

## **X-RAY COMPUTED TOMOGRAPHY (CT) STUDY OF THE TRANSITION REGIME IN TIMBER DRYING ALONG THE BLOW DEPTH**

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### **Abstract:**

*Drying green sawn timber to a specific moisture content is needed for further processing. Large batch kilns of approx. 100 cubic meters of timber loads are commonly used with heated air blowing across the packages. When the air reaches the end of the blow depth, it has considerably increased its relative humidity by the evaporation from the wet timber. To even out the climate at the beginning and end of the blow depth, the direction of air circulation is reversed periodically. This exposes timber at those locations to fluctuations in climate while the middle packages are exposed to a more even climate. This study aimed to find the influence of the location of timber along the blow depth in liquid-water-flow behavior during the initial stages of drying. A research drying kiln combined with a CT-scanner was used to mimic this environment across the load and obtain CT images simultaneously, which were used to study the moisture content evolution. The results found that the transition between the capillary and the diffusion regimes can be identified with this method. Additionally, the transition regime was entered earlier for specimens drying in the more even climate which modeled the middle of a drying kiln, but with larger water pockets nearer to the surface of the specimens.*

**Key Words:** *Transition Regime; Wood Drying; Timber drying; Computed Tomography; CT-Scanning.*

### **INTRODUCTION**

Water exists in wood in three different forms: liquid water, water vapor, and bound water (Morén 2014). Liquid water and vapor exist in the cell cavities (lumen and pit chambers) of wood and bound water is chemically connected to the wood constituents of the cell walls that have hydroxyl groups with sites available for water to bond through hydrogen bonds (Nilsson 2009). In a living tree, capillary action of liquid water in the cell lumen along with soil osmotic overpressure and evaporation in the leaves or needles causes liquid water movement up the living tree and flow of nutrients down (Nilsson 2009). Liquid water in the sapwood also moves tangentially along the growth rings and radially in the pith-to-bark direction, but to a considerably lower degree. This is likely due to the differences in anatomical and chemical composition of the cells in those orientations including differences in density of early- and latewood, between microfibrillar angles of the cell wall, and between ray cells and tracheid cells (Dinwoodie 2000). Additionally, heartwood formation in the living tree involves the closure of the liquid water pathways to that part of the tree (Morén 2014). Thus, liquid water transport occurs mostly in the longitudinal direction of the sapwood of a living tree.

Wood is a hygroscopic material meaning it has changes in moisture content over time depending on the relative humidity (RH) and temperature (T) of the surrounding air once it is sawn down (Hartley and Hamza, 2016). Sawn wood is also susceptible to biological attack in certain environmental conditions of T and RH (Nilsson 2009). It is therefore of interest to the end user of wood products that these conditions are not met. Additionally, under fiber saturation point (FSP), i.e. the state when no more liquid water exists in the material, wood will swell or shrink as it absorbs or releases moisture from/into the environment (Morén

2014). This action can cause cracking due to the anisotropic behavior of the dimensional changes, which can further propagate if the moisture content of the wood continues to fluctuate or simply under normal loading conditions (Dinwoodie 2000). Therefore, wood in modern production is dried to the conditions of the climate it will be in its final use.

In the sawmill industry, large kilns and simulation software are used to achieve optimal drying conditions and final moisture content for the sawn timber. Two common types of kilns are batch kilns and progressive kilns, both of which are conventional kilns using heated air or steam as the medium for heat transfer (Bond and Espinoza 2016). They contain heating elements, fans for air circulation, ventilation for climate control, baffles, pressure frames, and well insulated walls and doors. They are additionally equipped with multiple sensors to ensure accurate measurements and provide feedback to the software and operator (Morén 2014). Batch kilns in Sweden can have a capacity from 50 to 450 cubic meters of sawn timber (Valutec 2023). The packages are carefully arranged with stickers in between the sawn timber to promote airflow (Morén 2014).

The package arrangement can be quite deep from the door to the back and/or from wall to wall depending on the volume of the kiln. The blow depth, the distance the air must pass through the timber batch, causes major differences in external climate around the individual piece of the drying timber (Morén 2014) referred to as temperature drop across the load (Bond and Espinoza 2016). Moisture from the packages at the beginning of the depth evaporates from the wood and into the air. This means the packages at the inlet of air (beginning of the blow depth) experience very warm and dry air, but at the end due to the endothermic nature of evaporation, the air is less warm and more humid (Morén 2014). This also means that packages in the middle of the blow depth experience the most consistent environment. The air flow direction is reversed periodically to provide all packages with warm dry air over the course of the schedule (Morén 2014). This means that packages in the middle of the blow depth experience the most consistent environment.

The first regime in the drying schedule is the warming up. During this regime, liquid water or steam (high-pressure hot water steaming) is used to heat the wood and make it more plastic. The RH inside of the kiln is then kept near saturation, preventing the timber from drying until it reaches the desired temperature. The next regime of the drying is the capillary regime where liquid water moves by capillarity until it reaches the evaporation front some millimeters below the surface (Wiberg 2001), after which it must move through the so-called dry shell via diffusion. Once the water reaches the surface of the sawn timber, it evaporates into the air. Near the end of the capillary regime, the dry shell recedes from the board surface and inwards increasing the distance that liquid water needs to move through diffusion.

The next regime is the transition from capillary water transport to diffusion moisture transport which involves both capillary action of the liquid water and diffusion of moisture through the drying timber. During this regime, pockets of liquid water may form. These pockets are regions of connected liquid water surrounded by wood with only bound water. The water within the pockets can move by capillarity, but it must diffuse through the cells to reach the evaporation surface of the timber (Morén 2014). Water transport by diffusion is slower than movement by capillarity and can require more energy (Morén 2014). The identification of the transition regime is therefore of interest to decrease energy and time costs of timber drying. A later start in the transition from capillary to diffusion moisture transport means a quicker total drying time as liquid water can continue to move by capillarity, i.e. the free-water-pocket volume should be minimized. The start of the transition regime is difficult to identify on the scale of a batch kiln as each package along the blow depth receives a different environment. The end of the transition regime is marked by the timber reaching FSP (Morén 2014), at which point, all remaining water moves via diffusion.

Many improvements have been made in drying technology in recent years, largely aided by X-ray computed tomography (CT) research in the facilities of Luleå University of Technology (LTU) in Skellefteå, Sweden where timber can be dried and scanned simultaneously. The data extracted from CT scans can be processed to obtain density values which can be used to calculate moisture content as density decreases during drying reflect a loss of water (Couceiro 2019). However, this process is hindered by the deformation of wood while it dries (Hansson and Fjellner 2013). It is not possible to compare these images pixel by pixel as the wood changes shape during drying, but with the help of registration algorithms, image processing has become more accurate, and the moisture content can now be measured on at least millimeter scale in the entire volume of sawn timber (Hansson and Fjellner 2013). With more accuracy, each step of different drying regimes can be analyzed for areas of improvement which is important with green renewable energy as a goal for sustainable societies and for the reduction of costs of energy consuming processes. This study aimed to fill a gap in the knowledge of drying regimes in batch kilns, particularly the transition regime which can impact both the time and energy required to dry timber.

## OBJECTIVE

The objective of this experimental study was to determine the point in time of a batch kiln drying schedule where the mode of water transport switches from capillarity to transition regime (where both capillarity and diffusion occur), and to identify if the location of timber within a batch (air inlet/outlet or in the middle) affected this point in time. The hypothesis was that timber located at the edges of a batch, the furthest points in air flow depth, would enter the transition regime of drying sooner than timber in the middle due to the extreme variances in climate on the kiln edges compared to the consistent environment in the middle. This means that kilns with shorter blow depths i.e. more consistent environments could have shorter drying schedules.

## METHOD

In this study, 4 pairs, each pair from the same log, of specimens were tested on two different drying schedules while simultaneously scanning with an X-ray CT scanner to collect density data for moisture content calculations. The schedules, produced from data collected at a local kiln, represented two different environments within the same batch kiln, one from the edge (near the inlet or exit of air) and one from the middle of the batch, further described below. The density data collected from the CT scanner was first used to identify the transition regime of drying by looking for pockets of liquid water after converting the density to moisture content. The data from the opposing schedules was then used to identify if the start of the transition regime was different for each pair of specimens.

## MATERIAL

- Logged data of wet and dry bulb temperatures from batch kiln at a sawmill in the region of Västerbotten, Sweden.
- 8 Scots pine (*Pinus sylvestris* L.) specimens predominantly formed by sapwood, with a cross sectional area of 70x150 mm (Fig. 1), were sawn from raw logs harvested in mid Sweden, and cut roughly to 350mm length.
- Siemens Somatom Emotion Duo medical X-ray CT Scanner (Siemens, Munich, Germany) show in Fig. 2 below.
- Custom made research drying kiln (LTU-Skellefteå) that allows simultaneous CT scanning.
- MATLAB and MATLAB algorithm developed by Hansson and Cherepanova (2012) and Hansson and Fjellner (2013).

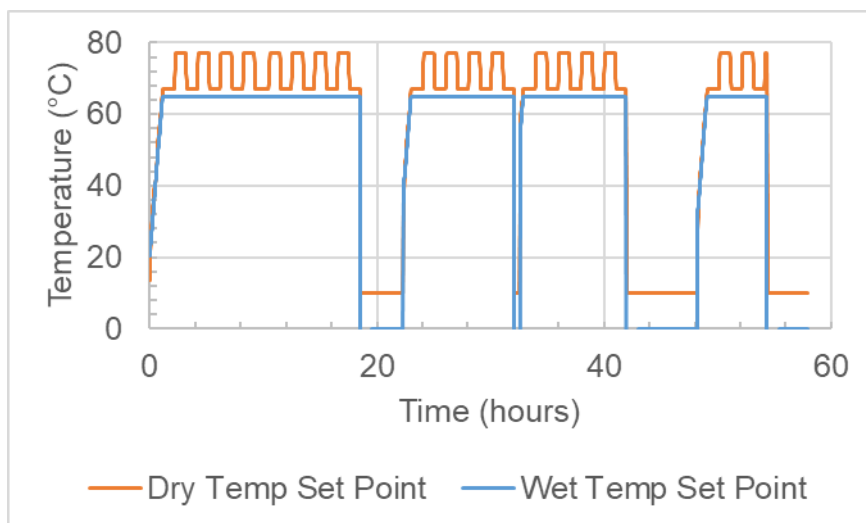


**Fig. 1.**  
**Specimens of Scots pine used in the study after experimental completion.**



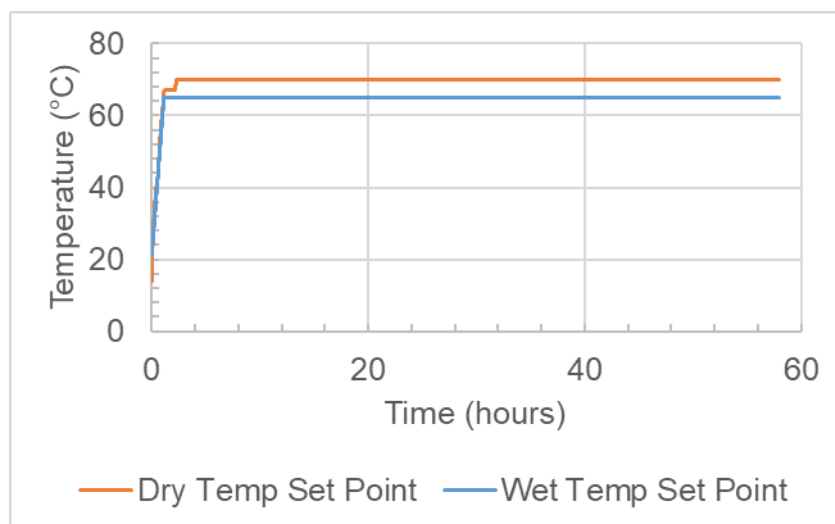
**Fig. 2.**  
**X-Ray CT Scanner and Research Kiln Setup.**

Data was used from a batch kiln at a local sawmill in northern Sweden to determine the interval at which the air flow direction in the kiln was reversed as well as the average temperature in the middle of the batch and on the edges (near an air inlet or exit). The most extreme changes in average temperature from the edge sensors and an air reversal time of one hour were used for this experiment. These climates were then replicated in the research kiln at LTU in two schedules referred to as Mid (the most even climate) and Edge (the most extreme climate) schedules. During pretests, a limitation in the kiln software was discovered. Modifications to both schedules were made to simplify both schedules to accommodate the software. Fig. 3 and 4 show the schedules used for this experiment.



**Fig. 3.**

**Data from run 1 showing dry temperature set points (orange) and wet temperature set points (blue) for the edge schedule.**



**Fig. 4.**

**Data from run 2 showing dry temperature set points (orange) and wet temperature set points (blue) for the mid schedule.**

One pair of specimens was sawn from each log, labeled by pair, end-sealed with Casco SuperFix+ (Sika, Baar, Switzerland) to avoid longitudinal drying, wrapped in plastic, and frozen until the time of the experiment. The specimens were selected using one from one pair and one from another pair and then left wrapped at room temperature 24 hours before the start of the experiment to thaw. The other specimen of the same pair was used for the next run with the opposite schedule. In the first pair of experimental runs, the schedules ran for 3 days each followed by oven drying according to the EN 13183-1 standard (CEN 2004). Inspection of this data showed that the specimens still had free water present at the end of the 3 days. Therefore, the drying was extended to 5 days for the next pair of runs. When running an edge schedule, the schedule required resetting every 9 hours, but this did not always occur in time and therefore the

temperature did drop between resets on several occasions as shown in Fig. 3. Table 1 shows which schedule each specimen was dried by and for how long. Specimen pairs have matching letters in the specimen number and opposite schedules indicated by odd (edge) or even (mid) numbers.

Table 1

**Specimen numbers and associated schedules: specimen numbered 1 followed the edge schedule while specimens numbered 2 followed the mid schedule**

Test Number	Run Number	Schedule	Drying time (h)	Specimen Number
1	1	Edge	55	A1
2	2	Mid	55	A2
3	1	Edge	55	B1
4	2	Mid	55	B2
5	4	Edge	120	C1
6	3	Mid	120	C2
7	4	Edge	120	D1
8	3	Mid	120	D2

The moisture content was calculated by pixel for each image using the algorithm described by Hansson and Cherepanova (2012) for which the final oven dry image is needed. To study the time the transition regime begins, the MATLAB functions *imerode* and *bwconncomp* were used together to find groups of pixels with a moisture content more than 0.255, which is FSP at 70°C (Siau 1984), separated by more than 3 pixels (0.3mm). The function *imerode* performs binary image erosion and has inputs of a binary image and a structuring element (MathWorks 2023). The inputs for this experiment were the CT images showing MC greater than FSP and a square structuring element of size 3. This function was used to filter out noise and the excess data on the edges of the wood specimens where the density changes sharply and the data is not accurate. Fig. 5 shows one scan before and after image erosion using this MATLAB function.

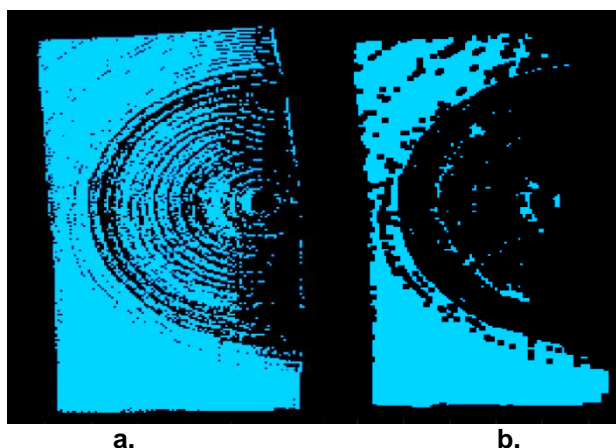


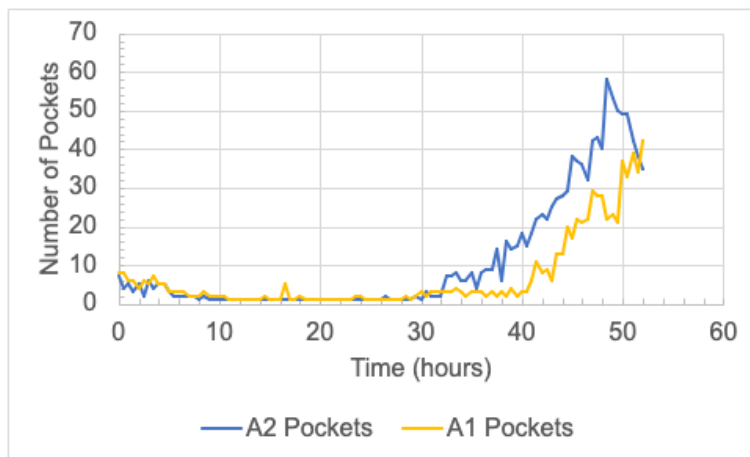
Fig. 5.

**Comparison of one scan before and after image erosion; blue indicates liquid water  
a. Before erosion b. After erosion.**

The function *bwconncomp* was used to find and count the liquid water pockets over time. This function has inputs of a binary image and a second numeric value related to how the connectivity is determined (MathWorks 2023). For this experiment, the inputs were the eroded image and 8. The number 8 indicates connectivity horizontally and vertically as well as diagonally (MathWorks 2023). Each pocket indicates a region where water in the wood has begun to separate from itself and therefore can no longer move through capillary action. This set of functions used together produced the number of pockets of liquid water for each scan (i.e. over time of drying). This information was plotted to show the number of pockets over time. The peak number of pockets was used as the time comparison to determine if the location of a package within a chamber kiln affected the time of the transition regime. For specimens which had two clear peaks, both peaks were calculated, and the latest peak was used as the comparison.

**RESULTS AND DISCUSSION**

Fig. 6 does not have enough data to determine if the peak of pockets for these specimens was reached or not. However, specimen A2 (Test 2) did likely reach its peak. This indicates that the transition regime for Test 2 (mid) was likely reached earlier in the schedule than Test 1 (edge) for this pair of specimens as indicated in Table 2. Additionally, Fig. 7 shows that Specimen A1 (Test 1) has more liquid water discontinuity further from the edges.



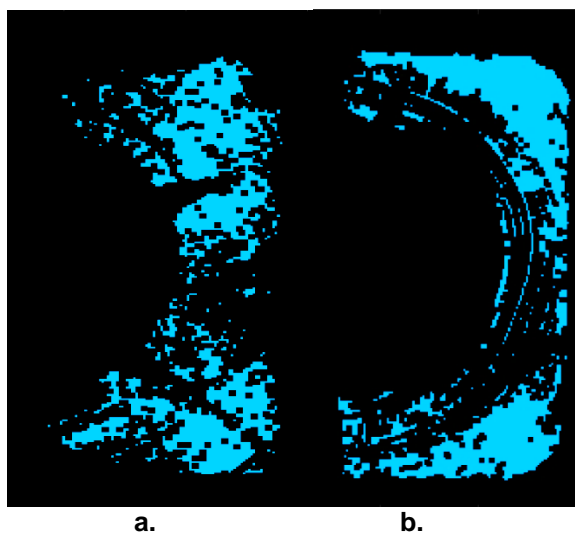
**Fig. 6.**

**Number of water pockets as a function of drying time for test 1 (A1, edge) and test 2 (A2, mid).**

Table 2

**Maximum values for test 1 (edge) and test 2 (mid)**

Test Number	Maximum Number of Pockets	Time (hours) at Max Pockets
1: Edge	42	52.5
2: Mid	58	49

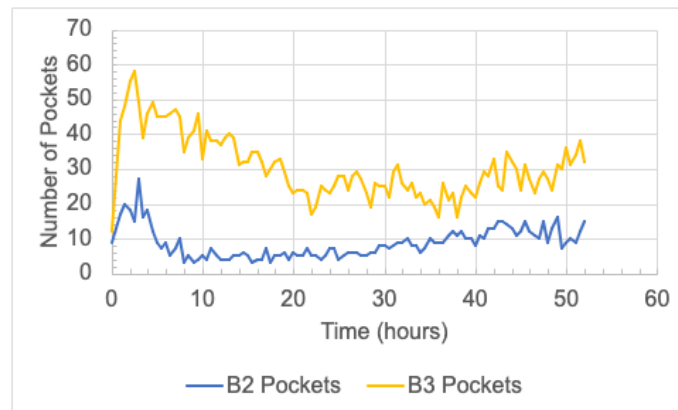


**Fig. 7.**

**Scans corresponding to maximum number of pockets showing areas (blue) over FSP (>0.255) after erosion: Test 1 (Edge), 52.5 hours; b. Test 2 (Mid), 49 hours.**

Fig. 8 does not have enough data to determine if the peak of pockets for these specimens has been reached or not. Additionally, both specimens have an earlier peak followed by a decrease and rise again. This log may have had more water in the heartwood than the others or a physical difference, for example compression wood or resin pockets, which are denser and appear to be water. Without more data, i.e., a longer drying time (increased schedule length), it is difficult to interpret the results from Fig. 8 and therefore

Table 3. However, similarly to the previous pair, this pair of images shows larger liquid water pockets closer to the surface for the mid schedule (Fig. 9b).



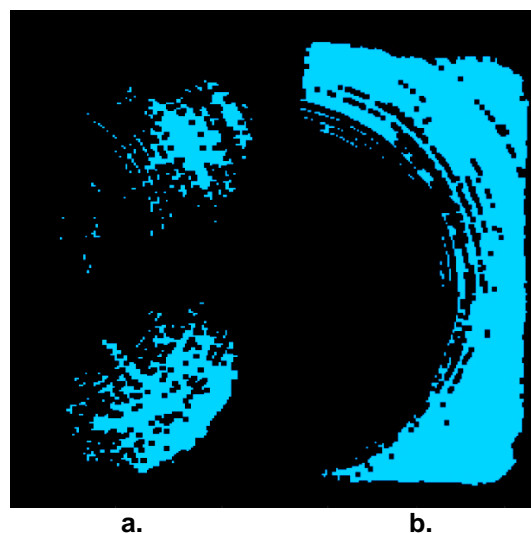
**Fig. 8.**

**Number of water pockets as a function of drying time for test 3 (B1, edge) and test 4 (B2, mid).**

*Table 3*

**Maximum values for test 3 and test 4**

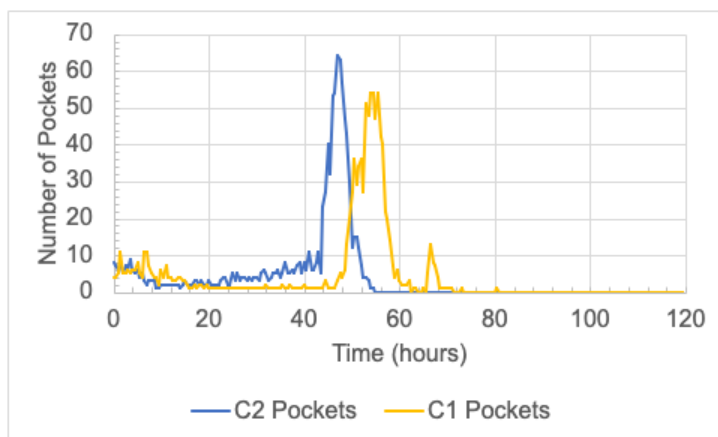
Test Number	Maximum Number of Pockets	Time (hours) at Max Pockets
3: Edge	58	3
3: Edge 2 <sup>nd</sup> Max	38	52
4: Mid	27	3.5
4: Mid 2 <sup>nd</sup> Max	16	49.5



**Fig. 9.**

**Scans corresponding to maximum number of pockets showing areas (blue) over FSP (>0.255) after erosion: a. Test 3 (Edge), 52 hours; b. Test 4 (Mid), 49.5 hours.**

Fig. 10 for this pair shows much clearer peaks after increasing the length of the drying schedules used. As indicated in Table 4, Test 6 (mid) reached a peak sooner than Test 5 (edge). As with the previous two pairs, this pair also shows large pockets nearer to the surface for the mid schedule (Fig. 11b).



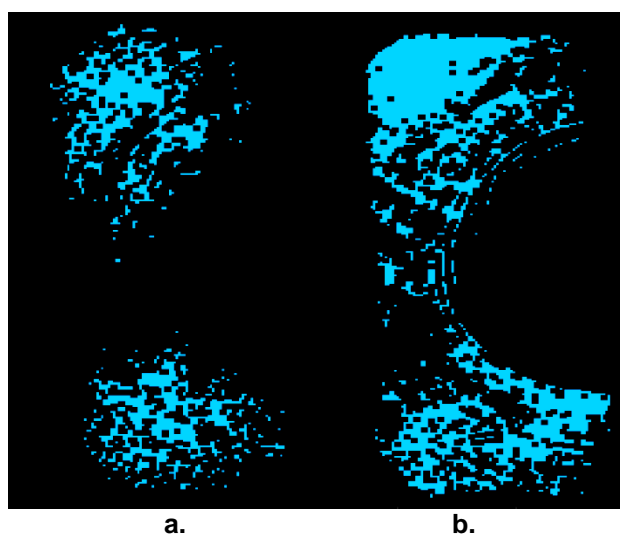
**Fig. 10.**

**Number of water pockets as a function of drying time for test 5 (C1, edge) and test 6 (C2, mid).**

*Table 4*

**Maximum values for test 5 and test 6**

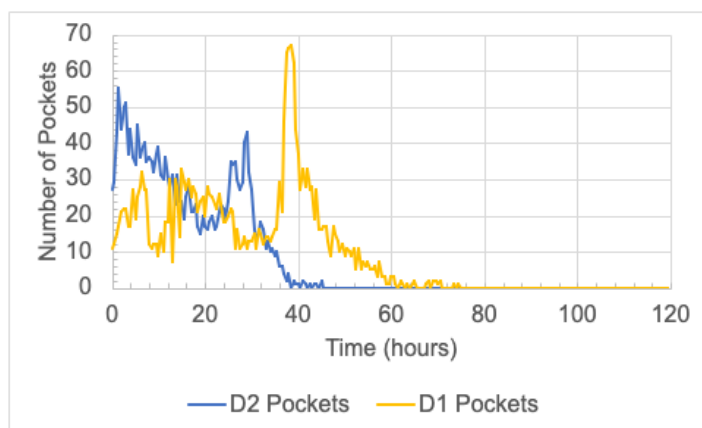
Test Number	Maximum Number of Pockets	Time (hours) at Max Pockets
5: Edge	54	54.5,55,56
6: Mid	64	47.5



**Fig. 11.**

**Scans corresponding to maximum number of pockets showing areas (blue) over FSP (>0.255) after erosion: a. Test 5 (Edge), 55 hours; b. Test 6 (Mid), 47.5 hours.**

As with specimen pair B (Tests 3 and 4), this pair also showed an initial high peak of pockets, Fig. 12. Further data analysis is required to understand this initial peak. As with previous pairs, this pair also shows that peak for Test 8 (mid) occurs earlier than the peak for Test 7 (edge), as shown in Table 5. This pair had a much earlier peak compared to the rest. This is likely due to the thickness of these specimens being less than the rest and/or the specimens may have had less liquid water at the start. As a result, the images for the peaks (Fig. 13) of each specimen also look quite different compared to the others. There is much less water in both specimens. In this figure, specimen D2 (mid) seems to have less water than D1 (edge) and the remaining larger pockets are closer to the surface of the specimen.



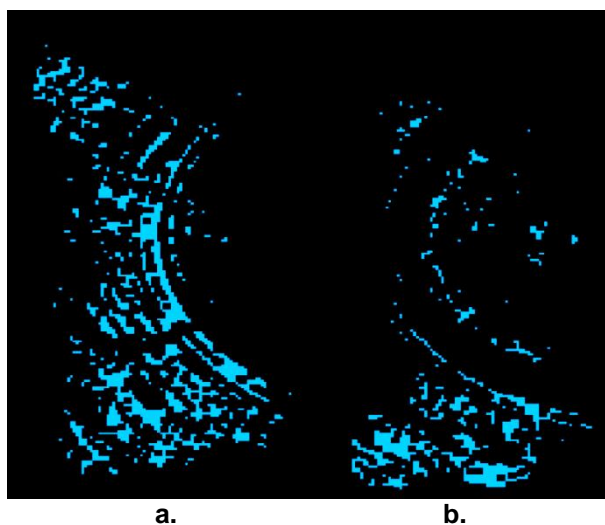
**Fig. 12.**

**Number of water pockets as a function of drying time for test 7 (D1, edge) and test 8 (D2, mid).**

*Table 5*

**Maximum values for test 7 and test 8**

Test Number	Maximum Number of Pockets	Time (hours) at Max Pockets
7: Edge	67	39
8: Mid	55	2
8: Mid 2 <sup>nd</sup> Max	43	29.5



**Fig. 13.**

**Scans corresponding to maximum number of pockets showing areas (blue) over FSP (>0.255) after erosion: a. Test 7 (Edge), 39 hours; b. Test 8 (Mid), 29.5 hours.**

The data from this experiment shows that the specimens dried with a mid-schedule had earlier peaks in the number of pockets of liquid water. Furthermore, the images collected show that the location of the pockets in the mid specimens were closer to the surface of the boards which means that the liquid water moves less distance by diffusion increasing the speed at which it leaves the wood. Together this information seems to indicate that packages dried in the middle of a batch kiln will dry sooner than packages at the edge. Future research could use other types of analysis for this data to locate when the boards reach FSP and therefore move to the diffusion regime or develop a more accurate method for locating the start of the transition regime.

## CONCLUSIONS

This study used an X-Ray CT scanner with a research kiln to obtain density values of wood board pairs while drying under two different schedules related to positioning in a batch kiln. The results of this experiment showed that it is possible to locate the transition regime of a drying regime using CT imaging of wood and connectivity analysis. Furthermore, the results indicate that there is a difference in the time to the transition regime of drying depending on the location of a package in a batch kiln. Boards dried with a schedule similar to the middle of the blow depth led to earlier starts in the transition regime with pockets of water closer to the surface of the boards, indicating quicker drying times for packages in the middle.

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