Optical characterization of wood properties using the tracheid effect

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ABSTRACT

Wood, with its exceptional characteristics of lightness and strength, presents notable technical possibilities in industry, as well as serving as a significant carbon sink for society. Nonetheless, the natural diversity of wood species, particularly in temperate areas, poses a challenge when attempting to assess associated mechanical properties and to anticipate widespread application in mass markets. The wood manufacturing community is therefore seeking to establish rapid and automated techniques to determine the characteristics of French wood species, focusing on wood of all grades. One such technique which has received much recent interest is based on the "tracheid effect" which provides information on the local orientation of wood fibres. However, this approach is not universally applicable to all types of wood, and the factors that impact the tracheid effect are still relatively understudied, relying on scattering models using Monte-Carlo simulations. ZEMAX OpticStudio@ANSYS (ZOS), a powerful optical design software suite, has a non-sequential module similar to Monte Carlo approaches and includes a CAD module for modelling complex structures. This presentation shows how the use of this software improves our understanding of the phenomena involved in the tracheid effect, and can enable a more thorough characterization of wood fibre orientations. We compare our models with experimental data from common wood species. In this way, we hope to improve the measurement of wood properties and optimize the use of secondary-grade wood in sectors such as construction, furniture and packaging.

Keywords: Wood, fibrous media, light diffusion

1. INTRODUCTION

Wood, renowned for its remarkable blend of lightness nature and inherent strength, stands as a pivotal resource offering multifaceted opportunities across various industries while concurrently serving as a vital carbon sink for society. However, the intricate natural diversity inherent in wood species, particularly within temperate regions, presents a significant challenge in comprehensively assessing their mechanical properties and extrapolating their potential for widespread application in mass markets. To address this challenge, the wood manufacturing community has been actively exploring possibilities to establish swift and automated techniques for evaluating the characteristics of various wood species, with a specific emphasis on encompassing all grades of wood. Among the array of techniques, the "tracheid effect" has emerged as a subject of intense interest (Figure 1)[1–3] . This effect, rooted in the intricate arrangement of wood fibers, offers valuable insights into local fiber orientations, thereby facilitating a deeper understanding of wood's mechanical behavior.

However, despite its promise, the applicability of the tracheid effect remains limited across different wood types, and the nuanced factors influencing its manifestation are still relatively underexplored. Existing studies primarily rely on scattering models employing Monte Carlo simulations to delineate these complexities[4,5] .

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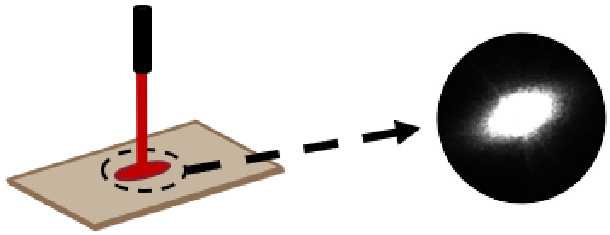

Figure 1. Illustration of tracheid effect

Recognizing the need for a more comprehensive understanding, we turn to advanced optical design software for insight. ZOS, an influential suite of optical design software, offers a non-sequential module related to Monte Carlo approaches, supplemented by a CAD module capable of modeling intricate structures. Leveraging the capabilities of this software, our study endeavors to enhance our comprehension of the phenomena underpinning the tracheid effect and, consequently, enable a more nuanced characterization of wood fiber orientations. In this study, we aim to validate the efficacy of our modeling approach by comparing it with experimental data gleaned from studies utilizing Monte Carlo simulations. By validating our model against established findings, we aspire to lay a solid foundation for further exploration, ultimately striving to refine wood property measurements and optimize the utilization of secondary-grade wood across key sectors such as construction, furniture, and packaging.

2. RESULTS AND DISCUSSION

2.1 Comparison to Kienle's results

Kienle et al. is one of the only ones who attempted to model the phenomenon of light in wood in their work using a Monte Carlo-type diffusion model.[4] ZOS, being a software that, through its non-sequential module, allows the use of a Monte Carlo diffusion model and importing CAD models, aligns well with our objective. We extracted the parameters from Kienle's article and then performed similar simulations in ZOS to validate our model (Figure 2). Wood is represented as a block of dimension 100 * 50 mm in which cylinders (tracheids) are placed, such that there is 35% wood and 65% void. The diameter of the tracheid is 30 micrometers, and the spacing between the fibers (wall thickness) is 3 micrometers. Since we are looking at the tracheid effect in reflection, we minimised the thickness of the sample to reduce the calculation time, with only 6 fibre layers. The refractive index varies according to the amount of water present in the tracheids. Here we take a refractive index of 1.55 for wood, which corresponds to dry wood, while that of air is fixed at 1 and when water fills the tracheid the refractive index of the tracheid is set to 1.33. The diffusion model used is the Henyey-Greenstein model[6] , as it was observed by Kienle et al[4] that wood scattering was closely behaving as that in biological tissues. This model is defined by a free parameter, the anisotropy factor g, between -1 and 1, which defines the angular distribution of light scattering. In accordance with Kienle's parameters, we take an anisotropy factor of 0.9. The beam is circular and has a diameter of 0.03 mm.

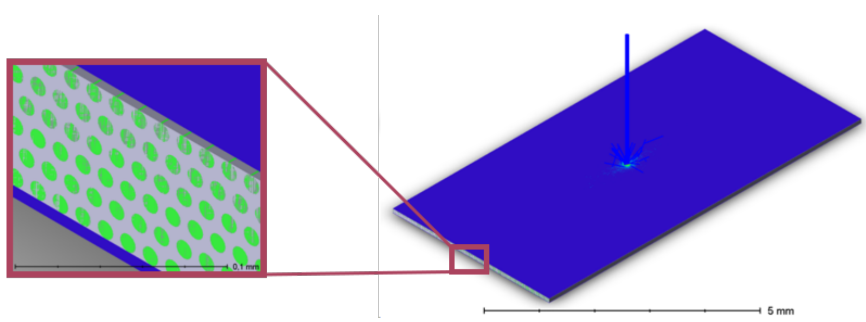

Figure 2. Illustration of the simulation carried out using ZOS

The result of the luminous flux obtained in reflection on the detector is shown in Figure 3. Qualitatively, we obtain the same things as Kienle in his article, with anisotropic scattering, as well as scattering perpendicular to the fibre axis at the centre of the beam epicentre. This result confirms our decision to use our model on ZOS.

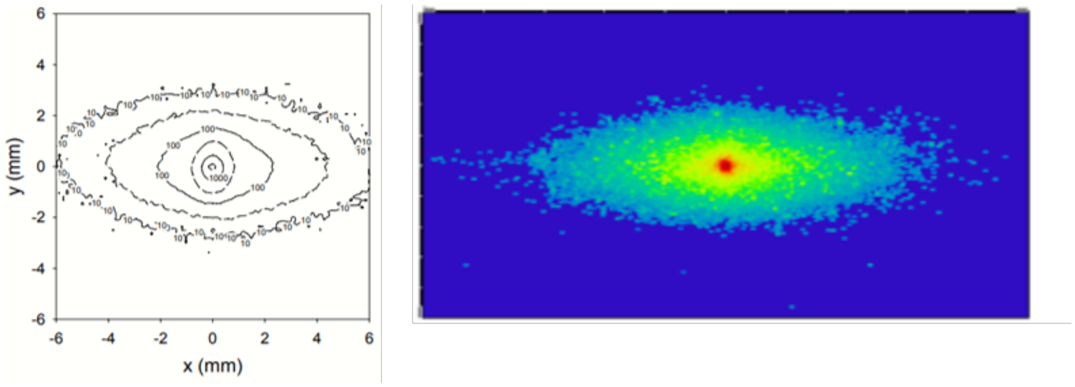

Figure 3. Left : Detector obtained by Kienle et al. Right : Detector obtained by our model on OpticStudio

2.2 Phenomena involved in the tracheid effect

To explain the tracheid effect, we conducted various tests by varying the diffusion parameters, refractive index values to observe the parameters that allow the creation of the anisotropic light diffusion observed in wood. If we assume that the refractive indices of wood and cylindrical voids are equal, we only observe diffusion phenomena between the tracheids' walls. However, if we assume different refractive indices and set diffusion to zero, we observe a lensing effect where light diffusion occurs only perpendicular to the direction of the fibers. Both effects are necessary to generate the tracheid effect, which is a combination of scattering and refractive effects.

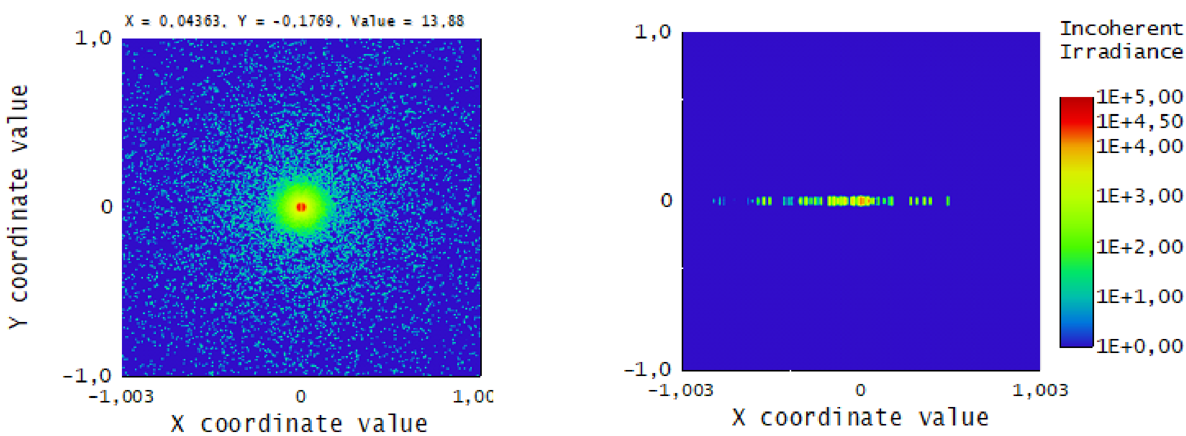

Figure 4. Left: Diffusion effect with no index difference. Right: Lens effect (no scattering effect, only index difference)

2.3 Comparing simulations with experimental data

Encouraged by the comparison of results with Kienle et al., it is now considered to push further by comparing our simulation results with experimental data, aiming to refine our understanding of the mechanism and validate the use of ZOS. We are going to modify our structure to correspond to two different types of wood (earlywood and latewood) and compare the results of the simulations obtained with the diffusions obtained experimentally. We took transmission tracheid images of a 1 mm thick Douglas fir sample. Wall and fibre size values for Douglas fir along a wood ring were referenced by Balanzategui et al.[7] These were used to construct reference timbers in order to test two different simulation configurations. The cross-sections of the wood models used in ZOS are shown in Figure 5. In the case of earlywood, the simulation gives a more spread-out spot, but with a smaller ratio of major axis to minor axis than for the simulation of latewood. In both cases, the simulation result matches the experimental results. A more detailed comparison between the simulations and the experimental results will be carried out at a later stage.

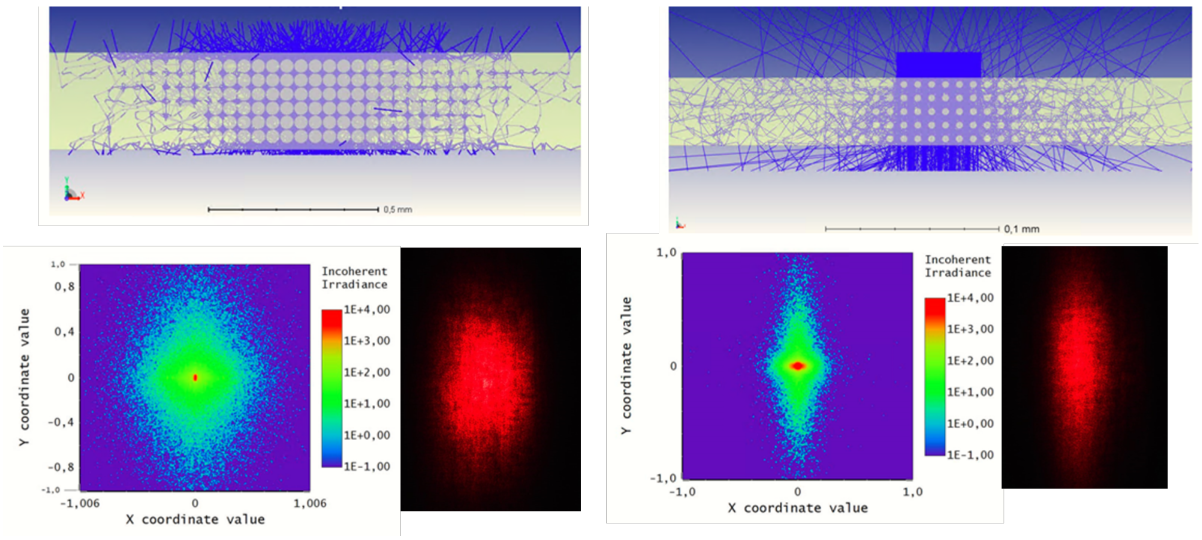

Figure 5. Structure used, with luminous flux obtained on the detector and image obtained experimentally: left for earlywood and right for latewood.

3. CONCLUSION

Based on the limited data available in the literature, we have reproduced and validated a model of light diffusion in wood using OpticStudio software. The initial comparisons between our model results and experimental results on earlywood and latewood are promising, providing us with a better understanding of the mechanisms that create the tracheid effect. Moving forward, we aim to delve deeper into comparing with experimental results using a more realistic wood model than currently available. This model will consist of microscopic wood sections, bringing us closer to reality, all with the aim of moving towards a predictive model of wood properties using the tracheid effect.

4. ACKNOWLEDGMENTS

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