal properties of wood-based products - Impact of moisture content and temperature”, presenting among others the vapour permeability of wood-fibre insulation. This discussion demonstrates that the measurement, the calculation and the presentation of this vapour permeability has suffered from various errors, invalidating the obtained intrinsic vapour permeabilities of wood-fibre insulation. This discussion moreover demonstrates that several subsequent authors have furthermore misinterpreted their air-gap-corrected vapour permeabilities as intrinsic vapour permeabilities, which in turn invalidates, at least in part, these authors’ challenges to the state-of-the-art on the measurement and simulation of hygroscopic moisture transport in porous materials.

KEYWORDS

Wood-fibre insulation, vapour permeability, cup tests, advection, EN 12572, EN12086

HIGHLIGHTS

- A prior paper in the journal studied vapour permeability of wood-fibre insulation
- Mistakes in measuring, calculating and presenting this permeability were made
- Actual permeabilities are most probably higher than widely adopted in literature
- This deviation has led to dubious claims challenging the diffusion state-of-the-art
- These challenges are partially contradicted by the investigation in this discussion

1. INTRODUCTION

In 2014, this journal published the paper “Characterization of hygrothermal properties of wood-based products – Impact of moisture content and temperature” [1]. In that paper, hygrothermal properties of wood-based products were measured, including the sorption isotherm and vapour permeability of wood-fibre insulation. In the four years since that publication, these results have been referenced frequently [2-11]. The present author contends though that the study in [1] contains flaws in the measurement, calculation and presentation of the vapour permeability of wood-fibre insulation. These have led to the wider adoption of incorrect permeabilities [2-11], which in turn have resulted in debateable claims, on the inaptitude of stationary vapour diffusion experiments [8,10] and on the importance of advection in hygroscopic ad-/desorption [9,11]. The goal of this discussion is to reveal the erroneous measurements, calculations and presentations in [1] as well as to discuss the ramifications for the investigations [2-11] making use of [1]’s outcomes.

2. FLAWED PRESENTATIONS AND CALCULATIONS IN [1]

Please note that most results are given as pairs of values, for dry cup and wet cup respectively.

2.1 Air-gap-corrected vapour permeabilities

The vapour permeability of wood-fibre insulation was measured in [1] via cup tests. In such test, the top and bottom surfaces of a sample are exposed to two different environments at two different vapour pressures. Typically one environment is maintained by a saturated salt solution in a small metal or glass cup while the other environment is provided via a climate chamber [12]; but alternatives exist. The vapour pressure difference between these two environments results in a vapour diffusion flow, which is measured via the mass change of the cup. This vapour flow then allows derivation of the intrinsic vapour permeability of the material. In this calculation however, one should correctly account for the additional diffusion resistances, between the cup’s solution surface and the sample’s bottom surface, and between the sample’s top surface and the climate chamber [12], see also equations 1-8 in [1]. The cup tests in [1] applied wood-fibre insulation at thicknesses of 2, 3 and 4 cm. The climate chamber was kept at 50 %RH, whereas 9 or 97 %RH was provided in the cups for dry cup and wet cup tests, respectively. The samples were preconditioned in two different ways: one series was dried in a ventilated oven at about 7 %RH, the second series was kept in a humid room at 100% RH. In [1], these are dubbed ‘dry’ and ‘wet’, not to be confused with ‘dry cup’ and ‘wet cup’ tests.

The primary findings in relation to the vapour permeability of wood-fibre insulation are collected in Tables 4 and 6 in [1]. The primary results are vapour permeabilities of $3.6 \cdot 10^{-11}$ s to $4.6 \cdot 10^{-11}$ s and $7.4 \cdot 10^{-11}$ s to $8.3 \cdot 10^{-11}$ s and vapour resistance factors of 4 to 6 and 2 to 3 (Table 4), which are subsequently synthesised to 6 and 2 (Table 6). Unfortunately neither of these represent the intrinsic vapour permeability of the material: the tables present ‘air-gap-corrected’ permeabilities, corrected for the resistance between cup solution and sample surface, but not for the resistance between sample surface and climate chamber. The air-gap-corrected values are an unfortunate presentation choice. Because they still include the impact of the top surface transfer resistance, they are not generalizable, as that resistance is specific to the set-up used. They are moreover not the primary interest for researchers and practitioners, which (almost) always require intrinsic permeabilities. It will be demonstrated below that most researchers who use [1]’s permeabilities [2-11] did not distinguish between the provided air-gap-corrected values and the desired intrinsic values. This lack of distinction is probably also exacerbated by an additional presentation flaw: in Tables 4 and 6 in [1] these air-gap-corrected permeabilities are used for calculating the water vapour resistance factor μ , while EN ISO 12572 [12], and equation 8 in [1], prescribe its calculation from the intrinsic permeability instead. Despite Tables 4 and 6’s explicit mention of air-gap-corrected permeabilities being presented, the use of the ‘water vapour resistance factor μ ’ formulation evidently has misled most readers.

A similar flaw is present in the related [13], among others comprising the results of [1]. In [13]’s Figure 16, dry and wet cup vapour permeabilities of wood-fibre insulation are shown. And while

it is admittedly not evident in that figure, the first author of [1] (in charge of [13]’s LMDC results) has confirmed that these are not intrinsic but again air-gap-corrected vapour permeabilities [14].

2.2 Intrinsic vapour permeabilities

The only mention of intrinsic vapour permeabilities is given just above Figure 12 in [1], where it is indicated that these range “between 10^{-10} s and 10^{-9} s”. The reader needs to be alert to detect this statement, and even more so to note the implicit ringing of alarm bells. The range spanning one order of magnitude, with the upper limit 5 times larger than the vapour permeability of air, is a concern. Indeed, this range is incorrect due to an erroneous identification of the surface transfer resistances between the sample surface and the climate chamber. The values in Table 5 in [1] are $7 \cdot 10^8$ m/s and $2 \cdot 10^8$ m/s, but these are believed to be incorrect for several reasons.

Firstly, Figure 1a repeats Figure 12 of [1]. This indicates that the above-mentioned resistances were determined at the intersections of the average regression line with the vertical axis. However, this axis represents a sample thickness of 1.5 cm and the given resistance values include 1.5 cm of material. The intersections of the average regression lines with the origin gives resistances of $5.5 \cdot 10^8$ m/s and $-0.4 \cdot 10^8$ m/s instead. Secondly, it is unclear how the regression lines were determined. Figure 1b overlays the excel-cloned average measurement results (markers), on which linear least-squares regressions are fitted (lines). It is evident that the slopes of these fits diverge from the original trendlines, the latter displaying a downward and upward bias. With these new regressions, the final resistances become $5.8 \cdot 10^8$ m/s and $-0.7 \cdot 10^8$ m/s.

The impact of such different surface transfer resistances is significant. Let us (illustratively) approximate the thickness/ π_{agc} values for 4 cm samples as $9.5 \cdot 10^8$ m/s and $5.3 \cdot 10^8$ m/s. Applying [1]’s equation 7 with the original resistances yields intrinsic permeabilities $16 \cdot 10^{-11}$ s and $12 \cdot 10^{-11}$ s. On the other hand, intrinsic permeabilities of $11 \cdot 10^{-11}$ s and $6.7 \cdot 10^{-11}$ are obtained for the final resistances, 30 to 45 % lower than the original values. If similar calculations are performed for all results shown in Figure 1, the ranges of intrinsic vapour permeabilities become $15 \cdot 10^{-11}$ s to $38 \cdot 10^{-11}$ s and $11 \cdot 10^{-11}$ s to $170 \cdot 10^{-11}$ s for the original resistances, versus $8.2 \cdot 10^{-11}$ s to $15 \cdot 10^{-11}$ s and $6.0 \cdot 10^{-11}$ s to $7.3 \cdot 10^{-11}$ s for the final resistances.

It should be noted though that all recalculations above are to be treated with caution, as they are based on a reproduced excel-clone. It can be assumed though that the resistance and permeability magnitudes are fairly dependable. The analysis shows that the corrected surface transfer resistances lead to intrinsic vapour permeabilities in the range of $6 \cdot 10^{-11}$ s to $15 \cdot 10^{-11}$ s, dramatically lower than [1]’s original range “between 10^{-10} s and 10^{-9} s”. Additionally, these new values also clearly suggest that the air-gap-corrected permeabilities adopted in [2-11] are undoubtedly an underestimation.

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Figure 1: a. original of Figure 12 in [1], with π_{agc} [s] the air-gap-corrected vapour permeability; b. cloned version of Figure 12 in [1], with regression lines for dry cup and wet cup respectively; in the expressions for the latter, x and y are thickness and thickness/ π_{agc} , respectively. The arguments and calculations described however do completely not address the elephant in the room, which is the unphysical character of the original and final surface transfer resistances between sample surface and climate chamber. Firstly, there is that negative value for the final resistance for the wet cup data. Such calculated negative resistance belies physical reasoning, and it brings significant doubt on the entire transformation of air-gap-corrected permeabilities to intrinsic permeabilities by subtraction of the surface transfer resistance between sample surface and climate chamber. The principle put forward in Figure 5 of [1] evidently does not hold for the wet cup tests, and all intrinsic wet cup permeabilities should thus be considered unidentifiable. Secondly, the same conclusion holds for the intrinsic dry cup permeabilities, owing to the thickness/ π_{agc} value for the 3 cm wet sample. It is not easily discernible in Figure 1a, but more clearly visible in Figure 1b, with its thickness/ π_{agc} value about equal to $4.1 \cdot 10^8$ m/s. This is lower than the related surface transfer resistance of $7.0 \cdot 10^8$ m/s (original) or $5.8 \cdot 10^8$ m/s (final), which again defies physical reasoning. This leads to a similar conclusion that all intrinsic dry cup permeabilities should hence also be considered unidentifiable. While the first violation was not notable for the authors of [1], the second violation was also present in their analysis. However, at no point is this discussed in their text. Finally, some readers may find this conclusion of unidentifiability excessively strong, further support for this particular word choice will be offered in Section 4. It should additionally be noted that Table 5 in [1] moreover swapped the resulting h_m -values: $1/h_m$ equal to $7 \cdot 10^8$ m/s converts to h_m $1.4 \cdot 10^{-9}$ s/m, and vice versa. This mistake has no impact on the reported analysis however.

2.3 Final remarks

Notwithstanding that the intrinsic vapour permeabilities calculated above have been shown to be incorrect, the analysis offers strong indications that the widely adopted air-gap-corrected vapour permeabilities of wood-fibre insulation [2-11] in most cases significantly underestimate the actual intrinsic permeabilities. And such underestimation may have important ramifications for these studies' findings and conclusions, the extent of which depends on the actual application. These are discussed in Section 3, in order of increasing impact of the incorrect adoption of air-gap-corrected permeabilities as intrinsic permeabilities for the wood-fibre insulation.

3. RAMIFICATIONS FOR REFERENCING PUBLICATIONS [2-11]

3.1 Incorrect literature reviews

For studies [2-4], the impact remains limited to having incorrect values for the vapour permeability and resistance factor of wood-fibre insulation in their text and possibly incorrect observations on the relative ease of vapour diffusion in comparison to other materials. For example, Nguyen et al. [2] mention the vapour resistance factor 6, adopted from [1], in their introduction. Cetiner and Shea [3] bring up the vapour resistance factors of 6 and 2, taken from [1], and employ these as comparative reference for the diffusion capacities of wood waste. As [1]'s vapour resistance factors are too high, wood waste is actually relatively even less permeable than noted. Asdrubali et al. [4] similarly absorb the vapour resistance factors of 6 and 2, with again flawed findings on the relative ease of vapour transmission in wood-fibre insulation versus other materials.

3.2 Incorrect material properties

The situation gets slightly worse for researchers that use [1]'s air-gap-corrected vapour permeabilities and resistance factors for hygrothermal simulations. Pečenko et al. [5] apply [1]'s vapour resistance factor of 6 to model the vapour permeability of wood-fibre insulation and consequently arrive at inaccurate predictions on the relative ease of vapour transmission in the investigated materials. Berger et al. [6] likewise adopt [1]'s – via a reference to [7] – vapour resistance fac-

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tors 6 and 2 for calculating the vapour permeability of wood-fibre insulation. Strangely though, the authors translate these to $3 \cdot 10^{-10}$ s as intrinsic vapour permeability, while $0.3 \cdot 10^{-10}$ s to $1 \cdot 10^{-10}$ s are the more correct conversions.

The impact becomes far more worrying however for the validation study by Rafidiarison et al. [7], which similarly adopt [1]’s vapour resistance factors of 6 and 2. This creates the unfortunate situation that numerical simulations of a validation experiment are marred by incorrect material properties. This may erroneously persuade model developers to ‘correct’ their simulation program, inspired by divergences between measurement and simulations, caused not by their numerical model itself, but by the material properties used. The simple oversight by Rafidiarison et al. [7] may therefore snowball into something much bigger.

3.3 Incorrect research conclusions

Even more troubling are the incorrect research conclusions that originate from adopting [1]’s air-gap-corrected vapour permeabilities as intrinsic vapour permeabilities, which is the case for four studies [8-11], that all work on characterizing hygrothermal properties via dynamic experimentation and parameter identification.

3.3.1 Rouchier et al. [8] and Rouchier et al. [9]

Rouchier et al. [8,9] mistakenly adopt [1,13]’s air-gap-corrected vapour permeabilities as the expected intrinsic vapour permeabilities of the wood-fibre insulation. Averaging over three measurement results from [13], $3.6 \cdot 10^{-11}$ s and $7.2 \cdot 10^{-11}$ s are taken as the expected intrinsic permeabilities (in line with values in [1]’s Table 4). From their dynamic experimentation and parameter identification though, they obtain $6.5 \cdot 10^{-11}$ s and $14.0 \cdot 10^{-11}$ s [8] and $16 \cdot 10^{-11}$ s and $50 \cdot 10^{-11}$ s [9] (interpreted from Figure 6 in [9]). Because the latter values diverge strongly from other studies [8,10], the authors’ comments [9] on the overparameterisation and the underidentifiability of the vapour permeabilities – the latter perhaps a result of including the surface vapour transfer coefficient in the identification – may be invoked to disregard these disproportionately large permeabilities.

But still, in [8], the dynamic experimentation with parameter identification yields vapour permeabilities that are double the values taken from [1,13]. The authors then proceed by explaining the deviations 1) via the potential unreliability of stationary cup experiments for use in dynamic conditions [8]; or, 2) with the neglected contribution of advective vapour transport in hygroscopic ad-/desorption [9]. Both statements contradict a state-of-the-art that has been developed over decades of research. However, given the indications of higher intrinsic permeabilities put forward above, the actual deviations between expected and obtained intrinsic permeabilities most likely are less substantial, reducing the strength of their claims on the inaptitude of stationary cup experiments and on the impact of advection on hygroscopic ad-/desorption.

3.3.2 Busser et al. [10] and Berger et al. [11]

Busser et al. [10] and Berger et al. [11] similarly erroneously adopt the air-gap-corrected vapour permeabilities of [1,13] as expected intrinsic vapour permeabilities of the wood-fibre insulation. When calculating their vapour permeability expressions, for relative humidities 25 % and 75 % (representative for the dry cup and wet cup condition), these give $5.5 \cdot 10^{-11}$ s and $8.5 \cdot 10^{-11}$ s [10] and $3.8 \cdot 10^{-11}$ s and $6.6 \cdot 10^{-11}$ s [11] (consistent with [1]’s Table 4). The dynamic experimentation and parameter identification in [10], which exclusively includes diffusion as vapour transport mechanism, yields $12 \cdot 10^{-11}$ s and $14 \cdot 10^{-11}$ s, again substantially higher than their expected vapour permeabilities taken from [1,13].

Like Rouchier et al. [8,9], the authors refer to the potential unreliability of the stationary cup experiments for use in dynamic conditions and the neglected impact of advective vapour transport in hygroscopic ad-/desorption to explain these deviations [10]. However, in line with the discussion of [8,9], these deviations are probably inflated by adopting the air-gap-corrected permeabilities from [1] as expected intrinsic permeabilities. Based on the above indications of higher intrinsic permeabilities, the actual deviations between expected and obtained intrinsic permeabili-

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ties most likely are less significant, reducing the weight of their assertions on stationary cup experiments and on advection in hygroscopic ad-/desorption.

Berger et al. [11] proceed on the latter premise however, and include advective vapour transport in a next iteration of their parameter identification model. Based on that, their estimates for the intrinsic dry cup and wet cup vapour permeabilities are substantially smaller, particularly $5.1 \cdot 10^{-11}$ s and $6.4 \cdot 10^{-11}$ s. These outcomes are much closer to their air-gap-corrected values adopted from [1,13], but require a substantial vapour transport via advection to contribute to the vapour transfer process [11]. The authors then use these findings to promote their opinions on the vital role of advection in hygroscopic ad-/desorption processes, a claim that was already put forward in an earlier publication [6].

The earlier indications of higher intrinsic permeabilities make the study in [10], where only diffusion is considered, more plausible, while rendering the analysis in [11], in which significant advection is embraced, less credible. That being said, one must wonder how a sample wrapped in aluminium tape at the lateral and bottom surfaces [11] would permit the continuous permeation of air through the sample. The same question is valid for [6], where a continuous air permeation through an airtight sample [15,16] is invoked to explain deviating experiments and simulations of hygroscopic ad-/desorption.

3.4 Final remarks

Several authors [2-11] have improperly adopted the air-gap-corrected vapour permeabilities from [1,13] as expected intrinsic vapour permeabilities of the wood-fibre insulation. The impact of this fault ranges from minimal to substantial, depending on the use of the incorrect values. In some studies [2-6], it is limited to including too low permeabilities in literature reviews, or applying too low permeabilities in numerical simulations. The effect of the error becomes more significant in [7] though, where too low permeabilities are considered for validation simulations. The influence of this error is strongest though for the studies on dynamic experimentation and parameter identification [8-11], where they escalate the deviations between the expected and obtained vapour permeabilities. This in turn results in challenges to the current state-of-the-art on measurement and simulation of hygroscopic moisture transport in porous materials. The arguments in Section 2 indicate however that the actual intrinsic vapour permeabilities are likely higher than the adopted air-gap-corrected vapour permeabilities, hence invalidating, at least in part, the support for their claims.

4. DISCUSSION

This issue would not have become an issue had the vapour transmission measurements in [1] been performed according to the guidelines in EN 12572 “Hygrothermal performance of building materials and products – Determination of water vapour transmission properties” [12]. Firstly, the standard explicitly states that the cup test is not always sufficiently accurate for very permeable materials: “This standard is not applicable in the case of test specimens with water vapour diffusion-equivalent air layer thickness values less than 0,1 m, as a result of increasing uncertainty in the measurement results.” More importantly though, the standard also explicitly states that the surface transfer resistance between sample surface and climate chamber should be negligible when measuring on very permeable materials: “To ensure that the resistance of the air layer above the test cup is negligible, when very permeable materials ... are tested the air in test chamber shall be stirred and the test assemblies arranged within the chamber to ensure that the air velocity above each specimen is at least 2 m/s.”

In relation to the first restriction, an assumed intrinsic permeability of $1 \cdot 10^{-10}$ s brings the minimal sample thickness at 5 cm, while the authors use samples of 2 to 4 cm. Regarding the second requirement, a 2 m/s air velocity would reduce the surface transfer resistance between sample surface and climate chamber to below $2 \cdot 10^7$ m/s [17-19], equivalent to an air layer of roughly 4 mm.

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Compared to the imposed 0.1 m of equivalent air layer thickness for the samples, this is indeed negligible. Abiding by both clauses would nullify the differences between air-gap-corrected and intrinsic permeabilities, avoiding [1]’s misrepresentation of the air-gap-corrected permeabilities as well as miscalculation of the intrinsic permeabilities, and avoiding [2-11]’s misinterpretations. Regrettably though, [1]’s tests do not comply with the EN 12572 guidelines, by allowing too high surface resistances and too low sample thicknesses.

By not abiding by these guidelines, the authors of [1] have made their tests on vapour diffusion in wood-fibre insulation improper for the actual determination of the desired intrinsic vapour permeabilities. And while the results displayed in [1]’s Figure 12 should have triggered caution (e.g. the disturbing findings for the 3 cm wet_dry cup samples), these triggers were not confronted by the authors.

Sadly though, this issue may go far beyond [1], since a second standard on vapour transmission measurements is available, particularly EN 12086 “Thermal insulating products for building applications - Determination of water vapour transmission properties” [20]. And whereas EN 12572 has the explicit demands on the equivalent thickness of the samples and the air velocity in the climate chamber described above, these are not to be found in EN 12086. EN 12086 moreover renders correcting for the diffusion resistance between the cup’s solution surface and the sample’s bottom surface optional instead of mandatory. A single example of its use for very permeable materials can be found in [21], but many more are available in the literature.

Finally, this issue would not have become an issue either if the possibly dubious claims based on it had not made it to print; it were these challenges to the state-of-the-art that drew attention. It would be prudent if authors, reviewers and editors alike would be more critical and demanding with respect to the burden of proof when decades of research are challenged by a limited set of new findings.

5. CONCLUSIONS

In 2014, this journal published the paper ‘Characterization of hygrothermal properties of wood-based products – Impact of moisture content and temperature’ [1], presenting among others the vapour permeability of wood-fibre insulation. This discussion has shown that the measurement, the calculation and the presentation of this vapour permeability has suffered from various errors, invalidating the obtained intrinsic vapour permeabilities of wood-fibre insulation. This discussion has furthermore demonstrated that many authors [2-11] have moreover misinterpreted [1]’s air-gap-corrected vapour permeabilities as intrinsic vapour permeabilities. This undermines, in part at least, their challenges to the state-of-the-art in relation to measurement and simulation of hygroscopic moisture transport in porous materials.

The main flaw of this discussion is that it has not been possible to provide corrected intrinsic vapour permeabilities for wood-fibre insulation; thus imparting numerous conclusions in the text a conditional status. There are strong indications that the real intrinsic vapour permeabilities are higher than the air-gap-corrected values adopted in [2-11], but that conjecture has not been factually established yet. It is thus kindly proposed that the authors of [1-11] make another attempt at determining the intrinsic vapour permeability of wood-fibre insulation via cup tests, to come to a reliable characterisation. Upon invitation, the author of this discussion will gladly participate in that effort.

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