

EXPLORING THE POTENTIAL OF CT IMAGE PROCESSING ANALYSIS FOR ASSESSING CAPILLARY FLOW IN PINE WOOD LOGS

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Abstract:

This research delves into the unexplored territory of using CT image processing techniques to assess capillary flow in freshly felled Scotch pine logs during the drying process. Leveraging a high-resolution CT scanner, the study captures intricate details of the wood's internal structure, which were then quantified using image processing algorithms. The findings confirm the efficacy of CT image processing in accurately determining capillary flow in wood. This opens up new opportunities for non-destructive testing methods and contributes to a deeper understanding of wood properties. The implications of these findings are far-reaching, offering substantial advancements in quality control and processing optimization in the wood industry.

Key words: CT scanning; image processing; capillary flow, pine log.

INTRODUCTION

Wood is an essential material widely used in various sectors such as construction, furniture, toys, and claddings. In its natural state, wood from living trees has a high moisture content that needs to be reduced to reach its equilibrium moisture content for final use. While the drying process of sawn timber is quite well-understood due to extensive research over the years (Perré 2007, Vikberg 2015), there are still some remaining issues that require further investigation. Nevertheless, in some applications such as log-houses, power poles, and playgrounds, there is a wish to use dried solid round wood. The drying of such round wood is still less investigated due to its lower market share. Recent advances in technology, particularly computed tomography (CT scanning), have opened up new avenues for studying the internal structure of wood during drying (Couceiro et al. 2022). This technology offers the potential for significant advances in wood drying, such as the development of more accurate simulation models. These enhanced models could optimize drying schedules, reducing drying times while maintaining or even improving wood quality.

OBJECTIVE

The primary objective of this study is to conduct a comprehensive investigation into the drying process of freshly felled Scotch pine logs. Using a multifaceted approach that combines state-of-the-art CT scanning technology, controlled environmental conditions, and advanced image analysis techniques, the study aims to shed light on the moisture development within its structure. The study also seeks to understand how CT scanning data can refine existing wood drying models or contribute to the development of new, more accurate models.

METHOD

Wood Log Preparation

In this test, a freshly felled pine log was used. A specific section of the wood log was selected, with a diameter of approximately 18cm and a length of around 50cm. The selected section included both sapwood with a high moisture content and heartwood with lower moisture content. To emulate drying of a longer log, the ends of the wood log were sealed with a single layer of heat resistant silicon to ensure water evaporation

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only from the surface area. During the drying process, the temperature of the interior of the wood were recorded using thermocouples in two positions: at the core of the board and 5mm below the surface. The thermocouples were previously calibrated and installed into drilled holes, which were then sealed with silicon, see Fig. 1.



Fig. 1.

The photo on the left-hand side displays the test piece positioned inside the climate chamber, while the photo on the right-hand side shows the placement of the thermocouples.

Climate Chamber & Drying Process

By utilizing a climate chamber specifically designed to work in conjunction with the CT scanner, a controlled drying process was implemented. The drying schedule commenced with a heating period using water steam inside the climate chamber, gradually increasing the dry temperature to 70°C while keeping a low wet bulb depression of less than 2°C. As the wet bulb depression was kept low, the wood was prevented to start drying during the heat up phase and the risk of introducing cracks or structural damage was kept at a low level. At the start of the drying period, the dry temperature was gradually increased, and the wet bulb temperature was kept constant at 70°C supporting the drying process.

CT Scanning Procedure

Simultaneously, a Siemens Somatom CT instrument captured high-resolution 3D images of the wood log with individual voxel densities. During the scanning procedure, the CT scanner rotated around the wood log, capturing a sequence of X-ray images in 3D. These acquired X-ray data were subsequently processed to generate cross-sectional density images, providing intricate details about the internal structures of the wood log during the drying process. For the CT scan, a tube current of 37mA and a voltage of 110kV were used. The scanning resolution in the plane was approximately 1mm × 1mm, with an axial spacing of 5mm between the cross-sectional images.

Equilibrium Moisture Content Calculation

The equilibrium moisture content (EMC) of a hygroscopic material, such as wood, depends on the relative humidity (RH) and temperature of the surrounding air. In this study, the RH value inside the climate chamber was calculated by utilizing the measured dry and wet bulb temperatures. The calculations were performed using a Python program with the MetPy library (May *et al.* 2023). The calculated RH value, along with the measured dry temperature from the climate chamber, was then utilized to apply the EMC calculation methodology outlined in the work of (Ross 2010).

Deformation & Capillary Flow Analysis

In order to calculate deformation and analyse capillary flow within the wood samples during the drying process, an image processing analysis was performed. Image registration techniques were utilized to align and compare images captured at different time points. This enabled the measurement and analysis of deformation, including dimensional changes, in the wood samples. In addition, image segmentation methods were employed to isolate and extract specific regions of interest within the wood samples, including sapwood, heartwood, and knots. These regions were of particular interest in relation to capillary flow analysis. By accurately segmenting and extracting these regions, the capillary flow behaviour within each specific area could be examined and analysed more effectively. By tracking the distribution of density over time, the capillary flow behaviour could be examined and quantified. The image segmentation processing and analysis, as well as the image registration, were performed using the SimpleITK and scikit-image libraries in Python. The registration method which was used was SimpleElastix, (Marstal *et al.* 2016).

The segmentation process begins by applying an Otsu thresholding technique to obtain a binary mask for the wood region. This initial mask is refined by filling any holes within the wood region using a binary hole-filling method. For the heartwood and knot regions, a similar approach is followed. Otsu thresholding is used to generate binary masks, which are further improved by applying binary hole-filling. To enhance the accuracy of the segmentation, the Otsu multiple thresholds technique is employed, resulting in refined masks for these regions. To obtain the sapwood region, the binary masks for the knot and heartwood regions are inverted, creating complementary masks. These inverted masks are then multiplied with the binary wood mask, resulting in a binary mask that represents the sapwood region.

To determine the average density change during the drying process from the surface towards the center, the following steps are undertaken. First, a binary erosion operation with a kernel radius of 1 is applied to the binary mask representing the wood region. This step generates eroded binary segments that extend from the surface to the center of the wood, and these segments are stored for further analysis. The stored binary segments are then used to calculate the mean density value for each segment. This is achieved by multiplying each binary segment with the density image, resulting in a density segment from the surface towards the center. Furthermore, the segments are then used to compute the mean density value by averaging the density values within each segment. This entire process is repeated for each time step throughout the drying process, enabling the tracking of the average density change from the surface towards the center of the wood over time.

RESULTS & DISCUSSION

Temperature, RH, and EMC Measurements during the Drying Process

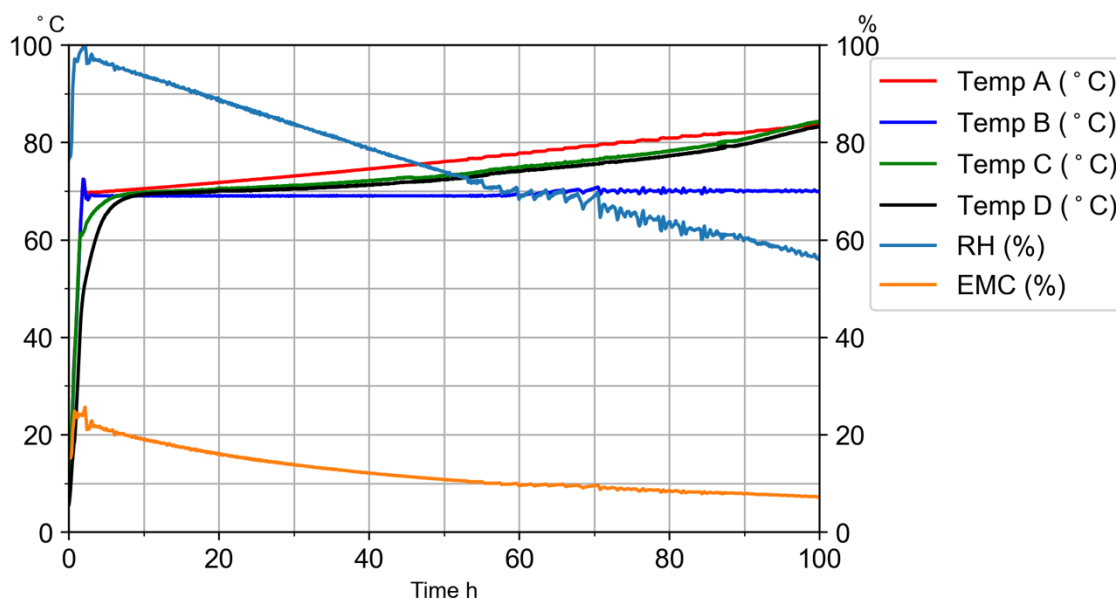


Fig. 2.
Temperature, RH, and EMC measurements during the drying process.

The figure (Fig. 2) presents the variation in temperature, relative humidity, and EMC during the drying process. Four temperature measurements were taken at different locations: Temp A represents the dry temperature, and Temp B represents the wet bulb temperature, measured inside the dryer. Temp C represents the temperature near the surface inside the wood piece, and Temp D represents the temperature in the centre of the wood piece. The y-axis on the left-hand side represents temperature in degrees Celsius (°C), and the y-axis on the right-hand side represents the derived RH and EMC as a percentage (%). The x-axis represents time in hours from the start of the experiment.

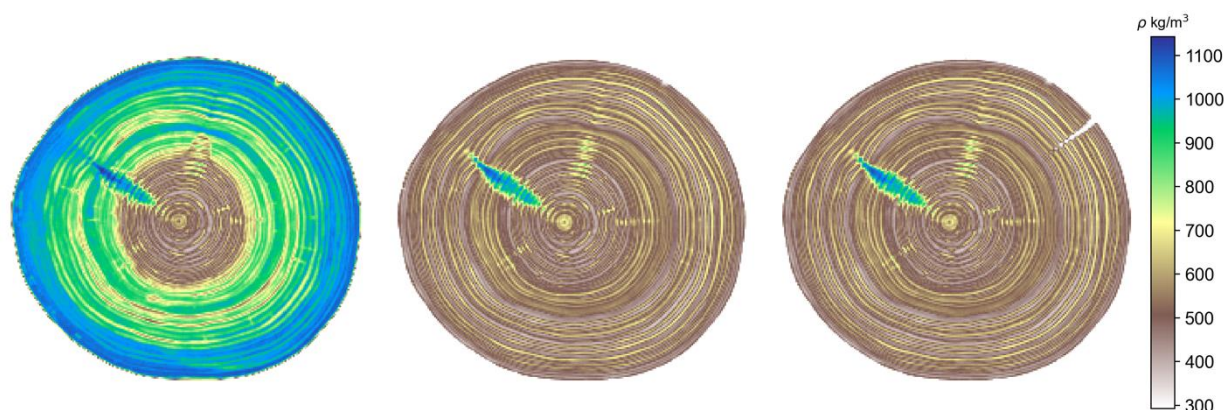


Fig. 3.
Sequential CT images demonstrating wood density changes over time.

Wood Density Evolution: A Glimpse through CT Imaging

The figure (Fig. 3) presents a set of three selected CT images chosen from a time series, showcasing the variations in wood density over time during the drying process. These images serve as the baseline for comparing density changes in the subsequent scans. The left-hand side image represents the initial scan conducted at the start of the drying process. The middle image corresponds to the wood density observed after 101 hours, immediately before the crack formation. The right image showcases the wood density observed after 101.5 hours of drying, after the crack has formed.

Decoding Wood's Anatomy: Knots, Heartwood, and Sapwood

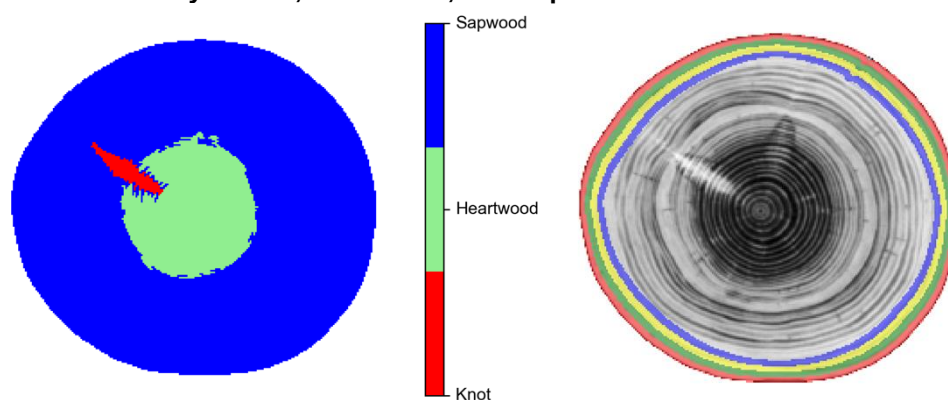


Fig. 4.

The left-hand side figure illustrates the segmentation of the sample CT image into distinct regions. The regions are labeled as 'Knot' (red), 'Heartwood' (light green), and 'Sapwood' (dark blue). The right-hand side figure illustrates four eroded segments from the surface towards the center.

The left-hand side figure in (Fig. 4) displays a segmentation map with distinct regions identified within a CT image. Each region is assigned a unique color for visualization purposes. The segmentation regions include the knot represented by red, the heartwood represented by light green, and the sapwood represented by dark blue. The right-hand side figure in (Fig. 4) provides a visualization example of how the eroded segments are placed from the surface towards the center. In reality, the segments are thinner and more numerous.

Density Dynamics: Sapwood's Journey through Drying

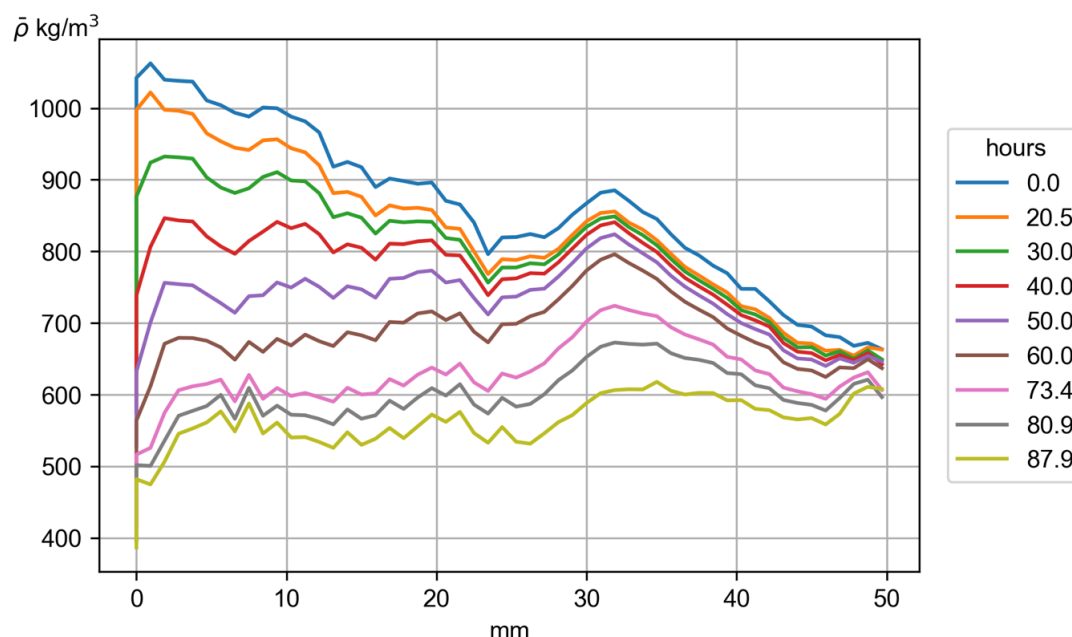


Fig. 5.
Shows the mean density vs distance from the surface in the sapwood segment at different times during the drying process.

Fig. 5 displays the relationship between mean density and distance from the surface in the sapwood segment at various time points during the drying process, derived as described previously. This technology has proven invaluable for capturing intricate details of the wood's internal structure and for tracking density changes over time. It should be noted that the time points may not be uniformly distributed due to occasional missing scans. In the figure, a prominent density gradient begins to emerge at the surface to a depth of 3 millimeters at around 20 hours from the start of the drying. Beyond 3 millimeters, the density change remains consistent throughout the drying process.

In summary, the study highlights several key points crucial for understanding and improving the wood drying process. Traditional diffusion models prove inadequate for describing the complexities of wood drying, particularly above the Fiber Saturation Point (FSP). A study from 1995 by Ranta-Maunus et al. reported uniformly distributed moisture content profiles in sapwood above the FSP in Scots pine (*Pinus sylvestris*), confirming the limitations of these models when moisture levels exceed the FSP.

The use of CT scanning technology has provided further insights into these limitations. Research by Wiberg (2015) and Wiberg and Morén (1999), as well as Hansson and Cherepanova (2012), supports these findings, emphasizing the role of capillary action and other alternative mechanisms in the drying process. These works collectively corroborate that water migrates from cell to cell and flows from wet zones towards the surface. Moreover, Siau (1971) and Salin (2008) offer alternative explanations for water movement above the FSP, detailing complex mechanisms such as cell-to-cell migration and flow from wet zones towards the surface.

While below the FSP, diffusion models are generally effective in describing the drying behavior of wood, the limitations of diffusion models become evident above the FSP. Therefore, to accurately describe the drying process above the FSP, alternative physical mechanisms, such as capillary action and pressure gradients, must be considered.

The capillary pressure is essentially the pressure difference between the liquid phase (water in the pores) and the gas phase (air in the pores and surrounding the wood). In drying scenarios, this pressure difference often results from a gradient in moisture content, with the core being wetter than the surface. As the surface of the wood dries and loses moisture to the surrounding environment, it generates a capillary pressure gradient within the wood. This gradient serves as the driving force that moves water from regions of higher moisture content to regions of lower moisture content, essentially "pulling" the water out, as outlined by Darcy's Law.

In contrast to the complexities observed above the FSP, it is worth mentioning that below the FSP, diffusion models are generally effective in describing the drying behavior of wood. This is because, in this moisture range, the primary method of water movement is through diffusion, making the use of diffusion

equations both appropriate and accurate. It is only when moisture levels are above the FSP that the limitations of diffusion models become evident, necessitating the consideration of alternative physical mechanisms like capillary action.

Moreover, the incorporation of CT scanning technology provides a high-resolution, non-destructive method for capturing the dynamics of density changes in wood during the drying process. Applying advanced imaging techniques allow for the quantitative assessment of water movement and moisture gradients at various depths, from the surface to the core. The valuable data obtained can be used to refine existing models or develop new simulation models that are capable of accurately representing the drying behavior of wood both above and below the FSP. Such models would offer a comprehensive understanding of the different physical mechanisms at play, including both diffusion and capillary action, thereby enabling more effective and efficient wood-drying processes.

Importantly, the development of more accurate simulation models, facilitated by high-resolution CT scanning data, has practical implications for the wood-drying industry. Enhanced models allow for the optimization of drying schedules, which could lead to faster drying times without compromising the quality of the wood. In some cases, improved drying schedules may even enhance the quality by minimizing defects.

CONCLUSIONS

The study highlights several key points crucial for understanding and improving the wood drying process. Traditional diffusion models prove inadequate for describing the complexities of wood drying, particularly above the FSP. The limitations of these models become increasingly evident as moisture levels exceed the FSP where alternative mechanisms, such as capillary action and pressure gradients, are essential for water movement.

The incorporation of CT-scanning data offers a pathway for refining existing models or developing new, more accurate simulation models. These enhanced models have the potential for practical applications, such as optimizing drying schedules. Such optimization could result in faster drying times without compromising, and possibly even improving, the quality of the wood.

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