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ORIGINAL RESEARCH

The fiber saturation point: does it mean what you think it means?

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Abstract Wood–water interactions are central to wood science, technology, and engineering. In the early twentieth century, the term "fiber saturation point" was coined to refer to the point of transition from the domain where wood properties change with moisture content to the domain where wood properties are constant. This conceptual model assumed that the wood cell walls are water saturated at this transition point and that capillary water appears above this point. This has since then been contradicted by multiple studies. Additionally, the fiber saturation point has been associated with techniques that do not necessarily measure the same moisture state. Some techniques characterize either the transition state at which wood properties change, or the state at which the cell walls are water saturated. These are, however, not the same moisture state. The aim of this paper is to clarify which moisture states the various fiber saturation points represent discussed from a conceptual model consistent with current experimental evidence. To avoid confusion, we propose that the transition state at which wood properties change is the only state called "the fiber saturation point", or, for even more clarity, "the property intersection point". For other moisture states, we strongly recommend that the term fiber saturation point is avoided. The term "maximum cell wall moisture content" should be used for the state at which the cell walls are water saturated. Finally, we highlight the importance of considering which moisture state is relevant for a specific application and selecting an appropriate method to characterize that state.

Keywords Wood · Water · Moisture · Fibre saturation point · Maximum cell wall moisture content · Capillary water

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Introduction

Wood-water relations play a dominant role in wood science, since water affects nearly all properties of wood (Glass and Zelinka 2021; Thybring and Fredriksson 2023; Thybring et al. 2022). In general, water in wood can be present both within and outside of the cell walls. In other words, it is either present as cell wall water interacting with the wood polymers (cellulose, hemicellulose, and lignin), or as capillary

water within voids or cavities within the porous structure of wood (e.g., cell lumina and pit chambers). Differentiating between these two types of water has large implications for wood properties and has been a major topic of study for many years.

The first model which partitioned water into two types depending on its location was developed by Tiemann (1906), who used the word "free water" to describe the water outside of cell walls. Tiemann coined the term "Fiber-Saturation Point" (often abbreviated as FSP in the wood literature) to describe the moisture content at which the crushing strength of wood began to increase as the moisture content was decreased from the green condition. In Tiemann's exact words:

> "*In drying out a piece of wet wood, since the free water must evidently evaporate before the absorbed moisture in the cell walls can begin to dry out, there will be a period during which the strength remains constant although varying degrees of moisture are indicated. But just as soon as the free water has disappeared and the cell walls begin to dry the strength will begin to increase. This point I designate the fiber-saturation point.*"

This original definition of the fiber-saturation point was based upon measurements of the mechanical properties of wood. At high moisture contents, the addition or subtraction of water does not affect the strength, and this point on the strength-moisture content curve is thus very important for the utilization of wood in practical applications.

Although Tiemann's definition of the fiber-saturation point was based upon observed physical measurements, it assumes a theoretical framework for how water in wood behaves. Tiemann's view on how water is taken up by wood implicitly assumes that water is absorbed/desorbed in series, or as Tiemann says "*free water must evidently evaporate before the absorbed moisture in the cell walls can begin to dry out*". Additionally, for absorption, Tiemann suggests that water is first added to the cell wall and only after the cell wall is saturated, free water (capillary water) is present in voids. We illustrate this series model of water equilibrium states in Fig. 1a. Tiemann, however, did not directly determine where the water was present. Instead, he measured the changes in mechanical properties as a function of moisture content and inferred how water could be distributed within the wood to explain these observations.

In many textbooks, the inferred water distribution suggested by Tiemann, i.e. that the threshold moisture content corresponds with a moisture state with empty lumina and water-saturated cell walls, is stated as a fact (Rowell 2013, 2016; Shmulsky and Jones 2011a; Siau 1984; Skaar 1988; Stamm 1964). The change in wood physical properties above and below this threshold moisture content then must follow as a logical consequence, since capillary water does not affect these wood properties. Another logical consequence of this understanding of the distribution of water concerns fungal decay of wood. Since decay generally occurs at high moisture contents, several sources have argued that the critical moisture level for decay is the fiber saturation point, since the capillary water required by fungi is only present above the threshold (Blanchette 2000; Kirk and Cowling 1984; Scheffer and Cowling 1966; Schmidt 2006; Smulsky and Jones 2011b). Therefore, the fiber saturation point has also within this field of research shifted towards meaning the moisture content when capillary water is present in the wood structure, i.e. based on the inference made by Tiemann rather than the point at which properties change.

In the years since Tiemann developed his model, there has been a lot of progress in terms of laboratory equipment and measurement techniques to study

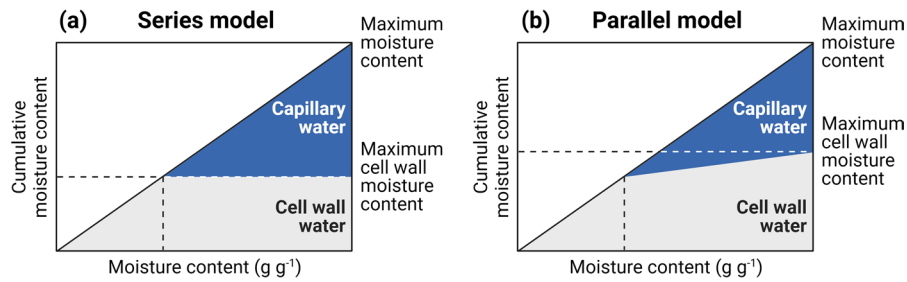

Fig. 1 Schematic illustration of the series model **a** i.e. that water is taken up first in cell walls and then in cell lumina, and the parallel model **b** i.e. that water is taken up in cell walls and cell lumina in parallel at high moisture states

different moisture states in wood. Direct measurements of the location of water at different equilibrium moisture contents have been made in several studies. Fredriksson and Thybring (2019) found that at high humidity levels, the cell wall moisture content increased with increasing relative humidity also when significant amount of capillary water was present. Differences between the cell wall moisture content at saturated state and the cell wall moisture content at other high moisture states were found in desorption as well as absorption. In another work looking at desorption, Passarini et al. (2014) observed that water existed in voids outside of cell walls in hardwoods when the cell wall was not fully saturated. These studies thus show that there is a range of equilibrium moisture contents, both in absorption and desorption, where non-saturated cell walls coexist with capillary water present. The results of these recent studies therefore contradict the series model. Instead, the data suggest that water equilibrium states in wood should be described by a parallel model, as illustrated schematically in Fig. 1b.

Apart from describing the moisture content above which properties do not change, the term "fiber saturation point" has also been used to describe the maximum moisture content that cell walls can hold. This maximum cell wall moisture content is typically defined as the amount of water in the cell walls at full saturation. As early as the 1960s, researchers began to use techniques such as solute exclusion to measure the fiber saturation point as the maximum cell wall moisture content (Ahlgren et al. 1972; Feist and Tarkow 1967; Stone and Scallan 1967, 1968; Stone et al. 1969).

If equilibrium states in wood could be described by a series model, the cell wall moisture content at saturation would be the same as the onset for detectable amounts of capillary water and the threshold moisture content below which wood properties change. However, since the series model is contradicted by recent measurements as described above these points describe different moisture states despite all being called the "fiber saturation point." Thus, a confusion in terminology has developed and the term "fiber saturation point" needs to be revisited. Furthermore, adding to this confusion, additional methods for FSP determination that do not necessarily relate either to when wood properties change or when the cell wall is saturated have been developed over the years. While several authors have noted an apparent discrepancy between reported values of the fiber saturation point measured with various techniques (Engelund et al. 2013; Thybring and Fredriksson 2023; Zelinka et al. 2016), until now the literature has not addressed which moisture states these reported values actually represent or the inherent assumptions they are based on.

The aim of this paper is to clarify which moisture states the different moisture contents called the fiber saturation point in the literature represent, and ultimately improve the terminology regarding this fundamental wood science concept. To facilitate this discussion, we review various definitions of the fiber saturation point and discuss the assumptions embedded in the resulting values. We then present recommendations for nomenclature to more clearly describe what is actually measured and which moisture state it represents. Finally, we discuss the implications for specific applications in wood science, technology, and engineering, including mechanical properties, dimensional stability, wood modification, and fungal degradation of wood.

Changes in wood properties

As stated in the introduction, water affects nearly all wood properties. Many of these exhibit a noticeable difference in behavior between low moisture states and high moisture states. They have therefore been used to derive the fiber saturation point as the intersection between these two moisture domains. In the following, three methods are described.

Mechanical properties

Tiemann (1906) investigated various mechanical properties of wood as a function of moisture content. Small specimens were tested to facilitate rapid moisture conditioning and to help achieve uniform moisture content in the test blocks. Tiemann (1906) observed that ultimate crushing strength (compression parallel to grain) had the sharpest dependence on moisture content. The strength is, however, not linearly correlated with the moisture content, and therefore Wilson (1932) suggested plotting the logarithm of the strength. The fiber saturation point is then determined as the intersection between a linear

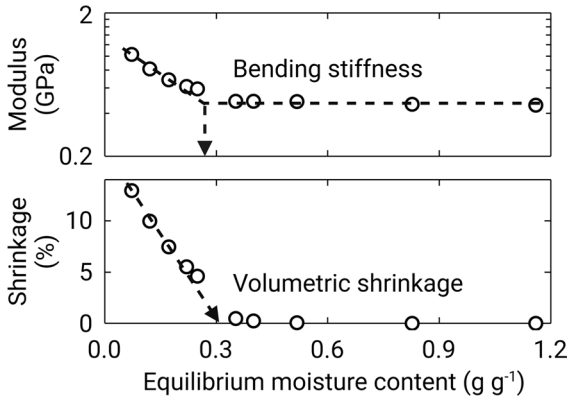

Fig. 2 An illustration of how the fiber saturation point has been determined from bending stiffness and volumetric shrinkage. Based on data for beech (*Fagus grandifolia* Ehrh.) from Almeida and Hernandez (2006)

regression at low moisture contents and a horizontal line, which is illustrated for bending stiffness data in Fig. 2.

This derivation of the fiber saturation point is based on the assumption that sorption of cell wall water and capillary water occurs in series, and that the observed change in mechanical properties reflects a transition between the sorption of cell wall water and capillary water.

Bulk dimensions

The shrinkage of wood is often expressed in terms of the change in external dimensions at a given moisture content as a percentage of the dimensions in the water-saturated condition. Shrinkage can be measured in the radial direction, the tangential direction, or the total bulk volume. The fiber saturation point has been derived from the x-intercept in a linear regression of bulk shrinkage against moisture content of specimens conditioned to equilibrium in the hygroscopic regime (Fig. 2). It is not clear when the fiber saturation point was first defined in this way, but the method is discussed by Stamm (1934, 1935). This derivation of the fiber saturation point is based on the assumption that sorption of cell wall water and capillary water occurs in series, and that the observed shrinkage reflects a transition between the sorption of cell wall water and capillary water.

Electrical properties

Stamm (1929) was the first researcher to use measurements of the electrical conductivity of wood to determine the fiber saturation point. The electrical conductivity of wood depends strongly on the wood moisture content and increases over 10 orders of magnitude from oven-dry wood to the fully water-saturated state (Glass and Zelinka 2021). However, most of the change in conductivity occurs at low moisture contents. Stamm (1929) determined the fiber saturation point by slowly drying small pieces of wood and measuring the electrical conductance. He found that the curve exhibited bilinear behavior on a semi-log scale; at low moisture contents the log of the conductivity increased with moisture content with a steep slope whereas at high moisture contents the log of the conductivity only increased slowly with moisture content. Stamm extrapolated these two linear regions and declared that the intersection was the fiber saturation point (Fig. 3). This is similar to Tiemann's approach of locating the point where a wood property's moisture dependence changes. This derivation of the fiber saturation point is based on the assumption that sorption of cell wall water and capillary water occurs in series, and that the observed change in electrical conductivity reflects a transition between the sorption of cell wall water and capillary water.

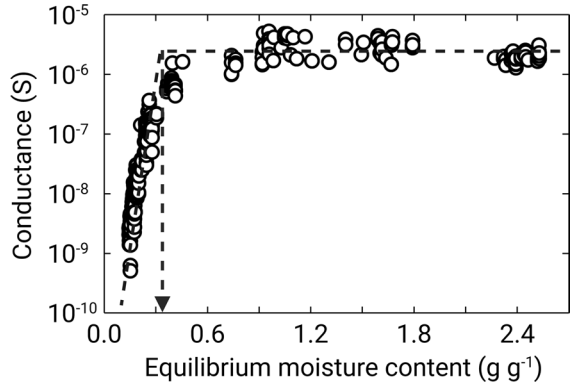

Fig. 3 An illustration of how the fiber saturation point has been determined from electrical conductance. The data shown are for Norway spruce (*Picea abies* (L.) Karst) from Fredriksson et al. (2021)

Partitioning of water in the saturated moisture state

A range of measurement techniques in the literature are based on an interpretation of the fiber saturation point as the amount of water in the cell walls in the water-saturated state. This requires experimental techniques that can distinguish the cell wall water from the capillary water. Four methods are reviewed here: differential scanning calorimetry (DSC), low-field nuclear magnetic resonance (NMR) relaxometry, solute exclusion, and the maximum swelling method. Figure 4 shows examples of literature data for Norway spruce (*Picea abies* (L.) Karst) where the total wood moisture content is divided into a moisture content representing water in cell walls and water outside of cell walls, respectively.

Differential scanning calorimetry

DSC measures the heat involved in the freezing and/or melting of water in the temperature range close to 0 °C. Since water confined within the cell walls does not exhibit a phase change close to 0 °C, the heat involved in freezing/melting of water-saturated wood correlates with the amount of capillary water (Fredriksson and Thybring 2019; Passarini et al. 2017; Simpson and Barton 1991; Thybring et al. 2020). By drying out samples after testing, the total moisture content can be determined and the cell wall moisture content is calculated by subtracting the amount of freezable water. This derivation of the fiber saturation point does not require assumptions about how cell wall water and capillary water change with the total moisture content. It does, however, assume that all water inside of cell walls does not freeze and all water outside of cell walls freezes at the lowest temperature used in the experiments. Capillary water close to surfaces (~ 1 nm thick layer) and in nano-pores can, however, be restrained from freezing or have a depressed freezing point, whereby it is counted as part of the cell wall water. However, the error in the determined cell wall moisture content is typically insignificant (Fredriksson and Thybring 2019).

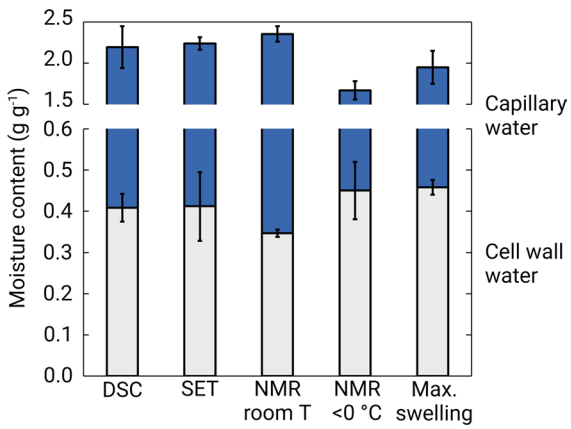

Fig. 4 Total moisture content of water-saturated wood divided into cell wall water and capillary water moisture contents. Based on data from the following references. Maximum swelling: (Babiak and Kúdela 1995), SET, DSC and NMR (room temperature): (Thybring et al. 2020), NMR (sub-zero temperature): (Telkki et al. 2013). All data are for Norway spruce (*Picea abies* (L.) Karst.)

NMR relaxometry

NMR relaxometry can differentiate between hydrogens of water molecules found in different physical and chemical environments. The basis is a measurement of the very small magnetic polarization that arises when an object is placed in a static magnetic field. This forces the spins of the hydrogen nuclei into one of two energy states (along and against the field). A tiny difference in abundance between these energy states is what causes the magnetization that is aligned with the direction of the magnetic field. By applying short-lived radio-frequency pulses, the magnetization is forced out of alignment with the static field after which the gradual re-alignment over time is recorded. The rate of re-alignment is different for hydrogens in different environments. Thus, hydrogens of water molecules strongly interacting with the solid cell walls re-align much faster than hydrogens of water molecules which only interact with other water molecules. With exponential decay analysis, the proportion of water molecules in various local environments can be differentiated. For water-saturated or green wood specimens, water is typically found in 3–4 different environments (Almeida et al. 2007; Araujo et al. 1992; Beck et al. 2018; Fredriksson and Thygesen 2017; Menon et al. 1987; Thygesen and Elder 2008) of which the fast re-aligning water (shortest relaxation time) corresponds with the cell wall water. By gravimetric determination of the total moisture content, the cell wall moisture content can be determined by the fraction of the total NMR signal attributable to

cell wall water. This derivation of the fiber saturation point does not require assumptions about how cell wall water and capillary water change with the total moisture content. One uncertainty of the method is, however, that the amount of cell wall water appears to be underestimated if the measurements are performed above 0 °C (Beck et al. 2018). Instead, another protocol is adopted which determines the fiber saturation point from measurements at sub-zero temperatures (Beck et al. 2018; Telkki et al. 2013).

Solute exclusion

The solute exclusion technique was developed for characterizing the nano-scale porosity of pulp and wood, but can also be used to determine the amount of cell wall water in water-saturated wood (Ahlgren et al. 1972; Feist and Tarkow 1967; Stone and Scallan 1967, 1968; Stone et al. 1969). This is done by placing water-saturated specimens in an aqueous solution of probe molecules of known size and measuring the change in probe concentration by chromatography after equilibrium has been established. By selecting probe molecules that cannot enter the nano-pores in the solid cell walls, these molecules will only diffuse into the water volume outside cell walls. The change in probe concentration is therefore related to the capillary water volume and from determination of the total water content, the cell wall moisture content can be calculated. This derivation of the fiber saturation point does not require assumptions about how cell wall water and capillary water change with the total moisture content. The method will, however, mischaracterize the cell wall moisture content if the probe molecules enter cell walls, are adsorbed on solid surfaces or are otherwise excluded from the solution in the capillaries, e.g. filtered by pit membranes.

Maximum swelling

This technique is based on a measurement of the increase in bulk wood volume and mass from the dry state to water-saturation (Babiak and Kúdela 1995). The masses are recorded with a balance and the dry volume with a caliper. The water-saturated volume can either be found with a caliper or by using a procedure based on Archimedes' principle, where the mass of a water-saturated specimen is determined both in air and in water. Whichever method is used for this, the underlying assumption is that the amount of cell wall water is directly correlated with the bulk wood volume increase. Thus, by multiplication of the maximum swelling with the liquid water density, the mass of cell wall water is found. This derivation of the fiber saturation point does not require assumptions about how cell wall water and capillary water change with the total moisture content. However, the method relies on the assumption that the density of cell wall water is equal to the liquid water density, i.e. that there is no compaction of cell wall water or that this is balanced by the formation of free volume during swelling. Furthermore, it is assumed that changes in bulk wood volume are directly correlated with water uptake, i.e. that the volume of the capillary structure is identical in the dry and water-saturated state. These assumptions are at best approximations, since cell wall water has been suggested to have a higher density than liquid water (Matthews et al. 2006).

The sorption isotherm

The relation between the equilibrium moisture content of a material and the ambient relative humidity at constant temperature is described by the sorption isotherm. Apart from the ambient climate, the equilibrium moisture content also depends on moisture history (sorption hysteresis), resulting in different sorption isotherms for absorption and desorption (Pidgeon and Maass 1930; Sheppard and Newsome 1929; Urquhart and Eckersall 1930; Weichert 1963). Figure 5 shows schematic sorption isotherms for wood both as total sorption isotherms (blue curves) including water both within and outside cell walls, and as cell wall sorption isotherms (brown curves) including only water within cell walls. The maximum cell wall moisture content $u_{\mathrm{cw,\ max}}$ (see "Partitioning of water in the saturated moisture state"), is marked in both Fig. 5a, b for reference. Total sorption isotherms are commonly determined using the pressure plate technique (Almeida and Hernandez 2007; Defo et al. 1999; Fredriksson and Thybring 2019; Thygesen et al. 2010) and the upper moisture content limit in such sorption isotherms depends on the wood density, but is typically 1.5–2.0 g g^{-1}, i.e. substantially higher than cell wall sorption isotherms where the upper moisture content limit is typically 0.30–0.40 g g^{-1}. Cell wall sorption isotherms can be determined by

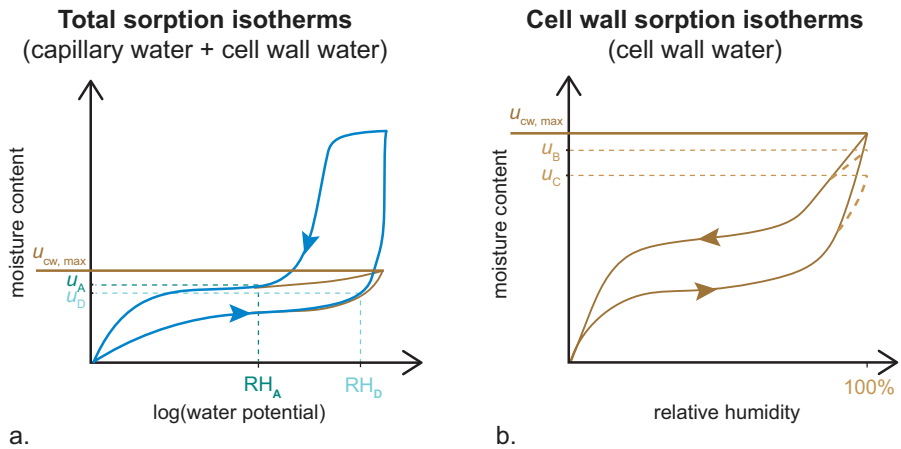

Fig. 5 Schematic sorption isotherms illustrating **a** total sorption isotherms including both capillary water and cell wall water (blue curves) and **b** cell wall sorption isotherm (brown curves) including only water in cell walls

combining conditioning with saturated salt solutions/pressure plate with DSC measurements as described by Fredriksson and Thybring (2019). Also, sorption isotherms determined in the range 0–95% RH using sorption balances or saturated salt solutions are typically cell wall sorption isotherms since detectable amounts of capillary water are normally not present at these RH levels, although exceptions occur (Passarini et al. 2014).

In the literature, attempts have been made to derive the fiber saturation point from sorption isotherms using primarily three methods. The first includes defining the fiber saturation point as the equilibrium moisture content at a certain relative humidity/water potential (typically in desorption in the over-hygroscopic region) as illustrated by u_A in Fig. 5a. The second method includes deriving the fiber saturation point by extrapolation of hygroscopic sorption isotherms to 100% relative humidity using various sorption isotherm models, illustrated by u_B and u_C in Fig. 5b. Finally, the third method includes determination of the moisture content after conditioning above liquid water (typically in absorption) illustrated as u_D in Fig. 5a. These methods and moisture states are described in detail in the following sections.

Equilibrium moisture content at a certain relative humidity/water potential

Defining the fiber saturation point as the equilibrium moisture content at a certain relative humidity/water potential, wood specimens are usually conditioned to different high moisture states in desorption using the pressure plate technique (Griffin 1977; Stone and Scallan 1967). A plateau on the desorption isotherm is then identified, and the moisture content at this plateau is considered to be the fiber saturation point (Griffin 1977; Stone and Scallan 1967), i.e. it is defined as u_A in Fig. 5a. This approach is thus based on the hypothesis presented by Tiemann (1906), i.e. that all capillary water is removed before the cell wall starts to dry and this is presumed to happen at the identified plateau in the desorption isotherm. Stone and Scallan (1967) chose the moisture content at 99.75% relative humidity in desorption to represent the fiber saturation point, while Griffin (1977) chose the moisture content at 99.93% relative humidity. A similar approach was also used by Perem (1954) and Choong and Tesoro (1989), but instead of using the pressure plate method, they centrifuged saturated wood samples. Both studies used a range of speeds and identified a plateau in moisture content at which the fiber saturation point was defined.

The approach to define the fiber saturation from a point in the desorption isotherm in the way described above is problematic for several reasons. Firstly, it assumes that desorption occurs in series where capillary water is entirely absent before cell walls begin to dry. However, as discussed in the Introduction, more recent research has shown that this is not the case. The shape of the total sorption isotherm by itself does not provide sufficient information to separate cell wall water from capillary water. Secondly, the macro void structure is different for different wood species, and some wood species include cell types with small pit openings and capillary water have been observed

down to 76–90% relative humidity in desorption for some wood species (Almeida et al. 2007; Hernández and Cáceres 2010; Passarini et al. 2015). Therefore, a relative humidity level that gives reasonable value of the fiber saturation point for one wood species can give an apparently higher value for another wood species since capillary water is still within the wood structure because of anatomical features.

Extrapolation of hygroscopic sorption isotherms

Regarding the second method, extrapolation of hygroscopic sorption isotherms, this is typically done by using sorption isotherm data measured between 0 and 95% relative humidity, i.e. parts of the sorption isotherms for cell wall water in Fig. 5b. The sorption isotherm data are then extrapolated to 100% relative humidity using various sorption isotherm models (Hill et al. 2009; Jalaludin et al. 2010; Shen et al. 2021; Stamm 1971; Yang et al. 2020a; Zhang et al. 2018). The measured moisture content at 100% relative humidity is actually in the range of 0.9–2.0 g g^{-1} depending on the density of the wood (Fredriksson 2019). One could argue that this extrapolated value is the maximum cell wall moisture content, but the extrapolation becomes uncertain because of the lack of cell wall moisture content data between 95 and 100% relative humidity. Additionally, different values will be obtained depending on the choice of sorption isotherm model (Babiak and Kúdela 1995) and depending on if desorption or absorption isotherm data are used (Stamm 1971) (see u_B and u_C, respectively, in Fig. 5b). This derivation of the fiber saturation point is based on the assumption that the sorption isotherm model fitted to hygroscopic sorption data also describes the increase in cell wall water absorbed in the over-hygroscopic range with an increase in RH.

Conditioning above liquid water

The third method, determination of the moisture content after conditioning specimens above liquid water (Meyer and Brischke 2015; Toba et al. 2013; Wang and Liau 1998), does not require any assumptions regarding a series or parallel nature of absorption/desorption of water in wood. It does, however, not represent a well-defined moisture state. Theoretically, this would give the equilibrium moisture content at 100% relative humidity if deionized water is used. However, such a conditioning environment is not practically possible (Perem 1954) since it would require infinitely precise temperature control. Very small changes in temperature result in condensation on colder surfaces, hereby decreasing the relative humidity below 100%; a temperature difference of just 0.1 ℃ would reduce the humidity to 99.4% while 0.5 ℃ difference would reduce it to 97% (Thybring and Fredriksson 2024; Zelinka et al. 2020a). As a result, the wood will be conditioned at an ill-defined level of relative humidity close to 100% (see u_D in Fig. 5a). Since the sorption isotherm of wood is very steep between 99 and 100% relative humidity (see e.g. Fredriksson (2019)), the moisture content will be uncertain and depend on the magnitude of temperature fluctuations in the experimental setup. This determination of the fiber saturation point is thus based on the determined moisture content at this uncertain external environment.

Presence of capillary water

In many wood science textbooks, the hypothesis by Tiemann, that the threshold moisture content found corresponds with a moisture state with empty lumina and water-saturated cell walls, is stated as a fact (Rowell 2013, 2016; Smulsky and Jones 2011a, b; Siau 1984; Skaar 1988; Stamm 1964). Especially within the field of fungal degradation, the fiber saturation point has become equal with the moisture content above which capillary water is present since this is required for fungal degradation. The fiber saturation point description presented in this way is not related to a specific experimental method, but is a statement based on the hypothesis from the original definition as a fact and subsequent derivation of its logical consequences for the behavior of wood. Hence, the values for this definition often given as a range derived from a variety of experimental methods. However, the presence of capillary water can be measured by two of the techniques described in "Partitioning of water in the saturated moisture state". The underlying assumption for these derivations of the fiber saturation point is that the presence of capillary water indicates saturation of the cell walls. It should be noted that condensation of capillary water will occur anywhere in the wood structure where conditions for equilibrium between the water meniscus curvature and external RH are fulfilled. For instance,

water menisci have been observed and their curvature studied experimentally in capillaries of mica down to 90% RH (Kohonen and Christenson 2000), fused silica down to 94.5% RH (Fisher et al. 1981), and graphite down to 70% RH (Yang et al. 2020b). The presence of capillary water in wood therefore refers to amounts that are detectable with the experimental techniques described below.

NMR relaxometry

NMR relaxometry can be used to detect the presence of capillary water as described in the section "Partitioning of water in the saturated moisture state by distinguishing between water in different environments". By using wood specimens with a range of moisture contents, the appearance of one or more components in the signal related to capillary water can be found after exponential decay analysis. The proportion of capillary water can be estimated from the weight of these component(s). The moisture content at which capillary water first appears can then be determined from the plot of components against the total moisture content (Cox et al. 2010). NMR relaxometry has been used in this way to detect the presence of capillary water during drying or water uptake studies (Cox et al. 2010; Gezici-Koç et al. 2017; Menon et al. 1987). However, monitoring specimens during wetting/drying means that there is a moisture gradient within the specimen. Capillary water can thus be present in some parts but not in others which introduces a difficulty in linking a certain amount of capillary water with a certain cell wall moisture content.

Differential scanning calorimetry

The presence of capillary water can be determined using the DSC technique as described in the section "Partitioning of water in the saturated moisture state by distinguishing between water in different environments" which distinguishes between freezable and non-freezable water in wood. By using wood specimens with a range of moisture contents, the appearance and amount of capillary water can be determined from the freezing/melting peak that arises in the DSC signal. The freezing/melting energy is linearly correlated with the amount of freezable (capillary) water. Therefore, the moisture content at which capillary water first appears can be determined as the intersection point on the moisture axis of the linearly increasing freezing/melting energy, see Fig. 6 (Passarini et al. 2017; Zelinka et al. 2012). However, proper moisture conditioning in the over-hygroscopic moisture range is required to ensure an even moisture distribution in the wood specimen (Fredriksson and Thybring 2019).

Thermodynamics

Thermodynamic analysis of water in wood relates to the energy of interaction as well as the thermal energy involved in the sorption of water in wood. Two different approaches have been described in literature for defining FSP that relates to either fundamental thermodynamic relations of water in wood or the change in thermodynamic properties with moisture content.

Phase diagram

Zelinka et al. (2016) proposed a method for determining the fiber saturation point based upon solution thermodynamics where cell wall water and capillary water are treated as separated phases of water in a two-component system (water and wood). Thermodynamically speaking, a phase refers to a portion of material where the physical and chemical properties are uniform throughout the phase.

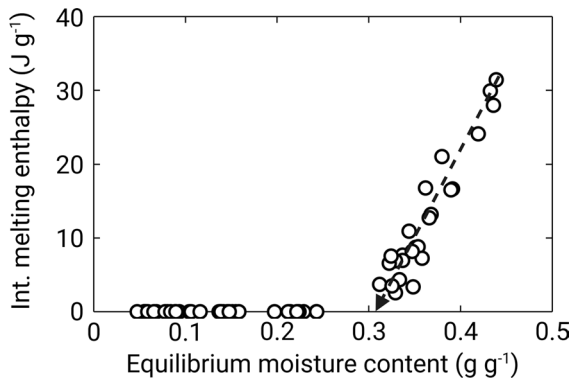

Fig. 6 The integral melting enthalpy obtained from DSC measurements at different moisture contents. Based on data from Fredriksson and Thybring (2019)

According to Le Maguer (1985), the chemical potential of the cell wall water for hydrophilic polymers can be expressed as

$$\mu_{cw} = RT\ln\left(a_w\right) = RT\ln(\varphi)$$

where μ_{cw} (J mol^{-1}) is the chemical potential of cell wall water, T (K) is absolute temperature, R (8.31528 J mol^{-1}K^{-1}) is the gas constant, a_w (-) is water activity, and φ (-) is the relative humidity. For a given moisture content, the chemical potential can thus be determined from the water vapor sorption isotherm in the hygroscopic range where the moisture content is dominated by cell wall water. Similarly, the chemical potential of the capillary water was determined through the Kelvin equation

$$\mu_{cap} = -p_c V_m$$

where p_c is the capillary pressure (Pa) and V_m is the molar volume of water (1.806 10^{-5} m^3 mol^{-1} at 25 °C). The chemical potential of the capillary water was determined by Zelinka et al. (2016) using mercury intrusion porosimetry. Hereby, the potential of the porous void structure in the wood for holding capillary water was explored based on the applied mercury pressure. From a conversion of mercury pressure to equivalent water pressure, the desorption isotherm of only capillary water could be constructed. The FSP was determined at the moisture content where the chemical potential of capillary water drops and meets the chemical potential of cell wall water derived from the hygroscopic sorption isotherm (Fig. 7). This location corresponds with a plateau in volumetric uptake of mercury as the capillary pressure increases, indicating a state close to mercury saturation of the void structure.

This derivation of the fiber saturation point relates to a state where a detectable amount of capillary water appears. In this way, this definition implicitly assumes that the presence of capillary water indicates saturation of the cell walls and thus relies on a series model of water sorption in wood.

Thermodynamic properties

Two closely related thermodynamic properties have been used to define the fiber saturation point, the integral heat of wetting and the differential enthalpy

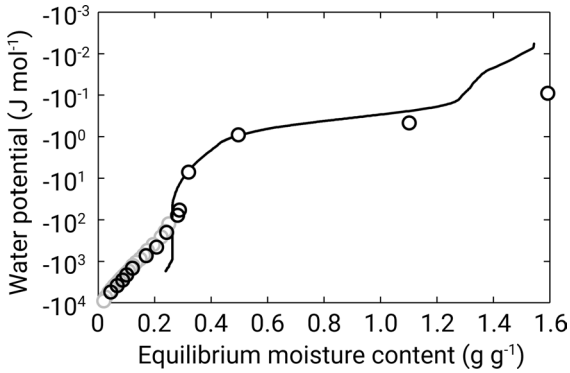

Fig. 7 Graphical method for determining the thermodynamic fiber saturation point through the intersection of the curves of the chemical potential of cell wall water and capillary water. Based on desorption isotherm data by Zhang and Peralta (1999) (black circles) and by Zelinka et al. (2016) (grey circles) as well as mercury intrusion porosimetry data (solid black line) by Zelinka et al. (2016)

of sorption. The integral heat of wetting is the amount of heat released when a wood specimen initially conditioned to a specific moisture content at a given temperature is immersed in liquid water and becomes water-saturated. The integral heat of wetting is expressed as a positive quantity in units of Joules per gram of dry solid. It is greatest for a dry material and decreases as the moisture content increases. The differential enthalpy of sorption is the difference in enthalpy between absorbed water in wood (with reference to a particular moisture content and temperature) and pure liquid water (at the same temperature). It is expressed as a negative quantity in units of Joules per mole of water (molar enthalpy) or Joules per gram of water (specific enthalpy). The differential enthalpy of sorption is equivalent to the derivative of the integral heat of wetting with respect to moisture content. The magnitude of the differential enthalpy of sorption also decreases as moisture content increases. Various methods for measuring and calculating these thermodynamic quantities are discussed by Nopens et al. (2019).

The fiber saturation point based on thermodynamic properties was first published by Stamm and Loughborough (1935). It is operationally defined as the moisture content at which either thermodynamic quantity reaches zero, found by extrapolation in a plot of either the integral heat of wetting or the differential enthalpy of sorption against the moisture content. It

is, however, unclear what mathematical model should be used to fit to the thermodynamic data. Stamm and Loughborough (1935) did not specify how they fit the data. Several researchers (Cooper and Ashpole 1959; Nopens et al. 2019; Skaar 1988; Weisser 1985) have used an exponential decay model, but that never reaches zero. Moreover, there is nothing thermodynamically to prevent the differential enthalpy of sorption to become positive or remain at zero even when the cell wall water is still increasing. It is therefore not clear if these thermodynamic quantities can be used to derive the fiber saturation point, and if so how this should be done.

Discussion

Different moisture states result in different fiber saturation points

In the previous five sections, we described different approaches that have been used over the years to determine the fiber saturation point. Many of these are built on Tiemann's assumption that moisture sorption in wood within and outside of cell walls occurs by a series process (see Fig. 1a). As discussed in the Introduction, Tiemann did not directly determine where the water was located but rather made an inference to explain observed changes in mechanical properties as a function of moisture content. This series model, however, is not consistent with more recent research that indicates there is a range of equilibrium moisture contents, both in absorption and desorption, where non-saturated cell walls coexist with capillary water (Fredriksson and Thybring 2019; Passarini et al. 2014). The data suggest that water equilibrium states in wood should be described by a parallel model (see Fig. 1b). Also, although the intention is to measure the fiber saturation point, the different methods and definitions do not necessarily represent the same moisture state, and hence, different values of the presumed fiber saturation point are obtained. To further illustrate this, fiber saturation point data for six wood species using some of the methods discussed above have been compiled in Table 1. The data for different methods are from different studies, on different pieces of wood (although the same wood species) which, of course, introduces a spread. Still, these data demonstrate that these methods result in different values of the fiber saturation point, which has also been emphasized previously in the literature (Engelund et al. 2013; Thybring and Fredriksson 2023; Zelinka et al. 2016). However, this is not (solely) because of methodical aspects but also because these values do not represent the same moisture state.

Suggestions for terminology

In this paper, we have shown that the term "fiber saturation point" has been used to refer to at least two distinct moisture states: the transition state at which wood properties change, and the state at which the cell walls are saturated with water. This confusion in the literature has likely arisen from the original definition of the fiber saturation point by Tiemann which implicitly assumed that these two points coincided. However, the experimental evidence currently available contradicts the series model (Fig. 1a) and supports the parallel model (Fig. 1b), i.e. that water uptake can occur simultaneously in cell walls and cell lumina at high moisture states.

The fiber saturation point as a transition point for changes in wood properties has practical implications for wood technology and engineering, such as construction, kiln drying, and composite manufacturing. The core data for practical applications, though, are the empirical, macroscale properties of wood and their dependence on moisture content. It makes no difference in practice that the cell walls are not actually saturated. The term "fiber saturation point" is well-established within this field and in line with Tiemann's original measurements, although the name is misleading regarding where the water is present. If choosing one moisture state to be called the "fiber saturation point" this should thus be it. However, for clarity, as an alternative to calling this the "fiber saturation point" we recommend using the term "property intersection point". This term has been used in prior literature as early as the 1930ies (Wilson 1932). This can be further classified according to the particular property of interest, i.e., the strength intersection point, the shrinkage intersection point, or the electrical conductivity intersection point. The methods used for determining the property intersection point are still relevant and useful, but conclusions about cell wall water or capillary water from these methods alone are not warranted.

Table 1 Literature data for the "fiber saturation point" (g g^{-1}) obtained with different methods. DSC is differential scanning calorimetry, NMR is nuclear magnetic resonance, and SET is the solute exclusion technique

Wood species		Douglas fir	Norway spruce	Radiata pine	Sitka spruce	Loblolly pine	Scots pine
Property changes	Mechanical	0.24[1]	0.27–0.31[x11]		0.25[31] 0.25–0.30[4] 0.27[1]	0.21[1] 0.31[37]	
	Dimensions	0.23–0.27[1] 0.24–0.27[2] 0.28[3]	0.26[x11] 0.30[12]	0.24–0.26[2] 0.26–0.30[26] 0.29–0.30[27]	0.24–0.26[1,31] 0.28[32] 0.28–0.30[33]	0.22[1] 0.28[37]	0.27[12]
	Electrical	0.31[4]	0.34[x13]		0.29[33]		
Partitioning at saturation	DSC	0.33[5] 0.35[6]	0.36–0.38[14] 0.41[6]		0.35–0.44[4]		0.34[44]
	NMR subzero	0.40[7]	0.43[7] 0.45–0.48[15]	0.32–0.35[28]			0.35–0.38[15] 0.40[45]
	SET	0.33[6] 0.46–0.56[8]	0.41[6]		0.31–0.40[34]	0.42[38]	
	Max. swelling		0.46[16]				0.34[16]
Sorption isotherm	Extrapolation	0.25[9] 0.28[x5]	0.25–0.26[x17] 0.28–0.33[x18] 0.30–0.31[19]	0.25–0.36[x29] 0.29–0.33[x26] 0.30[9]	0.31[1,35]	0.14–0.25[x39] 0.20–0.22[x40]	0.18–0.21[46,47] 0.24–0.25[x17] 0.25[48]
	Pressure plate	0.30[10] 0.34[x5]	0.32–0.33[x20] 0.38–0.42[x21]			0.32[x41]	
	Pure water conditioning		0.26[22] 0.30[23] 0.32[24]		0.32–0.34[36]		0.35[49,50] 0.37–0.44[51]
Presence of capillary water	DSC	0.31[x5]	0.36–0.38[14]	0.33[30]		0.26–0.27[42,43]	
	NMR		0.35[x25]				

[1]Wilson (1932), [2]Wang (2009), [3]Kang et al. (2012), [4]Stamm (1971), [5]Fredriksson and Thybring (2019), [6]Thybring et al. (2020), [7]Cai et al. (2020), [8]Ahlgren et al. (1972), [9]Popper et al. (2005), [10]Choong and Tesoro (1989), [11]Carrington (1922), [12]Silva et al. (2014), [13]Fredriksson et al. (2021), [14]Zauer et al. (2014), [15]Telkki et al. (2013), [16]Babiak and Kúdela (1995), [17]Bratasz et al. (2012), [18]Fredriksson and Johansson (2016), [19]Keunecke et al. (2007), [20]Zauer et al. (2016), [21]Thygesen et al. (2010), [22]Kamdem et al. (2002), [23]Brischke et al. (2017), [24]Ammer (1963), [25]Cox et al. (2010), [26]Herritsch (2007), [27]Pang and Herritsch (2005), [28]Beck et al. (2018), [29]Simón et al. (2016), [30]Simpson and Barton (1991), [31]Barkas (1936), [32]Higgins (1957), [33]Stamm (1929), [34]Feist and Tarkow (1967), [35]Stamm and Loughborough (1935), [36]Fitzpatrick et al. (2013), [37]Lee and Biblis (1976), [38]Zelinka et al. (2020b), [39]Neimsuwan et al. (2008), [40]Zelinka et al. (2018), [41]Zhang and Peralta (1999), [42]Passarini et al. (2017), [43]Zelinka et al. (2012), [44]Digaitis et al. (2017), [45]Gao et al. (2015), [46]Esteban et al. (2008), [47]Esteban et al. (2009), [48]Hosseinpourpia et al. (2018), [49]Meyer and Brischke (2015), [50]Meyer et al. (2016), [51]Harju et al. (2002)

[x]data from the specific literature source were used to derive the fiber saturation point in this study

The second quantity of interest, which is fundamental for understanding wood–water interactions, is the maximum amount of water held by the cell walls. This quantity may vary by wood species and may change because of chemical or thermal modification. We recommend the term "maximum cell wall moisture content" for this quantity. When viewing moisture uptake inside and outside of cell walls as a parallel model (Fig. 1b), the fiber saturation point defined as the transition point for changes in wood properties (property intersection point) is lower than the maximum cell wall moisture content, which is visualized in Fig. 8.

This leaves several techniques that measure neither the fiber saturation point as the property intersection point nor the maximum cell wall moisture content. These include those related to the sorption isotherm (see "The sorption isotherm") and to the presence of capillary water (see "Presence of capillary water"). There might be occasions where these moisture states are relevant to characterize; however, we strongly recommend that these states not be called the "fiber saturation point". Also included in the methods that

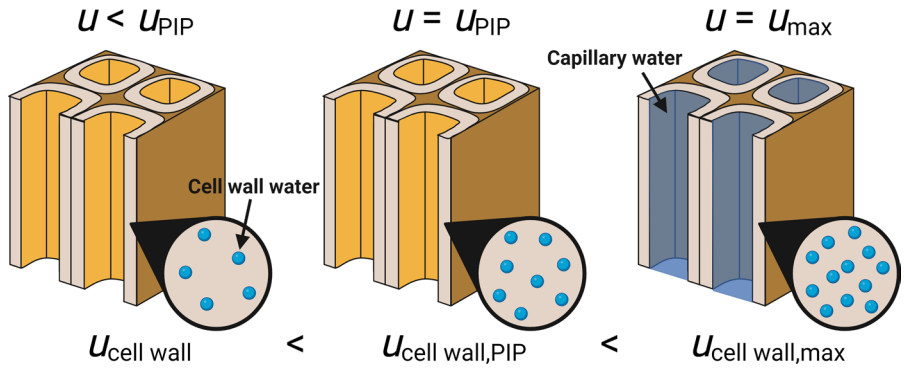

Fig. 8 Schematic illustration of the fiber saturation point defined as the property intersection point (PIP) and the maximum cell wall moisture content

determine neither the fiber saturation point from property changes nor the maximum cell wall moisture content are those that relate to thermodynamics (see "Thermodynamics"). While the extrapolation of thermodynamic properties appears highly uncertain, the thermodynamic definition of the fiber saturation point developed by (Zelinka et al. 2016) deserves further discussion.

Implications

The realization that methods used previously to determine a singular fiber saturation point in fact reflect different moisture states has implications in both wood science and practical applications of wood. Thus, it is essential to keep in mind which moisture state is relevant for a specific application and choose an appropriate method to characterize this state. Some examples:

Mechanical properties: The mechanical properties of wood depend on the moisture content and this relationship is thus of high importance for structural applications. Thus, *the fiber saturation point (strength intersection point, stiffness intersection point)* is of course suitable for calculating the lower limit of mechanical properties. This can be done as described in the subsection "Mechanical properties", i.e. by measuring the mechanical property of interest at different moisture contents and take care so that the conditioning of the specimens is done without creating moisture gradients.

Dimensional stability: Similar to the mechanical properties, the relationship between bulk dimensions of wood and moisture content is relevant for structural applications. Thus, *the fiber saturation point (shrinkage intersection point)* is suitable in the calculations of dimensional changes with moisture content. This can be done as described in the subsection "Bulk dimensions", i.e. by measuring either the change in length in a certain structural direction or by measuring the volume of a specimen at different moisture contents.

Wood modification: Within research on wood modification, it is often of interest to study how much the modification changes the capacity of the cell wall to hold water. This is thus an application where measurement of *the maximum cell wall moisture content*, i.e., the cell wall moisture content in the saturated state, is advisable. The maximum cell wall moisture content is determined in water saturated state by DSC, NMR relaxometry, or SET as described in "Partitioning of water in the saturated moisture state".

Limit state for fungal degradation: The presence of capillary water is often considered to be a requirement for fungal degradation. Therefore, the moisture content of wood in fungal tests is often discussed in relation to an unclearly defined "fiber saturation point". However, fungal tests rarely involve well-defined, uniform moisture states given that many fungi can relocate water from external sources or within the wood and that it is difficult to ensure stable high moisture conditions (Brischke and Alfredsen 2020). The moisture content is thus not uniform through the wood specimen. Therefore, discussing the limiting moisture state for fungal degradation in relation to the bulk fiber saturation point or to the bulk maximum cell wall moisture content does not make sense. Additionally, the role of the wood moisture content in fungal degradation processes is not clarified (Zelinka et al. 2020c). Possibly, it is rather the local water potential (relative humidity) or the local

distribution between water in and outside of cell walls that is the relevant parameter.

Conclusion

Over the years, the term "fiber saturation point" has been used to refer to several different moisture states obtained by a range of measurement techniques. The realization that these methods used to determine a singular fiber saturation point in fact reflect different moisture states has implications in both wood science, wood technology, and wood engineering. Thus, it is essential to keep in mind which moisture state is relevant for a specific application and choose an appropriate method to characterize this state.

Some of these measurement techniques characterize either of two moisture states: the transition state at which wood properties change, or the state at which the cell walls are saturated with water. These are, however, not the same moisture state, and to avoid confusion, we propose that the former, the transition state at which wood properties change, is the only state called "the fiber saturation point", or, for even more clarity "the property intersection point". We also recommend that the term "maximum cell wall moisture content" is used for the state at which the cell walls are saturated with water. There are also other methods that characterize other moisture states also referred to as the fiber saturation point in the literature, but we strongly recommend that the term fiber saturation point is avoided for these moisture states.

Author contributions All authors contributed to the study conception and design. The first draft of the manuscript was written by all authors. All authors provided comments on this, and the final version was prepared by MF based on these comments. EET and SG analyzed and compiled the data in Table 1. EET and MF prepared the figures. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethics approval Not applicable.

Consent to participate Not applicable.

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