Phytosanitary treatment of wood products and bio-composites by microwaves and radiofrequencies

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Résumé : Les échanges de produits commerciaux en bois et en bio-composites, à l'échelle internationale, introduisent, dans certaines conditions, des espèces indésirables de pathogènes et d'insectes. Les conséquences sont nombreuses et touchent particulièrement les ressources forestières et agricoles. À cet effet, l'Organisation Mondiale du Commerce (OMC) a établi, via la Convention Internationale pour la Protection des Végétaux (CIPV), la norme « ISPM 15 » sur l'utilisation des micro-ondes pour le traitement phytosanitaire. Étant donné la diversité des produits commerciaux et des matériaux qui les composent, comment s'assurer que les pathogènes seront totalement détruits en appliquant cette norme générale? Ceci est une tâche complexe. En effet, le temps de traitement est étroitement lié à plusieurs facteurs: les propriétés non isotropes du matériau (diélectriques, mécanique et thermique), le Design du produit et son état initial (température et humidité), la fréquence et la direction des micro-ondes. D'où la nécessité de développer (et/ou utiliser) des outils robustes (expérimentaux et numériques) pour prédire le temps de traitement de chaque produit. C'est dans ce contexte que la conférence est inscrite. Il vise deux volets : i) évaluation de l'utilisation du modèle de Bert-Lambert par rapport à la solution exacte des équations de Maxwell dans le cas des radiofréquences et des micro-ondes et ii) caractérisation numérique du temps de traitement phytosanitaire, par micro-ondes, de trois variétés de bois canadien (initialement congelé).

Abstract: Commercial trade in wood and bio-composites on an international scale introduces, under certain conditions, unwanted species of pathogens and insects. The consequences are numerous and particularly affect forest and agricultural resources. To this end, the World Trade Organization (WTO) has established, through the International Plant Protection Convention (IPPC), the "ISPM 15" standard on the use of microwaves for phytosanitary treatment. Given the diversity of commercial products and the materials that make them up, how can we ensure that pathogens will be destroyed by applying this general standard? This is a complex task. Indeed, the treatment time depends on several factorss: the non-isotropic properties of the material (dielectric, mechanical and thermal), the product design and its initial state (temperature and humidity), the frequency and the direction of microwaves. Hence the need to develop (and / or use) robust tools (experimental and numerical) to predict the processing time of each product. It is in this context that the conference is inscribed. It has two components: i) evaluation of the use of the Bert-Lambert model with respect to the exact solution of Maxwell's equations in the case of radio frequencies and microwaves and ii) numerical characterization of the phytosanitary treatment time, by microwaves, of three varieties of Canadian wood (initially frozen).

1. Introduction

Circulations of some products containing wood or other plant materials are identified as one of the causes that have facilitated the introduction of pathogens and insects in several countries of the world. This biological invasion has caused the destruction of plant species, causing significant economic and ecological losses for many regions of the world. Recent estimates of the economic impacts of these species on the agriculture, forestry and public health sectors exceed US $ 120 billion annually [1]. Similarly, the costs of the agriculture and forestry sector in Canada have been estimated at Can $ 7.5 billion [1]. Faced with this new global reality, the International Plant Protection Convention (IPPC) working group passed a regulation in 2009 called "International Standards for Phytosanitary Measures 15 (ISPM 15)" on the treatment of phytosanitary of all wood materials, of a thickness greater than 6 mm, used to ship products between countries. Its main purpose is to prevent the international transport and spread of diseases, fungi and insects that could significantly affect plants or ecosystems. This standard requires that all wood material be heat-treated or fumigated with methyl bromide [2]. In 2013, microwave heat treatment (dielectric heating) was approved in ISPM 15. This treatment technique is fast and easier to integrate into a production line [3]. However, given the diversity of commercial wood products, How can we make sure that pathogens will be totally destroyed by applying microwaves? This is a complex task. This is due to the fact that the treatment time is closely linked to several factors such as the non-isotropic properties of wood (dielectric, mechanical and thermal), the product design and its initial state (temperature, humidity, frozen or not). At this stage, several hypotheses and uncertainties about the effectiveness of such a treatment to penetrate wood and kill microorganisms and insects remain to be verified [2]. Indeed, this poses a considerable challenge to numerical simulation in determining the processing time. In its conditions, a multi-physical model must be considered for numerical modeling. The effectiveness of this multi-physics model is directly related to the mathematical approach used to couple Maxwell's equations with conservation equations (mass, motion, and phase change energy) for an anisotropic medium [4]. Faced with this major challenge, several models are proposed in the literature and primarily the use of the empirical model of Beer-Lambert. This model, which links the attenuation of the electromagnetic wave to the properties of the medium it passes through, is used to quantify the energy dissipated in the wood material by microwaves. This model, theoretically, is valid only for semi-infinite medium. The underlying question then arises: what is the limit of applicability of this model for wood (finished anisotropic medium)? Then, in the case where the wood is frozen, another question arises: what model should be used to describe the evolution of the temperature of an anisotropic medium that undergoes a phase change by microwaves? It is in this context that the work is written and concerns two aspects:

i) Study the influence of the frequency, temperature, moisture content and structural orientation of wood on the applicability of the Beer-Lambert law to radio frequency and microwaves. For this, more than 3,000 dielectric data from several wood species, from Canada and the United States, are used. Following this study, a general criterion was established on the applicability of the Beer-Lambert model, in radio frequency and microwave (20Hz-2.45GHz), vis-à-vis the thickness of the wood sample and its complex dielectric properties.

ii) Study the influence of the anisotropy of frozen wood on the time of phytosanitary treatment by microwaves. For this, a finite element 3D approach, using the energy equation in the form of enthalpy-volume, is developed. In this part, the incident microwaves are supposed to be planest and normal to the faces of a wood sample of parallelepipedal geometry..

2. Enthalpy model for heating of orthotropic media

Heat conduction and phase changes in the orthotropic media are naturally described by the energy conservation law in terms of the volumetric enthalpy H(T) [5]:

$$\frac{\partial H(T)}{\partial T} = \left(\frac{\partial^2 \theta_x(T)}{\partial x^2} + \frac{\partial^2 \theta_y(T)}{\partial y^2} + \frac{\partial^2 \theta_z(T)}{\partial z^2}\right) + P_{wave}(T) \tag{1}$$

where θ_x, θ_y and θ_z are components of the orthotropic thermal conductivity integral vector $\vec{\theta}$(T). P_{wave} is the internal volumetric heat generation of microwave energy:

$$P_{wave}(T) = -Re(\boldsymbol{\nabla} \cdot \mathbf{S}) \qquad (2)$$

where $\mathbf{S}$ is the instantaneous Poynting vector. To solve the problem, we introduce the boundary condition into eq. (1) as follows:

$$\left(n_x \frac{\partial \theta_x}{\partial x} + n_y \frac{\partial \theta_y}{\partial y} + n_z \frac{\partial \theta_z}{\partial z}\right) + \mathrm{h}(T - T_\infty) - \mathbf{q} \cdot \mathbf{n} = 0 \qquad (3)$$

q [W/m^2] is the radiative heat flux incident, **n** is the outward normal (n_x, n_y, n_z) to the surface h, [W/m^2/°C] is the surface heat transfer coefficient, and $T_\propto$ is the temperature of the surrounding medium (air). The term h (T–$T_\propto$) represents the convection heat transfer from the material to the environment.

3. Electromagnetic-wave energy absorption

The power density of an electromagnetic wave is expressed by Poynting vector **S** [5] :

$$\mathbf{S} = \frac{\mathbf{1}}{\mathbf{2}} \mathbf{E} \times \mathbf{H}^* \qquad (4)$$

E and $\mathbf{H}^*$ are the electric field (V m^{-1}) and the conjugate magnetic field intensity (A m^{-1}), respectively. In general, we are dealing with steady-state harmonic time-varying fields. According to the generalized electrophysical model of a wood sample proposed in [5], the power dissipated per unit volume is [5] :

$$P_{wave} = \frac{\omega}{2} \varepsilon_0 (\mathbf{E} \cdot Im(\bar{\bar{\boldsymbol{\varepsilon}}}) \cdot \mathbf{E}) \qquad (5)$$

ε_0 is the dielectric permittivity (=8.8541x 10^{-12} F/m) of the free space and $\bar{\bar{\boldsymbol{\varepsilon}}}$ is the complex relative dielectric tensor. Assuming the electro-neutrality of wood $\left(\nabla(\nabla \cdot E) = \mathbf{0}\right)$, we deduce for each principal direction from Maxwell's equations the expression of Helmholtz's equation of wave propagation [5] :

$$\nabla^2 \bar{\mathbf{E}} - \gamma^2 \bar{\mathbf{E}} = 0 \qquad (6)$$

where γ is the constant complex propagation $\gamma = \alpha + j\beta$, β is the attenuation constant and α is the phase (a constant). These parameters are related to the dielectric properties of the material and frequency of radiation by:

$$\alpha = \frac{\omega}{c}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta}+1\right)} \qquad \beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+tan^2\delta}-1\right)} \qquad (7)$$

$\mathrm{c} = \mathbf{1}/\sqrt{\mu_0 \varepsilon_0}$ is the speed of light. The term δ (=tg^{-1}(ε''/ε')) is the dielectric loss angle. The attenuation constant (β) controls the rate at which the incident field intensity decays into a sample. The term $1/(2\beta)$ is the penetration depth (d). The phase constant (α) represents the change of phase of the propagation radiation and is related to the wavelength of radiation by $\lambda=2\pi/\alpha$.

4. Analysis of power formulations

1. Maxwell solution for one-dimensional propagation

Consider one-dimensional propagation energy through the thickness 'L' of the sample wood material. The waves travel through the material from right to left with an electric field intensity E_{LR}. The regions external to the sample are denoted by index 1 for the left and index 3 for the right. The material is denoted by index 2. The incident microwaves are assumed to be normal to the face of the material. The exact solution for the power absorbed by one-dimensional material is given by [5] :

$$P_{e,LR}^{max\,well}(y)=2I_0\beta_2\left[\frac{e^{-2\beta_2 y}+\left(\overline{R}_{2,3}\right)^2 e^{-4\beta_2 L}e^{2\beta_2 y}+2\overline{R}_{2,3}e^{-2\beta_2 L}\cos\left(2\alpha_2(y-L)-\delta_{2,3}\right)}{1+\left(\overline{R}_{1,2}\right)^2\left(\overline{R}_{2,3}\right)^2 e^{-4\beta_2 L}-2\overline{R}_{1,2}\overline{R}_{2,3}\cos\left(\delta_{1,2}+\delta_{2,3}+2\alpha_2 L\right)e^{-2\beta_2 L}}\right] \tag{8}$$

I_0 is the transmitted power flux. $\overline{T}_{i,j}$ and $\delta_{I,j}$ are respectively the absolute value and argument of a complex transmission coefficient $T_{i,j}$ at the interface between layers i and j. $\overline{R}_{i,j}$ is the absolute value of the complex reflection coefficient $R_{i,j}$. β_2 is the attenuation constant and α_2 is the phase constant.

2. Case of Lambert's law

Beer-Lambert's law relates the absorption of electromagnetic field intensity to the properties of the material through which the intensity is traveling:

$$P^{Lambert}=-\frac{dI}{dy}=2I_0\beta_2\,e^{-2\beta y}=2\beta_2 I(y) \tag{9}$$

$P^{Lambert}$ is the power absorbed per unit volume by wood material.

3. Criterion of applicability of Beer-Lambert's law: penetration depth

The data consisting the dielectric constant and the dielectric loss factor for various materials (Douglas fir, oak, hardboards and Canadian eastern wood species: trembling aspen, yellow birch, white birch and sugar maple), under various conditions, extracted from [6] and [7], are used in this paper. In [6], the data were taken at radiofrequencies from 20 Hz to 50 MHz, temperatures from -20°C to 90°C and relative humidity levels from 0% to soaked; the average moisture content attained by these wood samples is given. In [7], the data were taken at microwave radiation values from 397 MHz to 2466 MHz at different temperatures and moisture contents.

For analysis purposes, we use the following dimensionless formula to estimate the error between the formulation of Lambert's law for absorbed power and the exact power dissipation:

$$Error=\frac{\mathbf{1}}{\beta I_{\mathbf{0}}}\sqrt{\frac{\mathbf{1}}{L}\int_{\mathbf{0}}^{L}\left[P^{Maxwell}(y)-P^{Lambert}(y)\right]^2 dy} \tag{10}$$

The above critical thickness for which the two formulations are approximately equivalent is calculated at 0.01 error. For analysis, the critical lengths are estimated by a logarithmic function :

$$\log_{10} L_{crt}=a\log_{10}(\beta^{-1})+b \tag{11}$$

where *a* and *b* are adjustment constants. Theoretical constants are obtained by minimizing the global absolute error, ER, between the computed critical length L_{crit} and the estimated critical length L_{est} by a least-squares algorithm:

$$\mathrm{ER}=\sum_{i=1}^{N_{exp}}\left[\left(a\log_{10}(\beta^{-1})+b\right)-L_{est}\right]^2 \tag{12}$$

The parameters of this model and the correlation coefficients between the computed and estimated critical length (over the different ranges of temperature, relative humidity, moisture content and frequencies), and for the three main structural orientations (longitudinal, tangential and radial), are excellent and agreement between all the computed values of the critical thickness and the model (see figures 1-3).

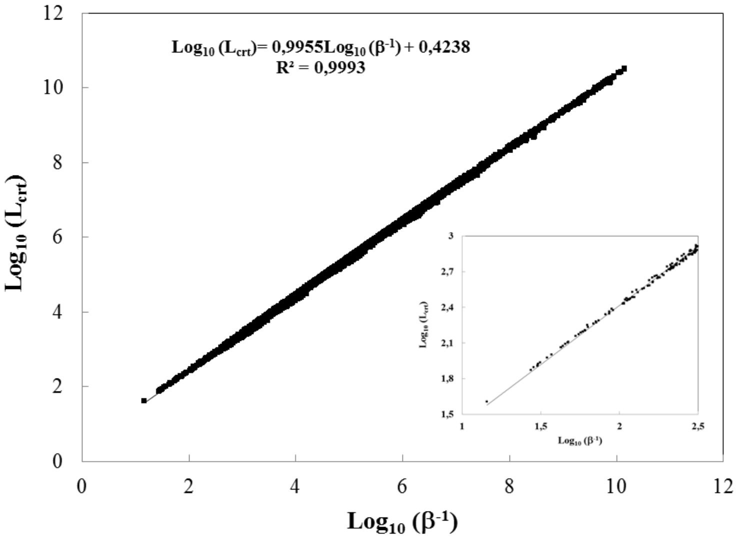


Figure 1. *The critical length L_{crit} distribution with penetration depth β^{-1} (cm) for Douglass fir, oak, hardborad No.1 to No.4; all temperatures, all relative humidity and all RF frequencies*

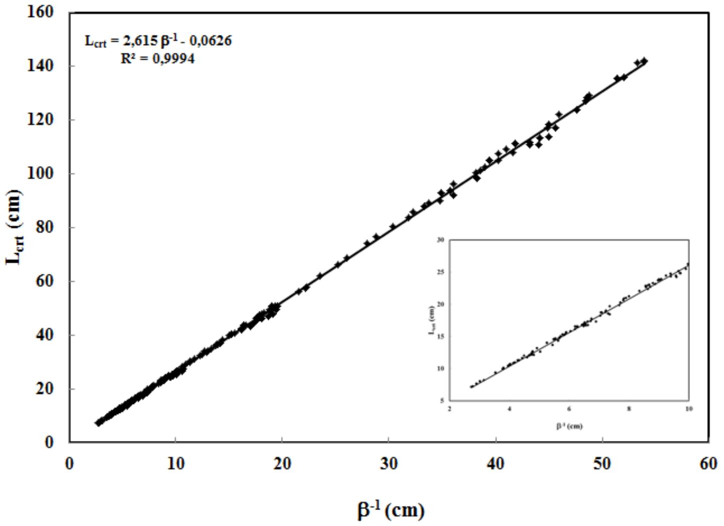


Figure 2. *Relation between critical length L_{crit} and penetration depth β^{-1} (cm) for Trembling aspen, white birch, yellow birch and sugar maple; all temperatures, all moisture contents and all microwave frequencies*

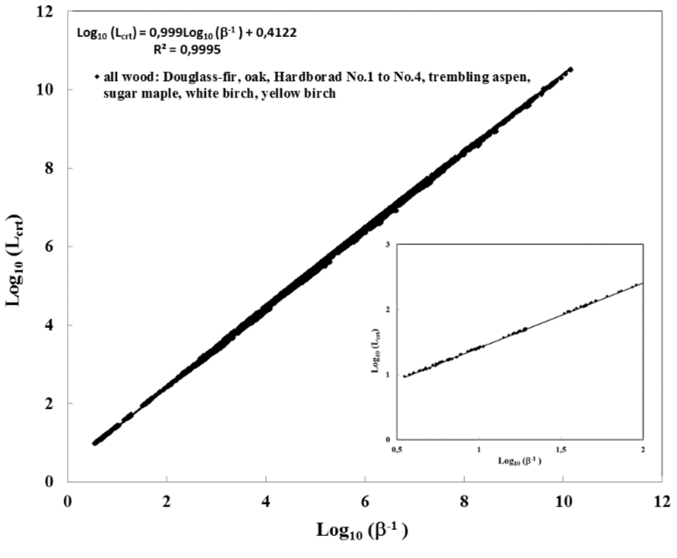


Figure 3. *Relation between critical length L_{crit} and penetration depth β^{-1} (cm) for all woods; all temperatures, all moisture contents, all relative humidity and all RF and microwave frequencies*

5. Numerical phytosanitary treatment by microwave

For analysis, we consider a parallelepiped simple wood and we assume that each component of the electric field $E = \left(E_x(z), E_y(x), E_z(y)\right)$ is a uniform plane microwave and each component of a wave is assumed to be incident normally to opposite faces of the sample wood (Figure 4.). The microwaves travel through the material with an incident power flux I_0.

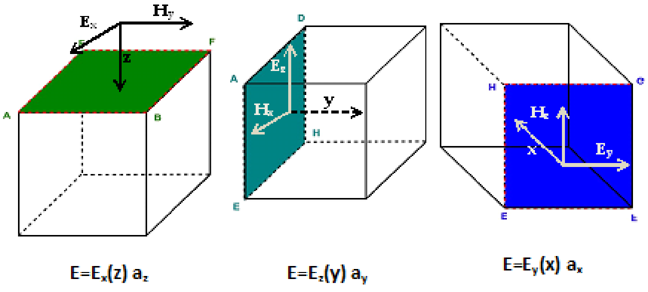


Figure 4. Wood sample exposed to plane microwaves from the three principal faces

This study focused on 22-mm-thick boards. This dimension corresponds to the standard value for boards used in the manufacture of EUR EPAL®pallets. For this, a 3D wood log is considered for three wood species: trembling aspen, white birch and sugar maple. The log is considered to be orthotropic and its thermal and dielectric properties are functions of temperature, moisture content and structural orientation. The log structure is square (Lx=Ly= Lz = 2.2 cm). For conductivity (k) and dielectric (ε) anisotropy effect on thawing wood, we considered the following situation:

$$k_L=1.8k_R \text{ and } k_T=0.9k_R \quad \text{and} \quad \varepsilon_L=1.8\varepsilon_R \text{ and} \varepsilon_T=0.9\varepsilon_R \qquad (7)$$

The indices L, R and T to designate, respectively, the longitudinal, radial and tangential directions

Table 1. Longitudinal dielectric properties

Trembling aspen Frequency = 2466 MHz at MC=131%

Relative dielectric constant, ε'	$26.419176 - 0.0013518T - 0.0006905T^2$
Relative dielectric loss , ε''	$5.9174270 - 0.051926T - 0.000118T^2$

White birch, Frequency = 2466 MHz at MC=131%

Relative dielectric constant, ε'	$30.633134 + 0.243143T - 0.010413T^2 + 0.000113\ T^3$
Relative dielectric loss , ε''	$5.238715 - 0.065994T - 0.000249T^2$

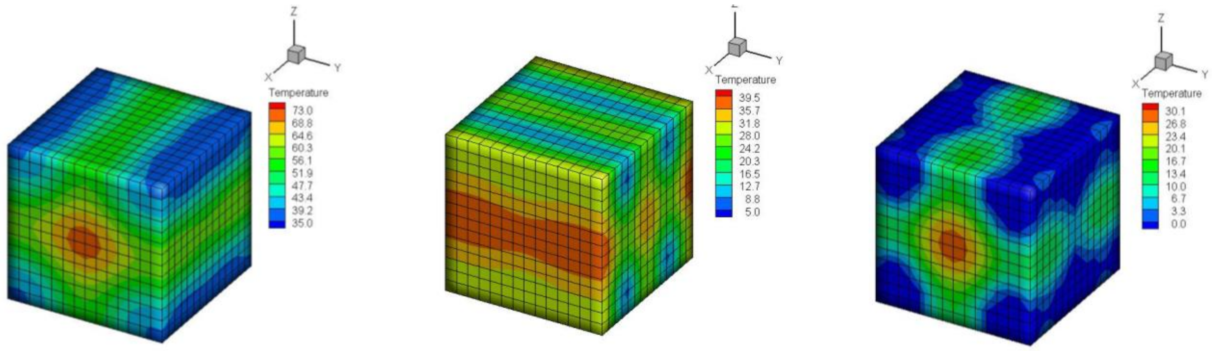
Sugar maple, Frequency = 2466 MHz at MC=131%

elative dielectric constant, ε'	$24.398804 + 0.079714T - 0.012118T^2 + 0.000153\ T^3$
Relative dielectric loss , ε''	$5.053700 - 0.027868T - 0.000523T^2$

The wood material is exposed to radiation of equal intensity (1 W/cm2) and frequency (2466 MHz from six faces): two faces in the x direction, two faces in the y direction, and two faces in the z direction. The initial wood temperature varies from -20oC to 30oC. The wood moisture content (MC) is fixed at 131% and the specific gravity (SG) is 0.32, 0.48 and 0.55 for aspen, white birch and sugar maple respectively. For numerical modeling, the structure is meshed with identical hexahedra comprising eight nodes (500 elements and 756 nodes).

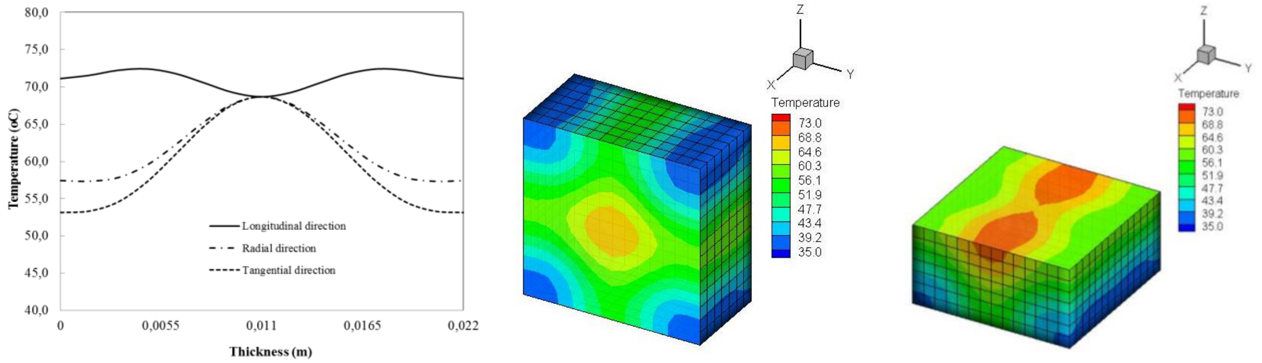
Figure 3 presents, at time 200 s and initial temperature -20 °C, different views of the surface temperature distribution induced by microwave treatment of the trembling aspen, white birch and sugar maple.

At this time, Figure 5 presents, for the trembling aspen log on the half-planes of symmetry (longitudinal, radial and tangential directions), the profiles of temperature distribution predicted from the power dissipation computed from Maxwell's equations.



Aspen trembling Birch white Sugar maple

Figure 3. Surface temperature distribution for aspen trembling, white birch and sugar maple, exposed to microwave at time= 200 seconds , I_0= 1 Watt/cm^2, f=2466 MHz, T_0= -20 oC



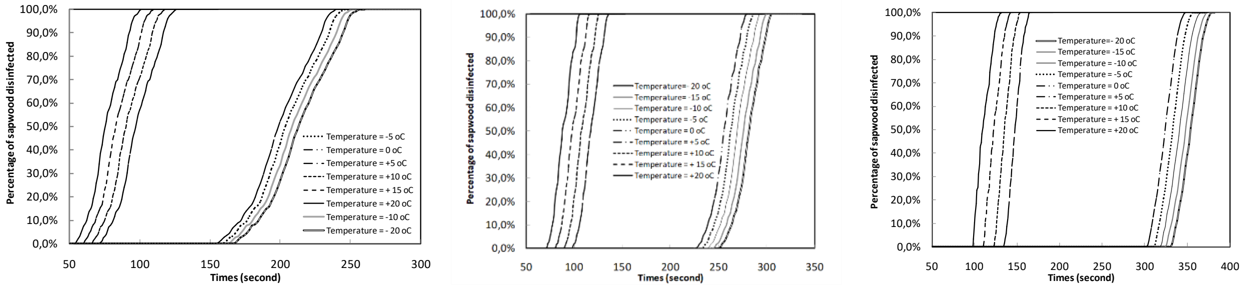
Temperature profiles distribution

Temperature distribution at half-planes of symmetry of X- direction

Temperature distribution at half-planes of symmetry of Z-direction

Figure 5. *Temperature distribution for aspen trembling sample exposed to microwave at time= 200 seconds, I0= 1 Watt/cm2, f=2466 MHz, T0= -20 °C*

Figure 6. compare the heat treatment by microwave energy of aspen, white birch and sugar maple. The percentage of disinfected sapwood, which is defined as the fraction of wood that reaches the temperature of 60°C, are presented as a function of time for various initial temperature intervals. The initial temperatures tested were -20 °C, -15 °C, -10 °C, -5 °C, 0 °C, +5 °C+10 °C, +15 °C and 20 °C.



Aspen trembling Birch white Sugar mapple

Figure 6. Evolution of percentage sapwood disinfected for aspen trembling

Table 1 summarizes various minimum times required to achieve 100% disinfection as a function of initial temperature and wood type for lower temperatures (T < 0°C) and higher temperatures (T > 0°C), respectively. One can clearly see that the minimum time to achieve 100% disinfection depends strongly on the wood type and on the initial temperature. For example, at the initial temperature of -20°C, this time is 262s, 306s and 380 s for trembling aspen, white birch and sugar maple, respectively. At +20°C, this time is 101 s, 106 s and 132 s for trembling aspen, white birch and sugar maple, respectively. Table 4 summarizes the value of all the temperatures corresponding to 100% disinfection as a function of wood type for all the temperatures studied

Table 2. Effect of initial temperature on critical time of heat treatment by microwave.

Initial temperature (°C),	*Critical time (s)*, trembling aspen*	*Critical time (s)*, white birch*	*Critical time (s)* , sugar maple*
-20	262	306	380
-10	252	294	366
-5	246	288	358
0	241	280	348
0.1	134	145	176
5	126	136	165
10	118	126	154
20	101	106	132
40	61	61	82
50	36	36	49

*Time required for 100% disinfection. It can also defined as: $\boldsymbol{t_{crt}} = \boldsymbol{min}(\boldsymbol{t_{crt}^{lon}}, \boldsymbol{t_{crt}^{rad}}, \boldsymbol{t_{crt}^{tan}})$

6. Conclusion

Firstly, this paper has examined the influence of radiofrequency and microwave energy under various conditions on the applicability of the Beer-Lambert law for wood species. The critical thickness L_{crit} above which the Beer-Lambert law is valid for all wood species studied obeys the condition $Log_{10}(L_{crt})=0.999Log_{10}(\beta^{-1})+0.4122$, where β^{-1} is the penetration depth (cm). Then, the paper describes a numerical investigation to predict and optimize phytosanitary treatment of wood by microwave according to International Standards N° 15 of the FAO. For this, the 3D heat conduction problem, involving phase changes such as wood freezing, is solved by a finite-element method. The dielectric and thermophysical properties are a function of the temperature, moisture content and structural orientation.

7. Bibliographie

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