Microwave heating in a pressurized chamber

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Presentation Overview

Background

- Research Goal and Study Objective
- Why model heat transfer in wood
- 2D Finite Element Heat Transfer Models
- 2D heat transfer model comparison

Current Research

- Why microwave heating
- Microwave Pressurized Chamber
- Conductive Heating Rates
- Microwave Heating Rates

Background

RESEARCH GOAL:

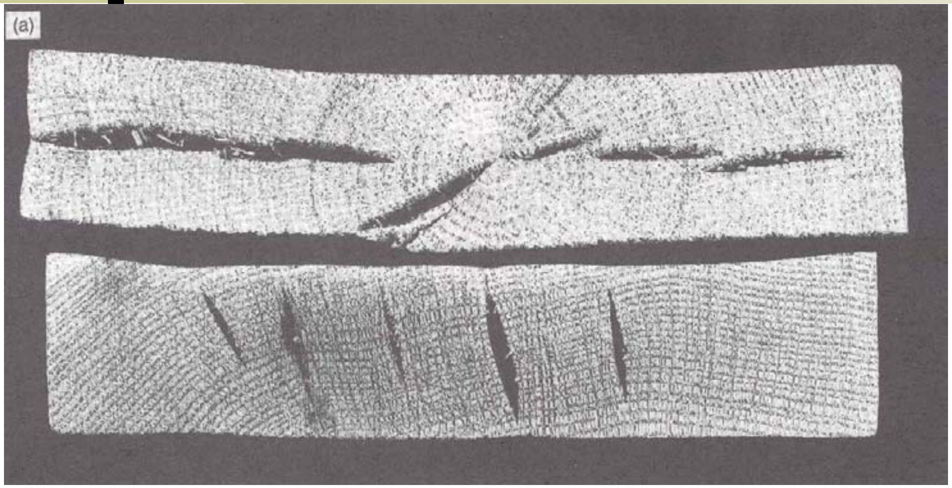
Maintain a healthy and sustainable forest through an understanding of processing conditions that can be used to manipulate the properties of wood and wood composites for specific performance characteristics.

STUDY OBJECTIVE:

To understand and evaluate the effects of conventional and microwave heating on dimensional wood in a pressurized environment.

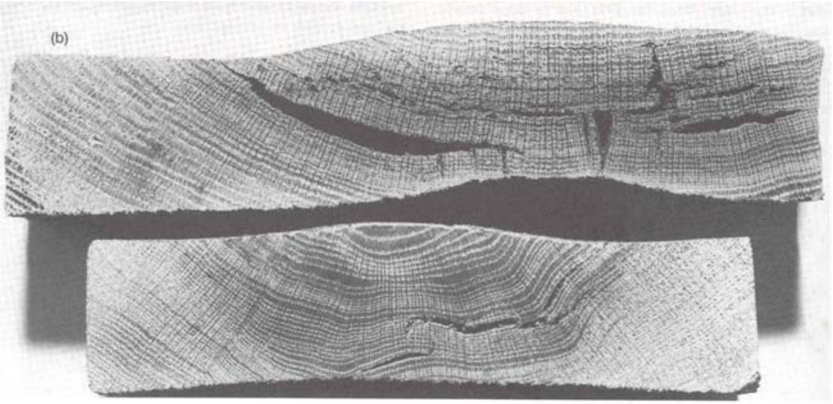
Background

Why model heating in wood?



Uncontrolled heating can cause serious defects in the products if not appropriately applied, either with conventional or microwave energy.

Understanding the flow and generation of heat energy within wood is critical to wood heating control to obtain the desired final product material properties.



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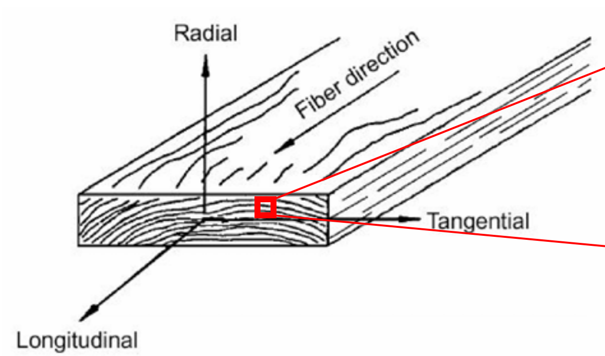
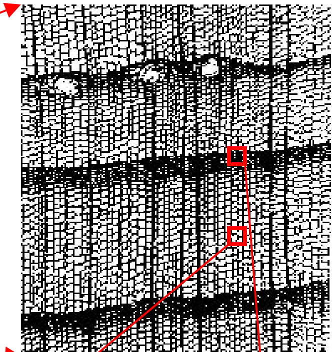
Background

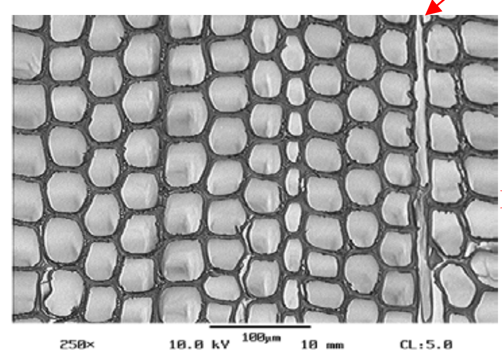
2D cellular model

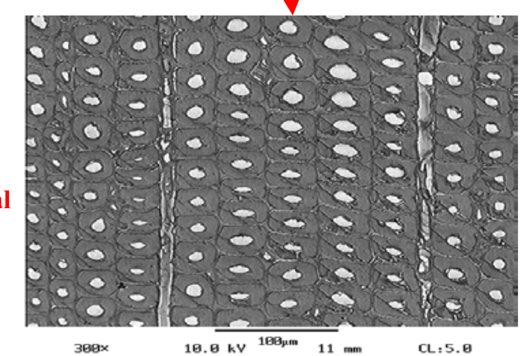




Wood is Anisotropic, axial-symmetric, porous material.

Each growth ring consists of two significantly different structures – earlywood and latewood.





Radial

Tangential

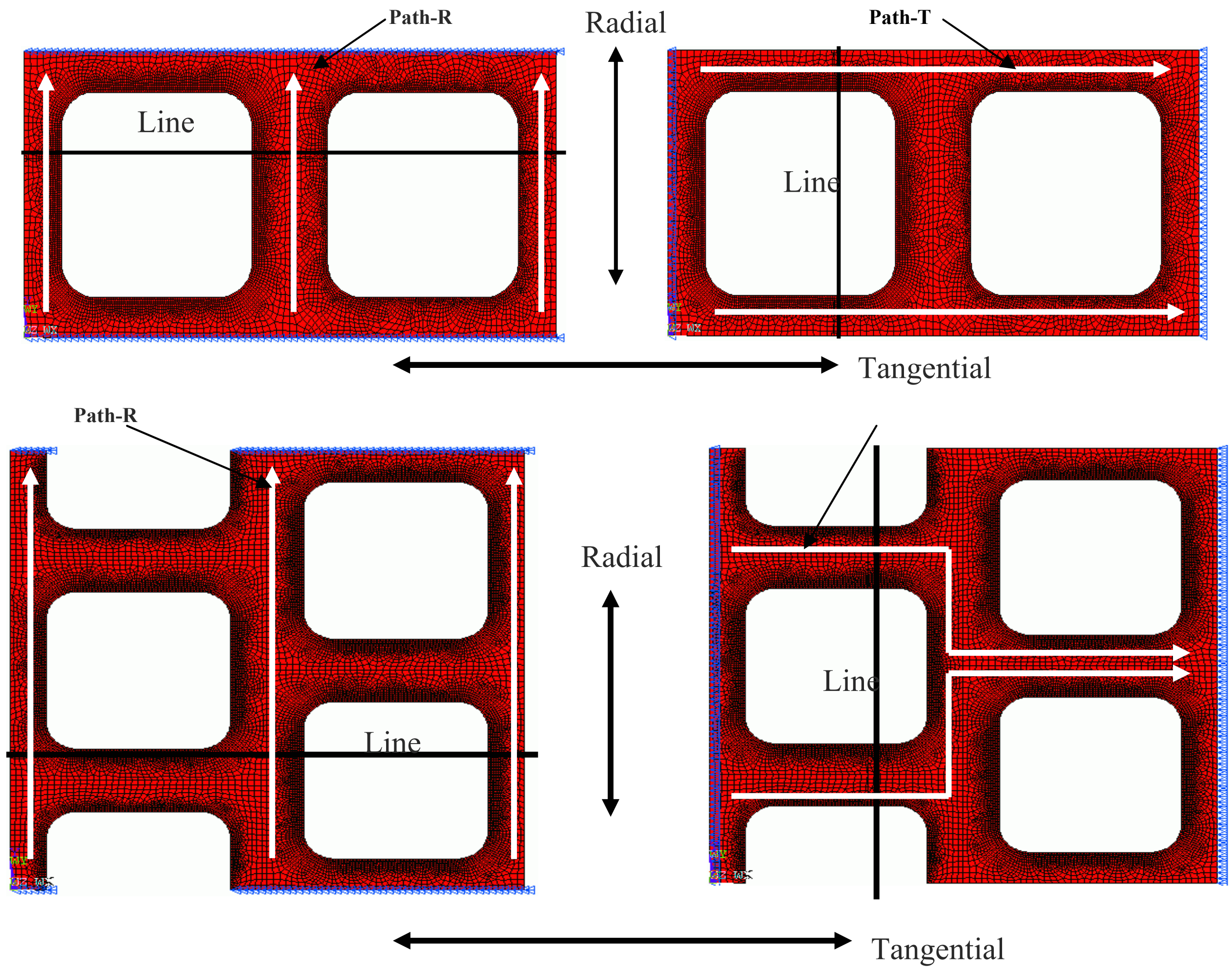
Background

2D cellular model

0% MC

Input parameter:s

- ➢Cell porosity
- ➢Cell alignment
- ➢Cellwall properties
- ➢Air properties



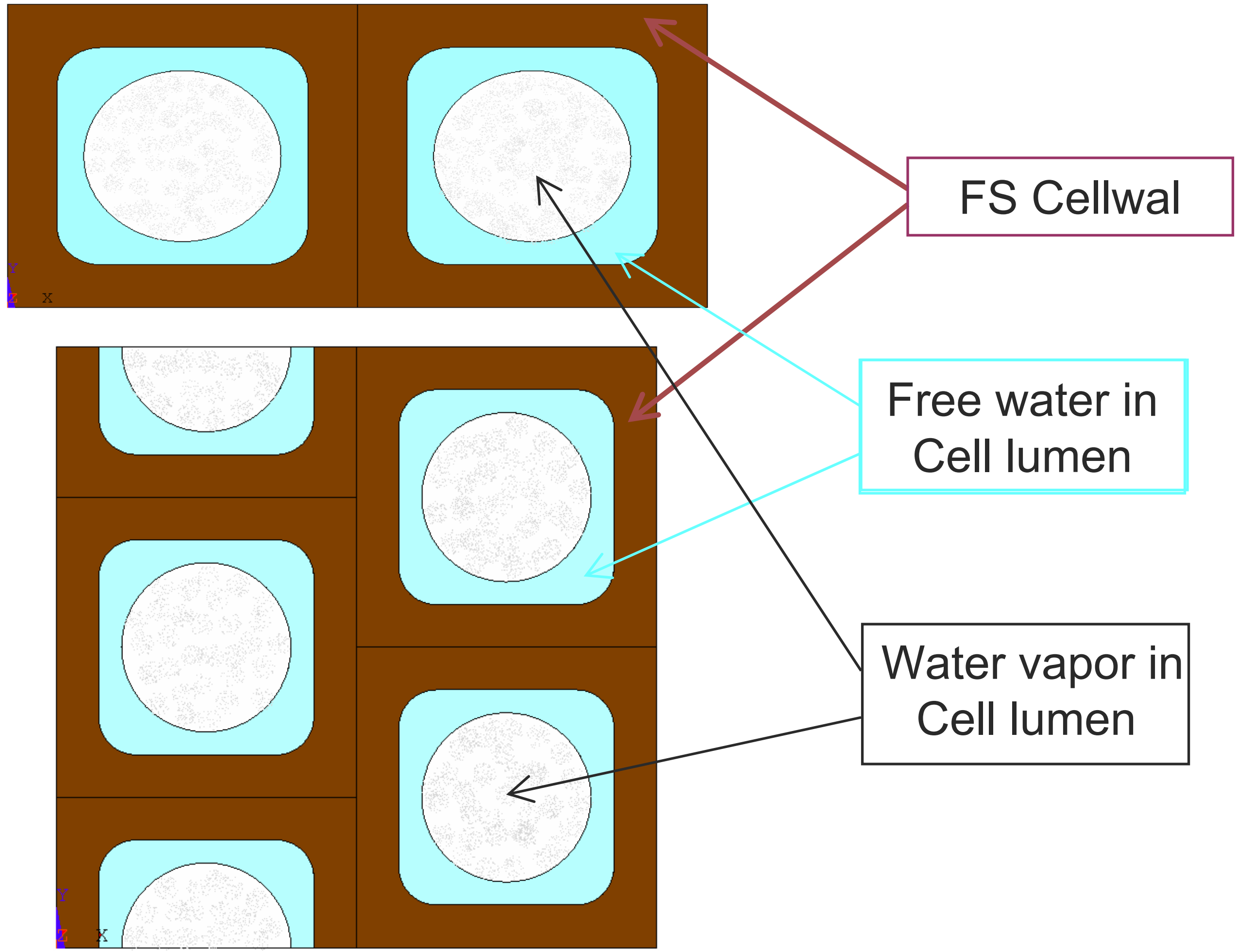
Background

2D cellular model

Cellular Model

With moisture content in wood at 3 MCs:

- Fiber Saturation Point (FSP);
- 50/50 water/vapor in the lumen;
- Fully saturated;



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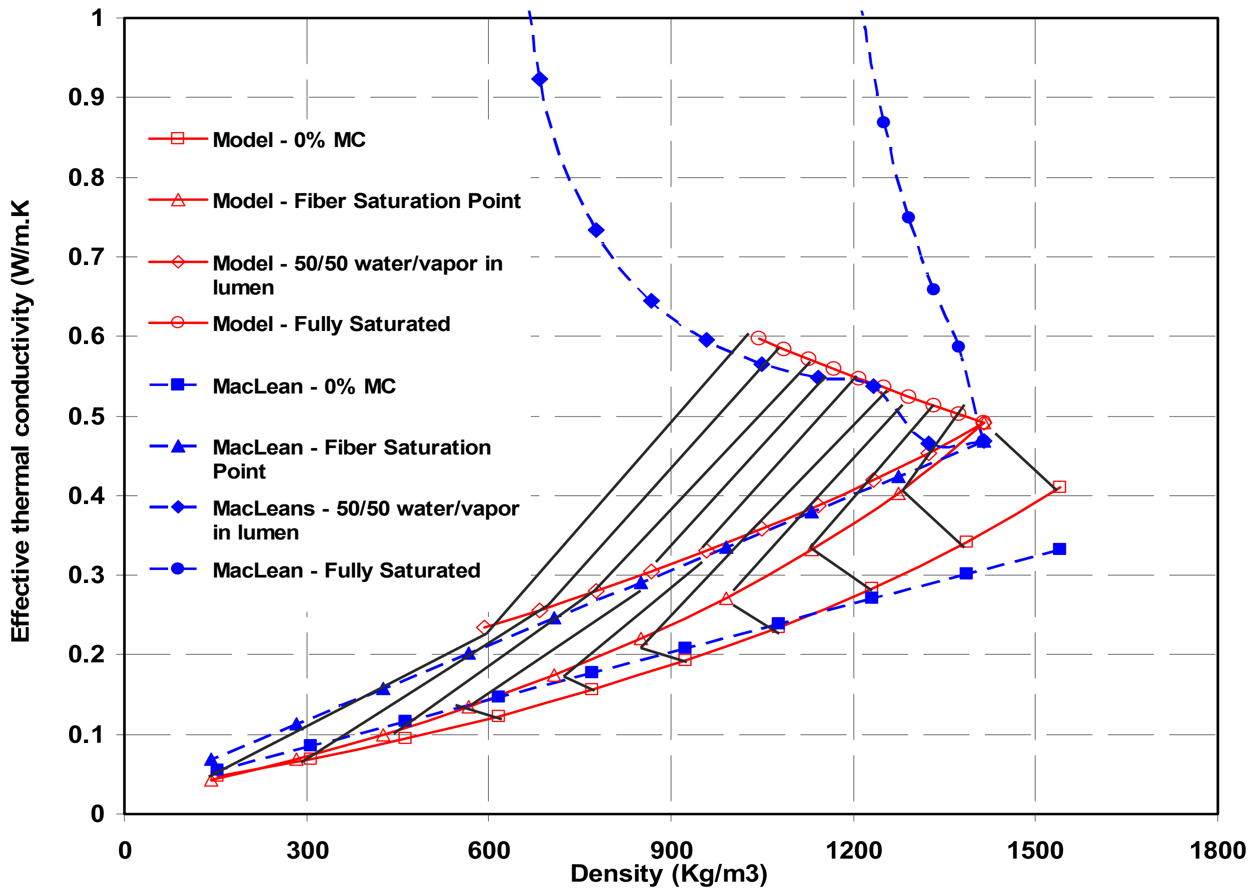
Background

2D cellular model

Effective Thermal conductivity (at four MC conditions)



Current Research

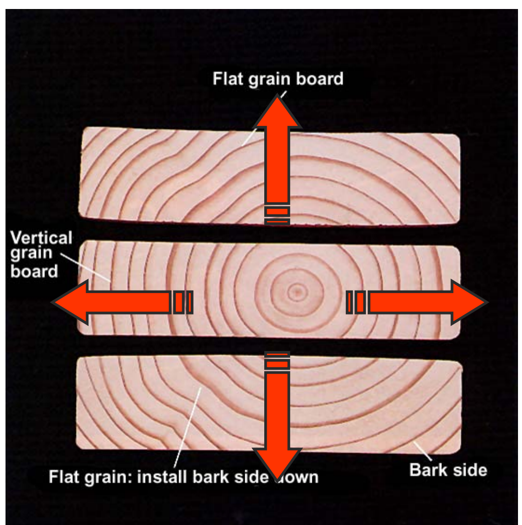
Microwave Heating of Wood

Because microwaves apply heat energy to wood using a significantly different mechanism than conventional conduction heating, it has the potential of imparting improved properties not possible with conventional heating and drying. Therefore with this research we hope to gain an understanding of the heating process and be able to evaluate and predict the effects of microwave heating on dimensional wood in a pressurized environment and compare those with conventional heating.

water molecules, "sugar"

water molecules, "sugar"

Vibrating the molecules



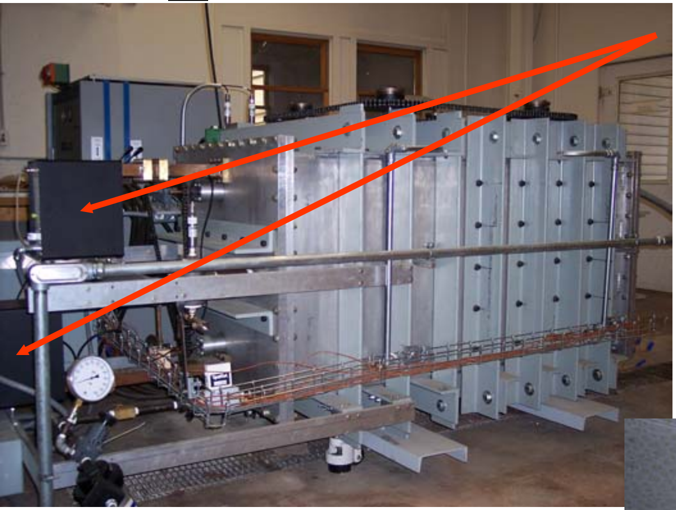
"Defrost" the article, Warm, heating/expansion moving the liquid out from the center of the article, soften the fiber, deep penetration.

Current Research

Microwave Pressurized Chamber

Right Side/End View

Currently: Two 1000 Watt 2.45 GHz household microwave generators



Left Side View

Top Microwave Radiator

Internal Press Mechanism

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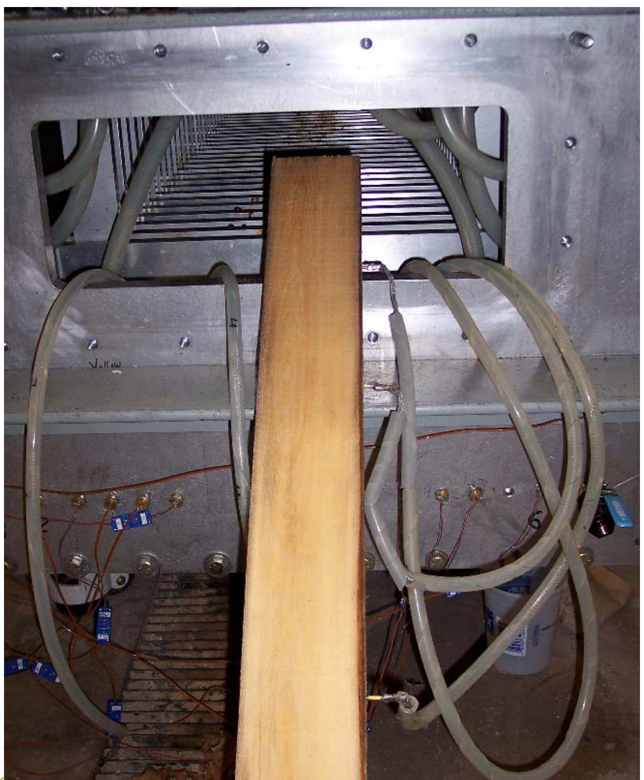
Current Research

Temperature Measurement

Temperatures inside the board are measured using either our own shielded thermocouples or commercial fiber optics.



Conductive Heating Rate

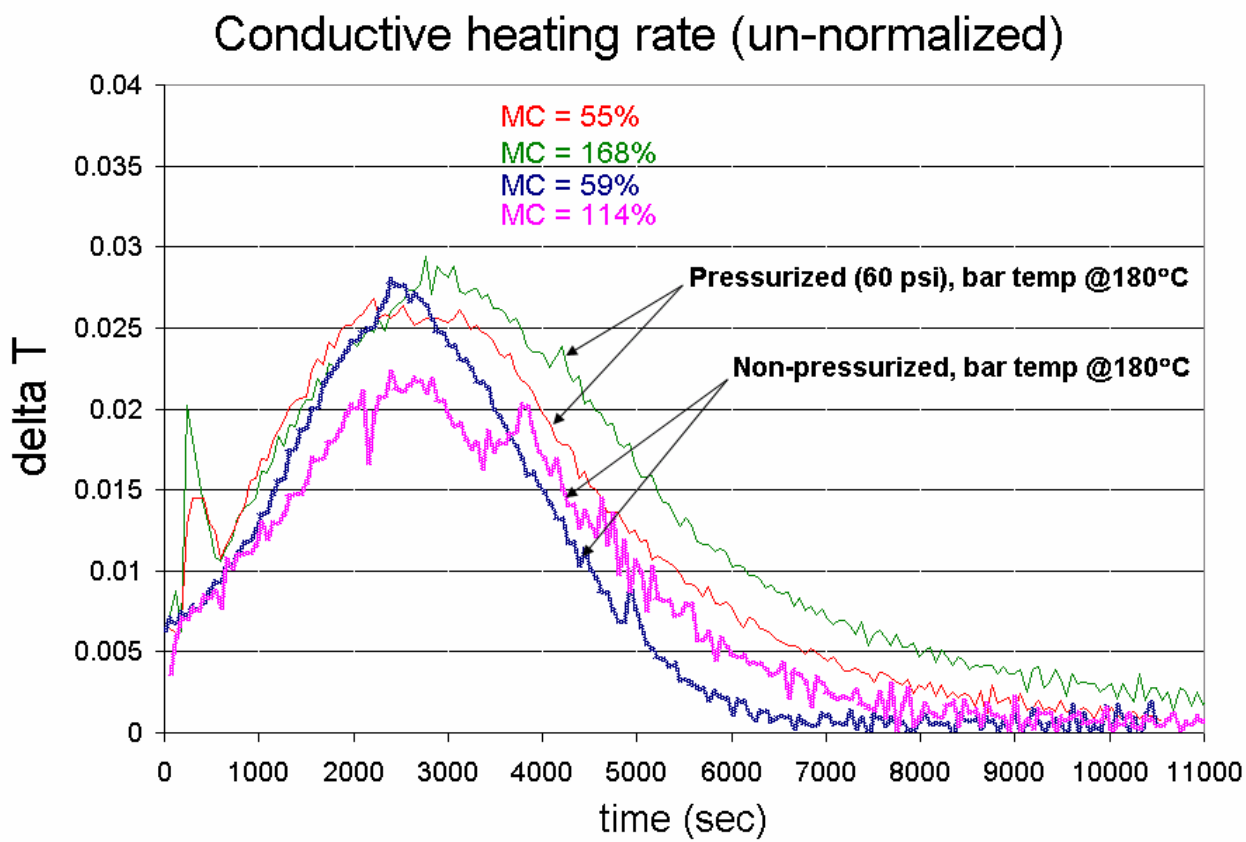
Conductive Heating Rate

- two boards at pressurized heating
- two boards at non-pressurized heating

Different

- moisture content;
- density
- thermal conductivity;
- specific heat;

$$\frac{\partial T}{dt} = \frac{k}{\rho C_p} \nabla T$$



Normalization – Conductive

$$\frac{\partial T}{dt} = \frac{k}{\rho C_p} \nabla T$$

$$\left(\frac{\partial T}{dt}\right)_{NEW} \left(\frac{\rho C_p}{k}\right)_{std} \approx \left(\frac{\partial T}{dt}\right)_{OLD} \left(\frac{\rho C_p}{k}\right)_{old}$$

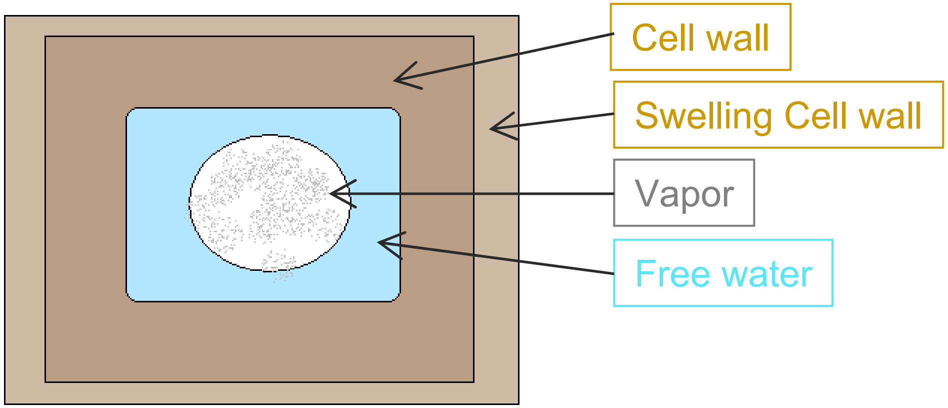
$$\left(\frac{\partial T}{dt}\right)_{NEW} \approx \frac{(\rho C_p)_{old} \times k_{std}}{(\rho C_p)_{std} \times k_{old}} \left(\frac{\partial T}{dt}\right)_{OLD}$$

k – thermal conductivity;
ρ -- density;
C_p – specific heat;
subscript *std* for standardized board, which assumes a board having 70% porosity and 30% moisture content (density of 431*g/cm*^{3});

Heat Capacity (ρCp)

$$(\rho C_p)_{Total} = V\%_{cellwall}(\rho C_p)_{cellwall} + V\%_{boundwater}(\rho C_p)_{boundwater} + V\%_{vapor}(\rho C_p)_{vapor} + V\%_{freewater}(\rho C_p)_{freewater}$$

	Density (Kg/m3)	Specific Heat (J/Kg·K)
Cell wall substance (0%MC) [1]	1540	1260
Air in the lumen (0%MC) [2]	1.161	1007
Bound water in cell wall [3]	1115	4658
Saturated cell wall (FSP) [4]	1412	2279
Water vapor in cell lumen [5]	0.734	2278
Free water in cell lumen [6]	1003	4176



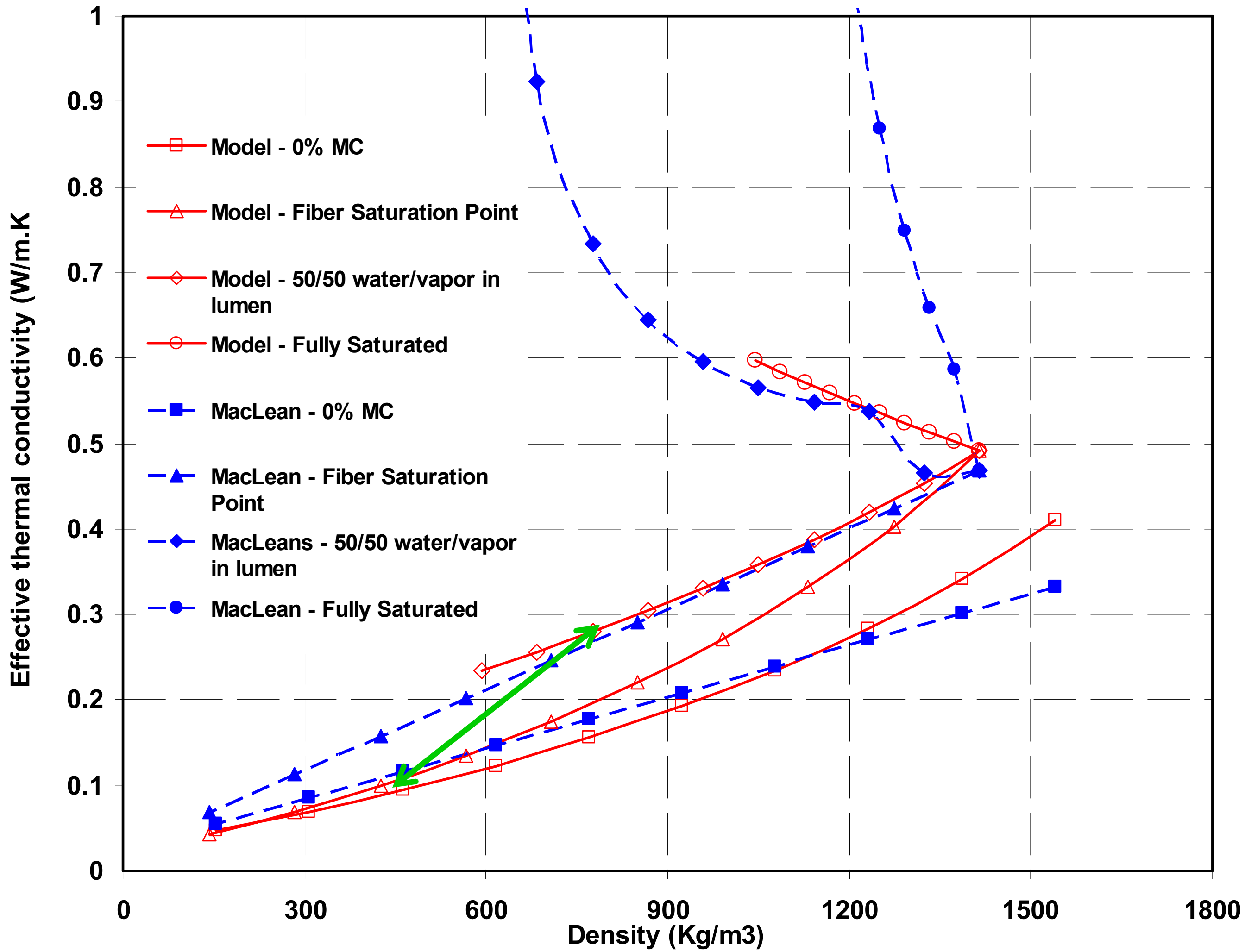
- Density and specific heat for each component in wood is summarized from the literature;
- Volume fraction for each component is calculated based on the microscopic structure of wood as a function of porosity and moisture content;
- Porosity is calculated from the ovendry density measured for each board by the relationship of:

$$\rho_{ovendry} = \rho_{air} \times Porosity + \rho_{cellwall} \times (1 - Porosity)$$

- Total heat capacity is also affected by the temperature. The linear relationship between temperature and specific heat from Siau's textbook was applied to the final total heat capacity

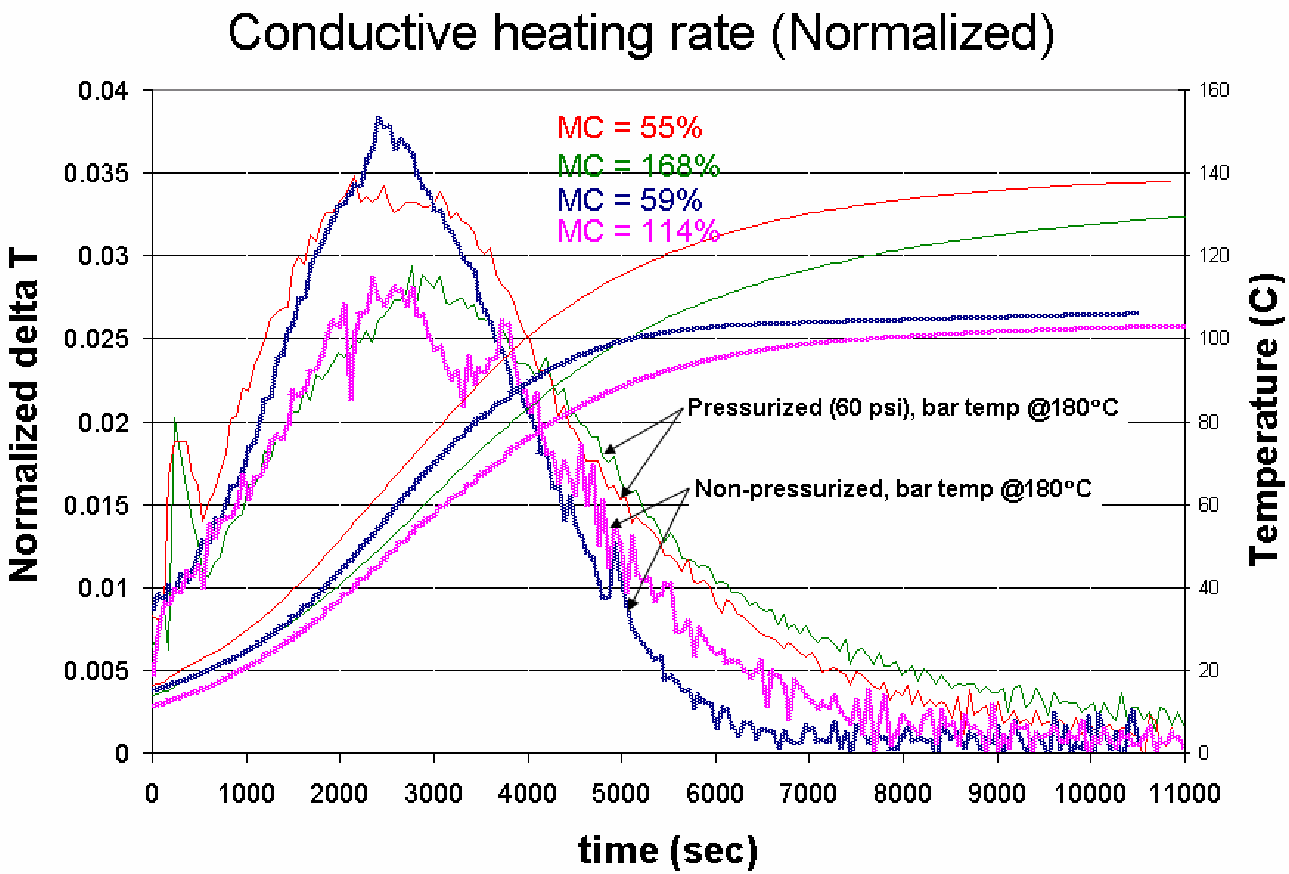
Thermal conductivity (*k*)

Thermal conductivity k is obtained from our previous cellular model -- a theoretical value as a function of density (or porosity) and moisture content;



Normalized Conductive Heating Rate

- Correlation between heating rate and moisture content for conductive heating is -0.825;
- Correlation with $(\rho Cp)_{total}$ is about -0.894.
- Higher internal temperatures are possible with pressurized heating;
- Moisture loss is less with pressurized heating;



Microwave Heating Rate

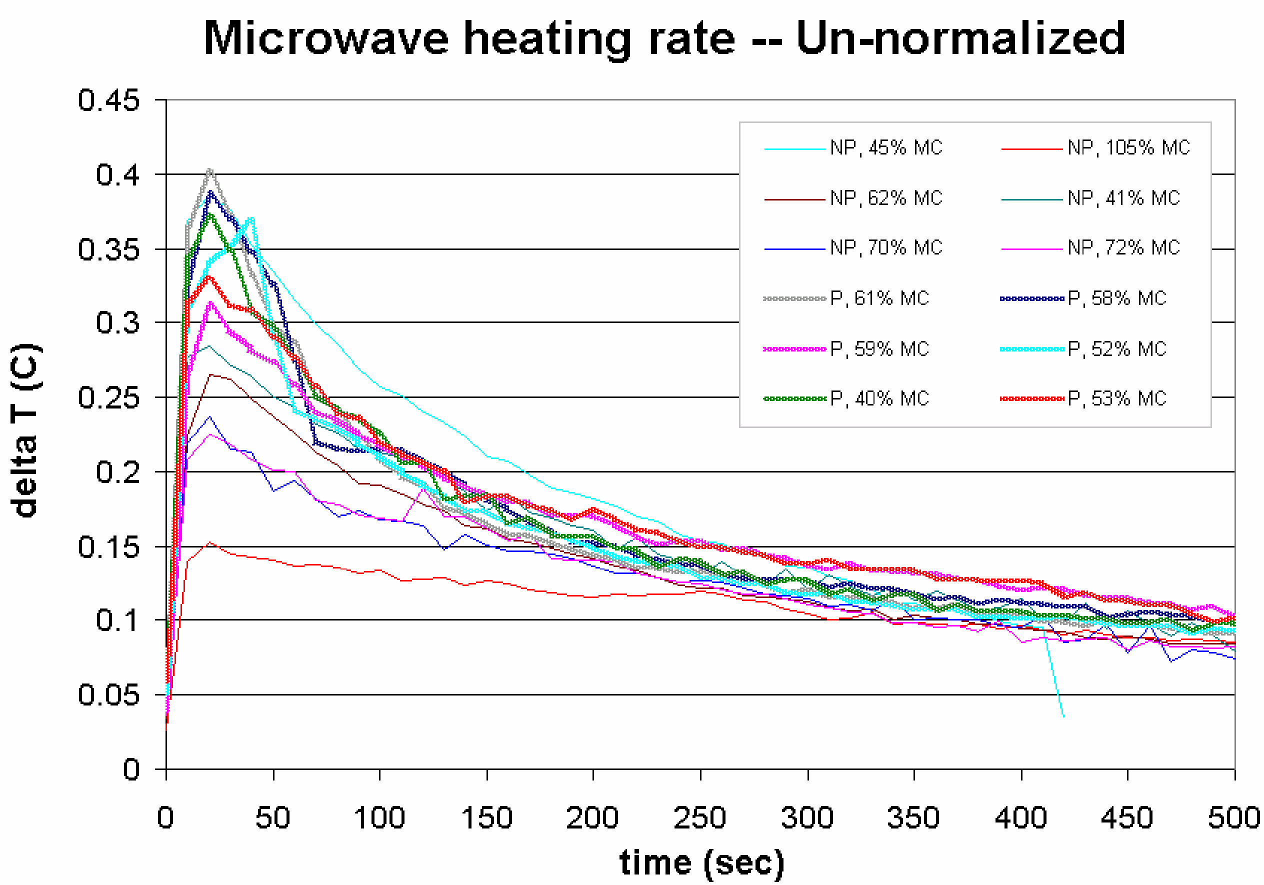
Raw MW heating rate

- 6 boards pressurized heating
- 6 boards non-pressurized heating

Different

- moisture content;
- density;
- specific heat;
- power value;

$$\frac{\partial T}{dt} = \frac{N}{\rho C_p} \nabla T$$



Normalization – Microwave

$$\frac{\partial T}{dt} = \frac{N}{\rho C_p} \nabla T \qquad (*\,see\ note)$$

$$\left(\frac{\partial T}{dt}\right)_{NEW} \left(\frac{\rho C_p}{k}\right)_{std} \approx \left(\frac{\partial T}{dt}\right)_{OLD} \left(\frac{\rho C_p}{N}\right)_{old}$$

$$\left(\frac{\partial T}{dt}\right)_{NEW} \approx \frac{(\rho C_p)_{old} \times k_{std}}{(\rho C_p)_{std} \times N_{old}} \left(\frac{\partial T}{dt}\right)_{OLD}$$

$N - Microwave\ power\ value;$

$N = 5.56 \times 10^{-11} f \varepsilon' \tan\delta \bullet E^2;$

$f - frequency;\ \varepsilon' - relative\ electric\ const.;$

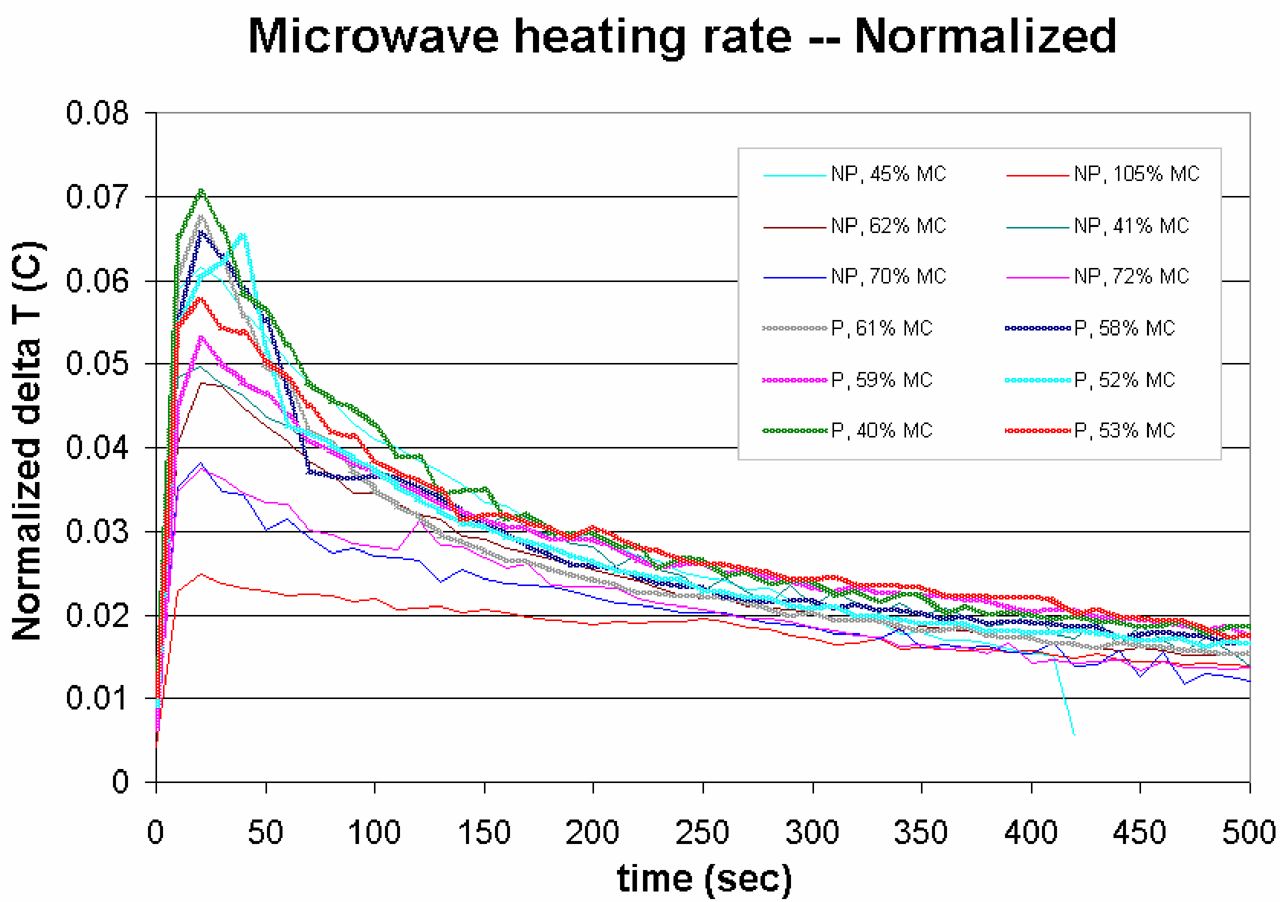
$\tan\delta - loss\,tagent;\ E - electric\ field\ strength$

N is a difficult parameter to obtain experimentally. But N might be able to be determined by studying the ratio of N/k (MW heating parameter over thermal conductivity). This ratio can be obtained by testing the same board (having the same porosity and relatively same MC and density conditions), comparing the two heating rates to obtain N/k ratio. This factor will be used in the MW heating rate normalization

* *from Gregory I. Torgovnikov. (Dielectric Properties of Wood and Wood-based Materials*

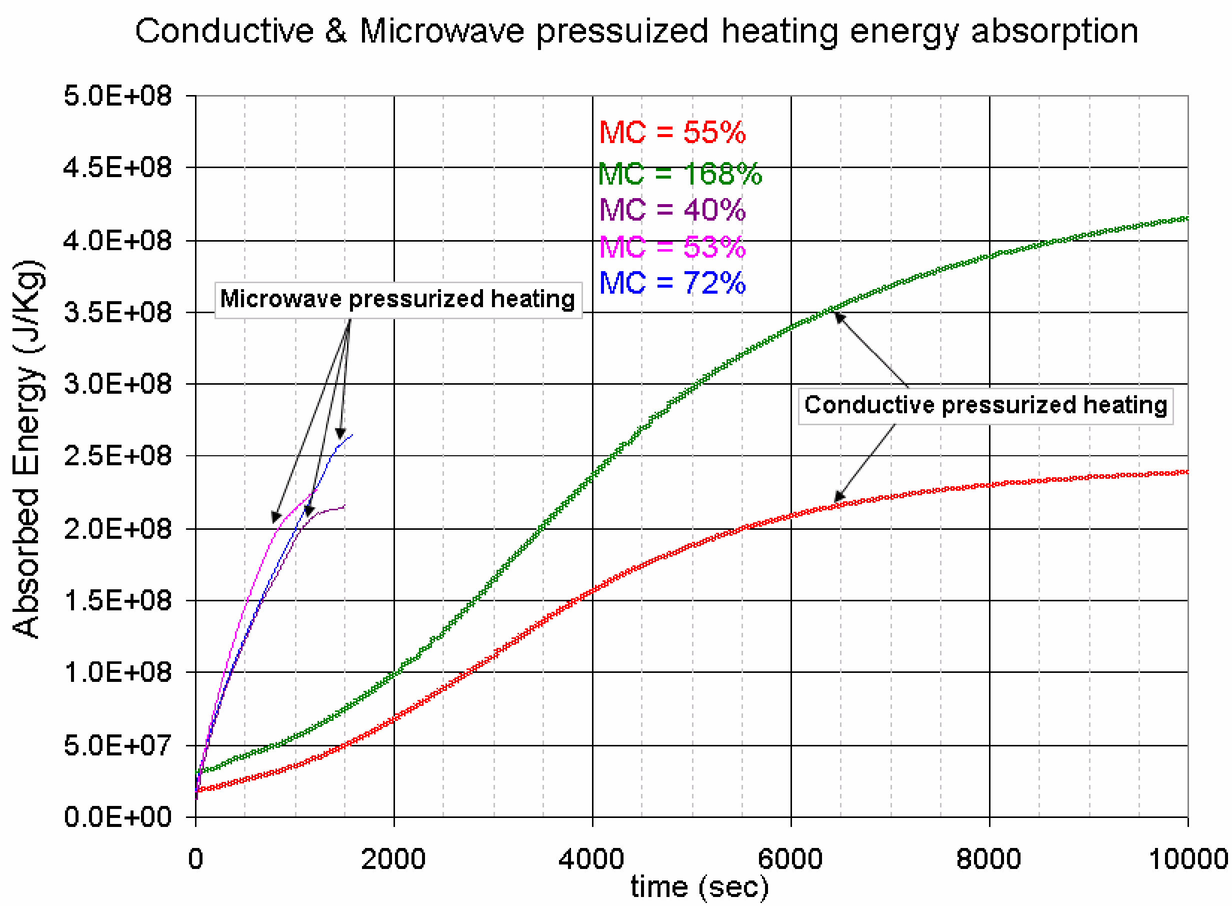
Microwave Heating rate

- Correlation between heating rate and moisture content for MW heating is about -0.778;
- Correlation with $(\rho Cp)_{total}$ is about -0.882.
- Pressurization increase the microwave heating rate;
- Higher internal temperatures are possible with pressurized heating;



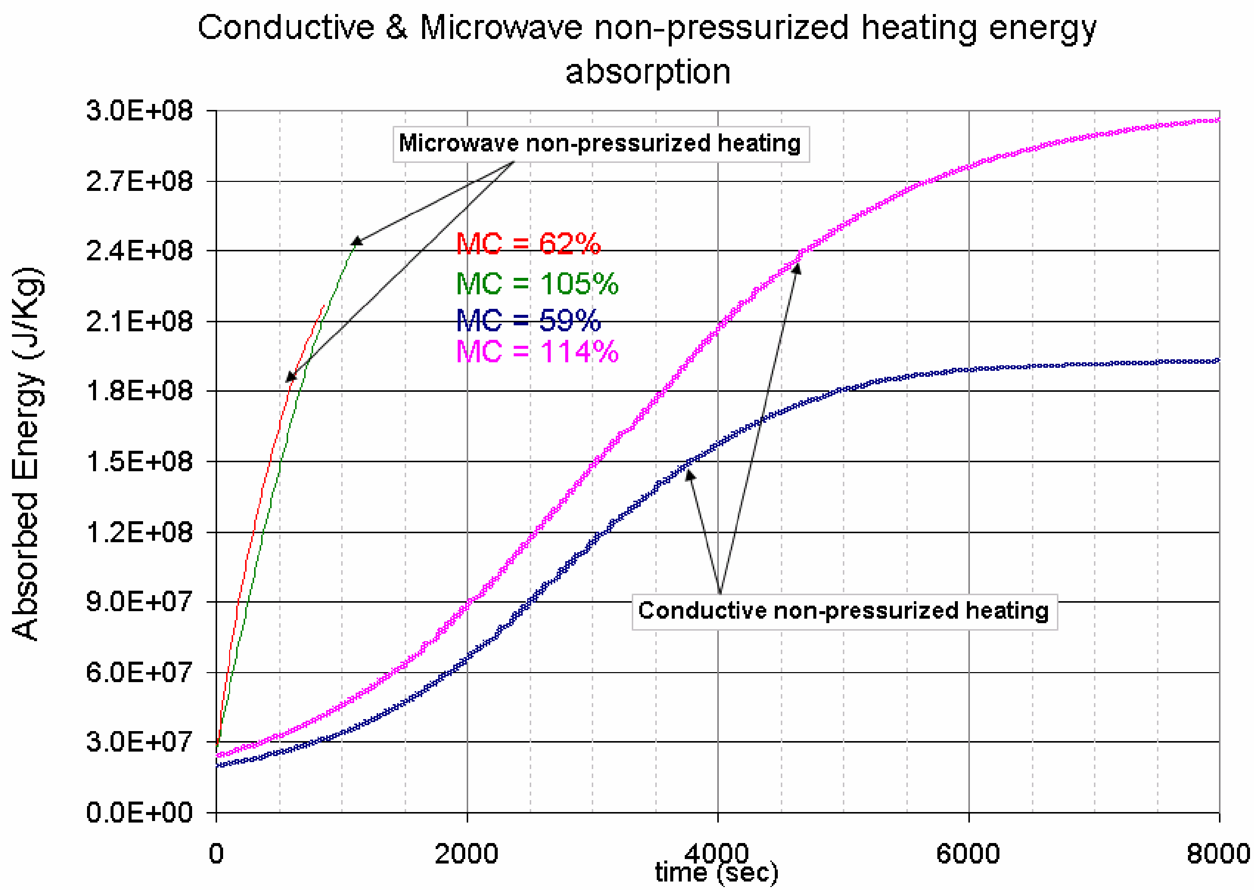
Absorbed Energy by Microwave vs. Conductive Heating

- Microwave heat up wood instantly;
- Energy absorbed into wood by Microwave heating is about 2-4 times more than the energy absorbed by conductive heating during the early 25 minutes;
- Moisture in wood has little effect on energy absorbed by MW heating, but significant effect on energy absorbed by conductive heating.

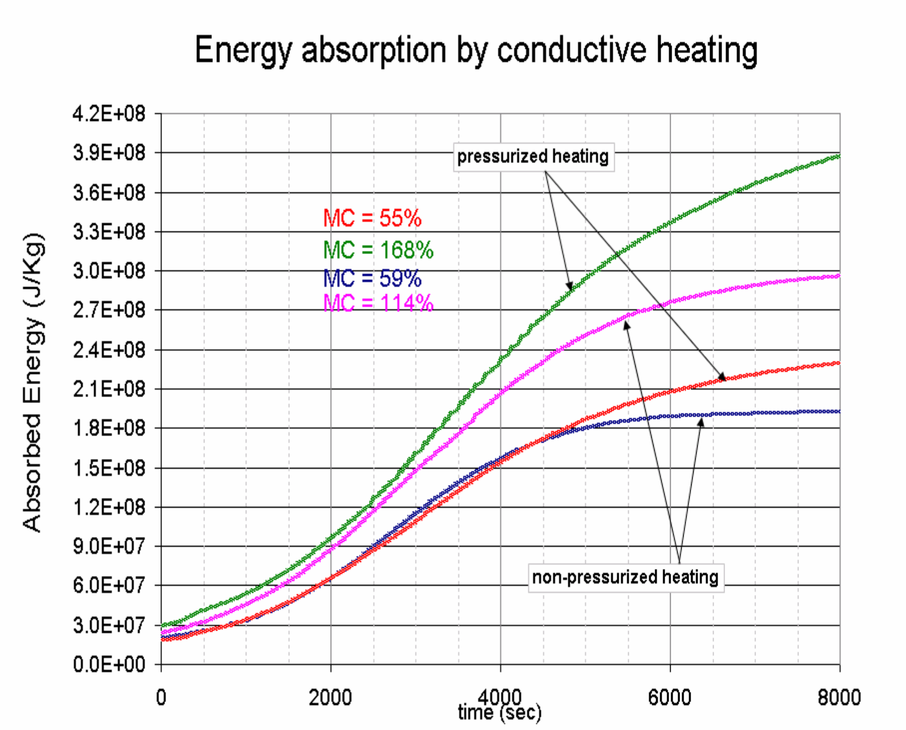


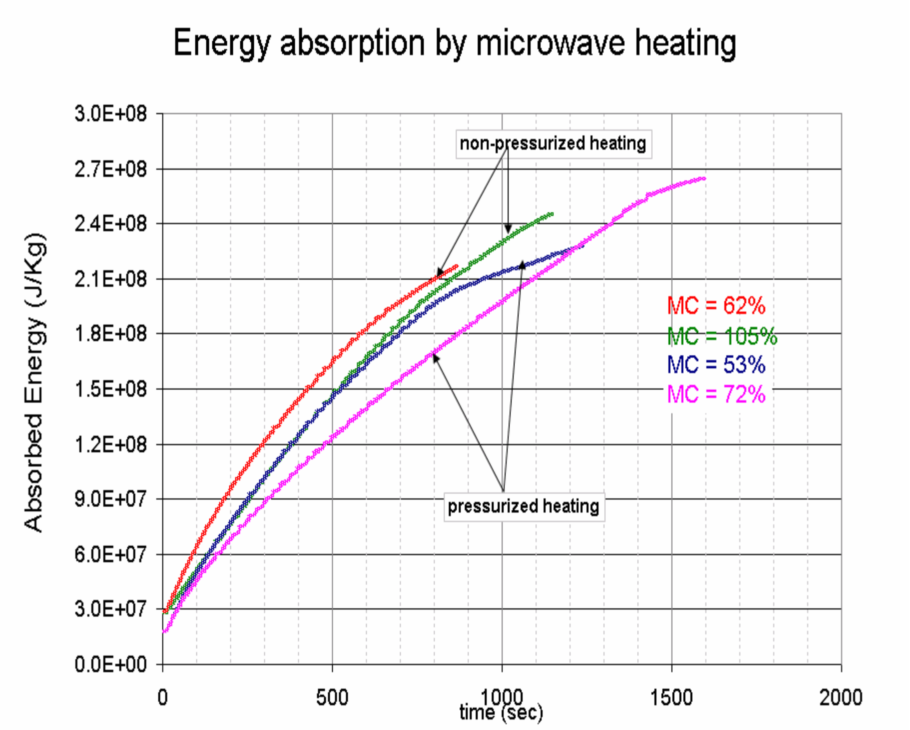
Absorbed Energy by Microwave vs. Conductive Heating

- Absorbed energy = $\rho Cp \times T$; Cp is function of temperature, too
- Energy absorbed into wood by Microwave heating is about 4-6 times more than the energy absorbed by conductive heating during the early 20 minutes;
- High moisture board absorbed more energy than low moisture board by conductive heating in a non-pressurized chamber.



Pressurized vs. Non-pressurized Heating Energy

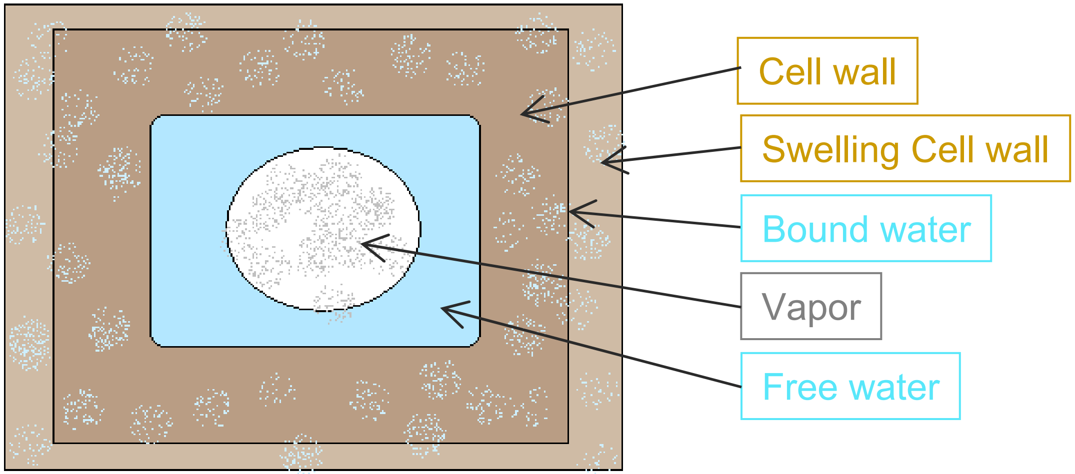




Pressurized environment has a positive effect on conductive heating energy absorption, but has a little negative effect on microwave heating energy absorption.

Heat transfer in wood – where does the energy go into wood?

$$(\rho C_p)_{Total} = V\%_{cellwall}(\rho C_p)_{cellwall} + V\%_{boundwater}(\rho C_p)_{boundwater} + V\%_{vapor}(\rho C_p)_{vapor} + V\%_{freewater}(\rho C_p)_{freewater}$$

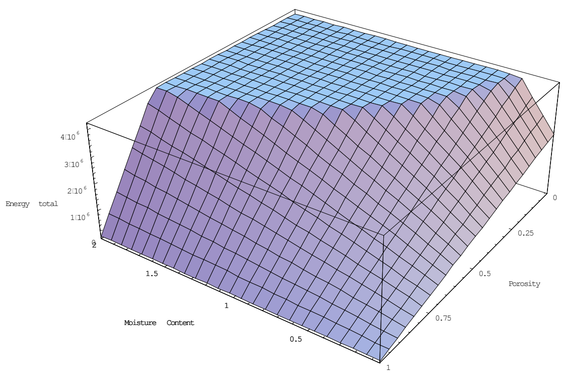


Volume fraction for each component is calculated based on the microscopic structure of wood as a function of porosity and moisture content;

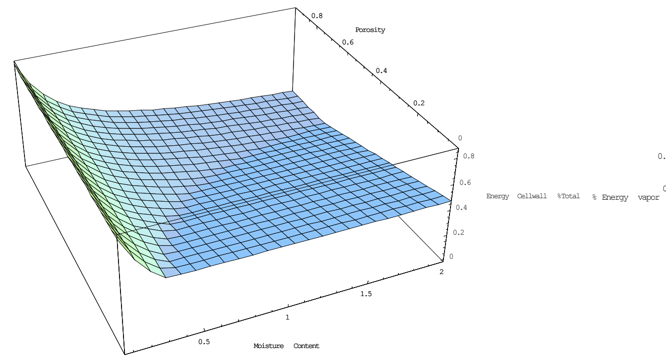
Assume a unit cell with porosity (0% - 95%) swells to $(1+\Delta\ell)$ $(1+2\Delta\ell)$;

Moisture content ranges from 0% to the maximum moisture content at each porosity;

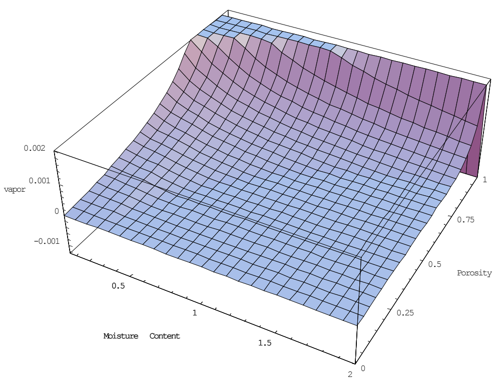
Heat transfer in wood – where does the energy go into wood?



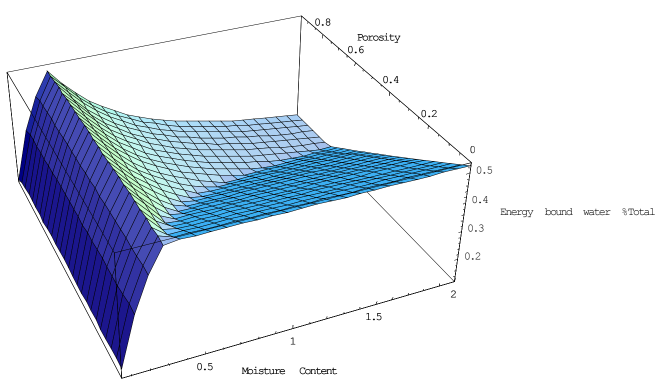
Total stored energy



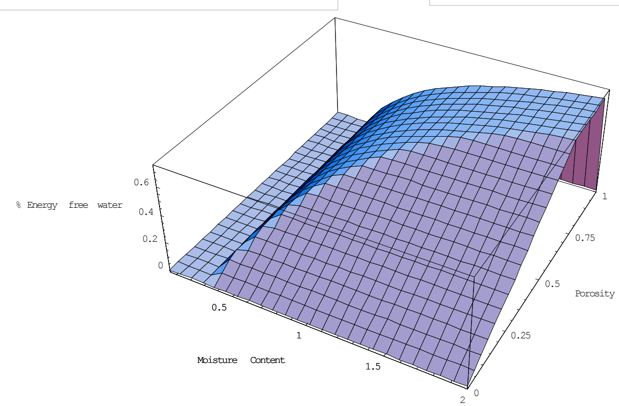
Percent of total energy stored in cell wall



Percent stored in lumen vapor

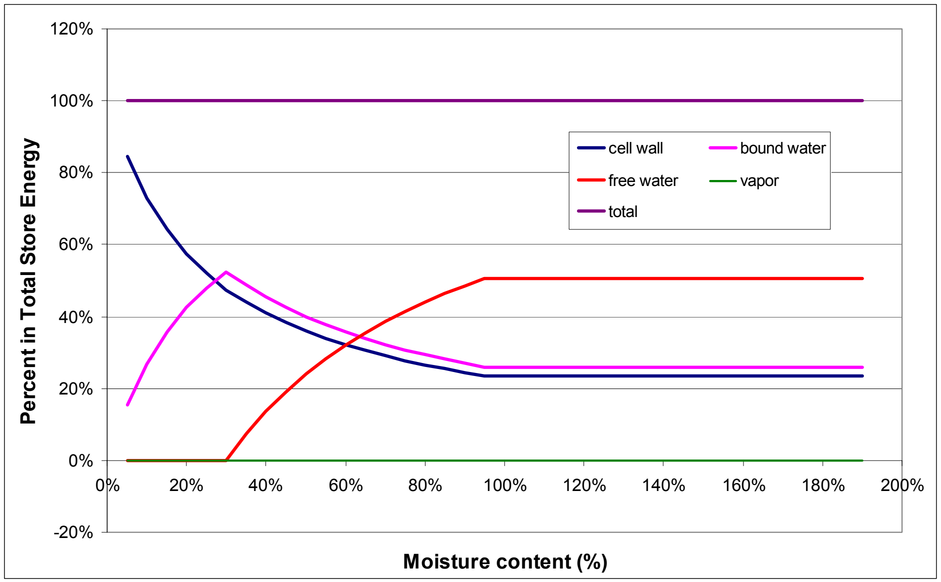


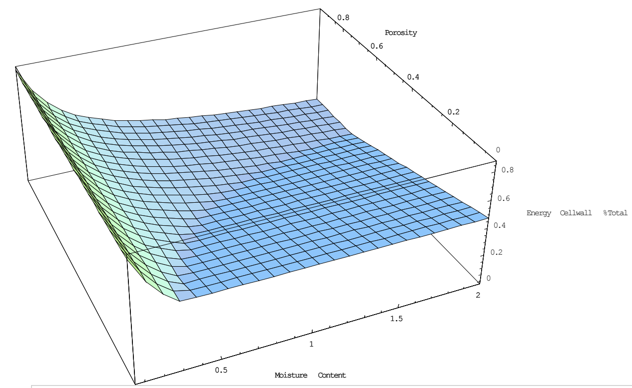
Percent of total energy stored in bound water



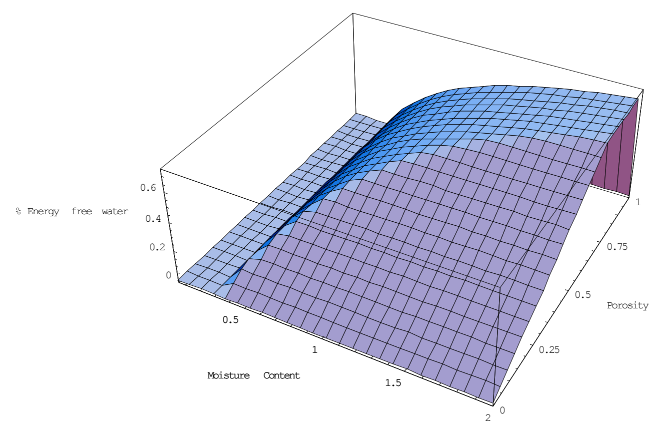
Percent of total energy stored in free water

Heat transfer in wood – where does the energy go into wood?

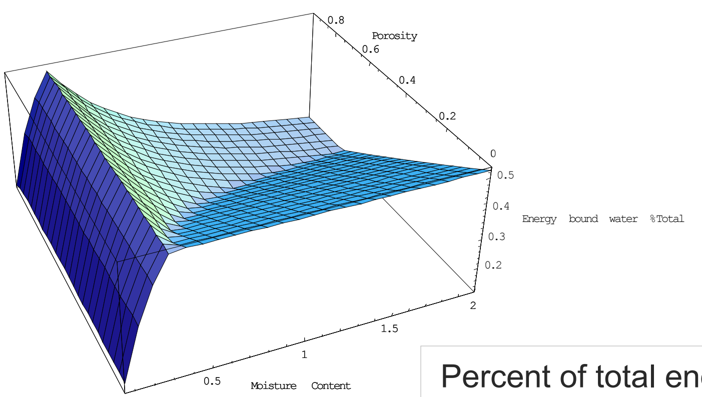




Percent of total energy stored in cell wall



Percent of total energy stored in free water



Percent of total energy stored in bound water

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Summary

- The heating rate is correlated to moisture content and heat capacity of each board by both conductive and microwave heating;
- Higher internal temperatures are possible with pressurized heating;
- Energy absorbed into wood by Microwave heating is instant and 2-4 times for pressurized and 4-6 times for non-pressurized more than the energy absorbed by conductive heating during the early 20 minutes;
- Moisture in wood has little effect on energy absorbed by MW heating, but significant effect on energy absorbed by conductive heating. High moisture board absorbed more energy than low moisture board by conductive heating in both pressurized and non-pressurized chamber.
- Pressurized environment has a positive effect on conductive heating energy absorption, but has a little negative effect on microwave heating energy absorption.

Acknowledgement

- Jane O’Dell, General Engineer, Forest Products Laboratory;
- The Performance Engineered Composite group, USDA Forest Products Laboratory.

Questions and Comments ?

Thank you!