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USE OF MICROWAVE RADIATION IN BUILDING INDUSTRY THROUGH APPLICATION OF WOOD ELEMENT DRYING

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ABSTRACT

This paper discusses theory and application of microwave radiation and experimental optimization of microwave radiation to eliminate moisture content in wood elements. Owing to its properties, microwave radiation has been used in the construction industry in modern times, in particular to dry wet masonry of buildings. Effects of electromagnetic radiation on building structures lead to relatively sharp decreases in moisture content from damp building structures or elements. The influence of electromagnetic radiation on building structures lead to oscillation of water molecules contained in the material, which cause a phase transformation of water into vapour. Consequently, the vapour evaporates from the moist material, thereby drying the element exposed to radiation.

The article describes experiments carried out at the Faculty of Civil Engineering of the Faculty of Technology in Brno that demonstrate successful decrease of water content in building materials using microwave radiation. First, the understanding of microwave radiation will be discussed.

Following an analysis of research results an optimum intensity of microwave radiation sources as well as the necessary length of the irradiation of microwave radiation have been determined with respect to the particular type of building material and the success rate of elimination of moisture.

KEYWORDS: Wood, remediation, microwave radiation, wooden construction, mould, wood moisture, wood-destroying insects.

INTRODUCTION

Microwaves are a term given to a part of electromagnetic radiation characterized by a wavelength ranging from 1 cm to 1 metre. In the form of waves the microwaves spread into space from the source. Worldwide, a frequency of 2.45 GHz with a corresponding wavelength of 12.2 cm has been designated for industrial purposes.

Fundamental theory of electromagnetic field

The fundamental theory of the electromagnetic field was developed on the basis of a number of laws of physics derived from a wide range of experiments and discoveries associated with names such as Coulomb, Savart, Ampere and Faraday. A crucial significance for the development of the theory was played by Faraday´s works, especially the discovery of the electromagnetic induction (1831), as well as the works of Maxwell, who created a model of an electromagnetic field following the discovery and introduction of the concept of displacement current. In 1873, J.C. Maxwell drew a general conclusion from theso-far-acquired knowledge about electricity and magnetism and formulated it in equations, today called Maxwell´s equations. (Baroň et al. 2012).

The general electromagnetic field, whether natural or created by human activity, is non-stationary (it is characterized by constant time variability). Field variability may often be considered negligible or slow. Having made this simplification, fields may be classified as follows:

- Static fields, where all charges (sources of a field) are considered at rest;
- Stationary fields are generated by charges moving in such a manner that they form stationary currents;
- A quasi-stationary field represents a certain simplification of a general non-stationary field, which consists in neglecting the so-called displacement current against currents of free electrons;
- Non-stationary fields are general electromagnetic fields (Baroň 2012).

Electromagnetic wave and its properties

Every electromagnetic wave (Fig. 1), (Electricity and Magnetism. Physical portal) consists of two inseparable components, namely electric and magnetic ones. The electric component is characterized by a vector of electric intensity E and the magnetic one is characterized by a vector of magnetic induction B. The E and B vectors are mutually perpendicular, they have a common phase in a travelling electromagnetic wave and at the same time are perpendicular to the direction of wave propagation. The electromagnetic wave motion is transverse (Haňka 1982, Basic properties of the wave guide).

The electromagnetic wave propagates in the direction of the positive x-axis. The electric field also oscillates parallel to the y-axis, i.e.E=(0, E, 0) and the magnetic field parallel to the z-axis, i.e. B=(0, 0, B). Both the fields may be then recorded as sine function of a position x and time t:

$$E = E_m \sin (kx-\omega t)$$

$$B = B_m \sin (kx-\omega t)$$

where: E_m and B_m - amplitudes of the fields;
k - the angular wavenumber;
ω- the angular frequency of the wave.

The magnetic field varies in a sinusoidal manner with the perpendicular electric field being induced to it (electromagnetic induction) while also varying in a sinusoidal manner as this field varies in a sinusoidal manner, a perpendicular magnetic field is induced thereto (magnetic-electric induction), while it also varies in a sinusoidal manner. Due to induction, these two fields constantly create a whole, and the resulting sinusoidal changes of these fields propagate as an electromagnetic wave. The electromagnetic wave does not require any material environment to propagate as it can propagate in a vacuum too (Halliday et al. 2000).

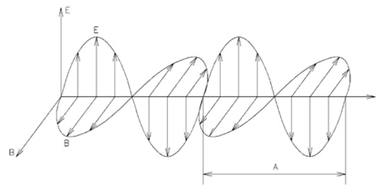


Fig. 1: Electromagnetic wave with the length λ – electric (E) and magnetic (B) components of the wave (Halliday et al. 2000).

Main vectors of the electromagnetic field

It has been described above that an electromagnetic field can be defined by vectors of electric intensity E and magnetic induction B. A completely equivalent description could be achieved by vectors of electric induction D and magnetic intensity H. These are four basic vectors of Maxwell's electromagnetic field theory, the marking of which is shown in Tab. 1, (Horák and Krupka 1976). Using material variables of permittivity of environment $\varepsilon=\varepsilon_r\varepsilon_0$, where ε_r is the relative permittivity, and permeability of environment $\mu=\mu_r\mu_0$, where μ_r is the relative permeability, relations can be defined as follows, Horák and Krupka (1976):

$D = \varepsilon E$
$H = \mu$^$^{-1}$ B

Tab. 1: An overview of basic vectors of Maxwell's theory.

Name of variable	Physical symbol	Unit
Vector of electric field intensity	$V \cdot m^{-1}$	E
Vector of magnetic field intensity	$A \cdot m^{-1}$	H
Vector of electric induction	$C \cdot m^{-2}$	D
Vector of magnetic induction	T	B

Speed of the electromagnetic wave

The speed of an electromagnetic wave is denoted by c, not v (applies to a vacuum). As shown, c has a value of

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

where: $\varepsilon 0 = 8.85 \cdot 10^{-12} F \cdot m^{-1}$ - the vacuum permittivity,
$\mu 0 = 4\pi \cdot 10^{-7} H \cdot m^{-1}$ - the vacuum permeability.

The resulting speed equals $c = 3.0 \cdot 108 m \cdot s^{-1}$, which implies that all electromagnetic waves including light have the same speed c in a vacuum (Halliday et al. 2000).

The speed of electromagnetic waves in a homogeneous isotropic dielectric material environment is of the following magnitude:

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_r\varepsilon_r}}$$

Maxwell's equations

Maxwell's equations show that electric and magnetic fields generate their own single physical whole, called the electromagnetic field. Maxwell's main contributions lie in the fact that he not only summarized the theory of electricity and magnetism in a small number of differential equations but that he also provided these equations with a simple and a general form to such extent that they may be also applied to any electromagnetic field, which varies in an arbitrarily fast manner, i.e. also to non-stationary electromagnetic fields too.

a. Maxwell´s first equation

$$rotH = i + \frac{\partial D}{\partial t}$$

note

$$rotH = \nabla x H = (\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}, \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}, \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y})$$

states that if current flows in a circuit, a magnetic field is generated around it. Here, I denotes Maxwell´s displacement current.

b. Maxwell's second equation

$$rotE = -\frac{\partial B}{\partial t}$$

states that with time change of the magnetic field a vortex electric field is present (lines of forces are enclosed) and voltage can be measured along the vortices.

c. Maxwell´s third equation

$$divD = \varrho$$

note

$$divD = \nabla \cdot D = \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z}$$

states that electric field lines of force begin and end at the point of space, where an electric charge is concentrated. The charge is thus the source of an electric field. P denotes the charge density.

d. Maxwell´s fourth equation

$$divB = 0$$

states that the magnetic field lines of force are without beginning or end, i.e. enclosed. There are no magnetic charges and themagnetic field is always of a vortex-like character (Horák and Krupka 1976, Maxwell's equations. Encyclopedia of Physics).

Propagation of electromagnetic energy

When an electromagnetic wave propagates in space it also - like any wave motion - bears energy, which advances through space. In terms of Maxwell's theory the flow of energy (power) in a time-varying electric field can be explained by the change of energy contained in the selected volume of the electromagnetic field, the changes of which propagate in space at v-speed, specified by the equation. Energy transfer rate per unit area by the electromagnetic wave is described by the P-vector, with $W.m^{-2}$ unit, called the *Poynting vector*. The P-vector is defined as Novotný (2005):

$$P = E \times H$$

Its value represents the directional energy flux density and the P direction of an electromagnetic wave indicates the direction of energy transfer in every point. This indicates the direction of wave propagation in a homogeneous environment. P is a function of time, since the vectors E and H are also functions of time, (Habash 2002, Sutter 2002, Horák and Krupka 1976).

Electromagnetic spectrum

When dealing with electromagnetic wave motion in relation to sources emitting it, we talk about different kinds of electromagnetic radiation. The electromagnetic spectrum (sometimes also called Maxwell´s rainbow) includes electromagnetic radiation at all wavelengths. Electromagnetic radiation of λ wavelength has f-frequency and a photon attributed to it has energy E. The relationship between them is expressed by the following equation:

$$\lambda = \frac{c}{f}$$

$$E = \mathrm{h} \cdot f$$

where: c - the speed of light,
$h = 6.62 \cdot 10^{-34}$ J•s.

The wavelength scale (and corresponding frequency scale) has open ends: Wavelengths of electromagnetic waves have no fundamental lower or upper limit. There are no gaps in the electromagnetic spectrum.

Electromagnetic radiation can be divided into non-ionizing and ionizing radiation. Non-ionizing radiation is a general term used for part of the electromagnetic spectrum where radiation displays such low photon energy that cannot break bonds between atoms in the irradiated material; however it still displays a very strong effect, i.e. heating. The field of the spectrum for non-ionizing radiation includes ultraviolet and infrared radiation, visible light and radiation of higher wavelengths (microwaves, radio waves), the effects of which are mainly thermal.

The border of transition between ionizing and non-ionizing radiation is set at the value of 1 nm wavelength. Radiation of shorter wavelengths is ionizing and its quantity has sufficient energy to ionize atoms or molecules of the irradiated material (Habash 2002).

Non-ionizing radiation

As mentioned above, ionizing radiation is radiation which does not have sufficient energy to cause ionization in living systems. Natural sources of non-ionizing radiation are extremely weak. In recent years, the use of non-ionizing electromagnetic radiation has increased phenomenally in various fields such as telecommunications, healthcare and industry, etc. A new generation of issues in electromagnetic radiation has arisen as a result of an increasing use of various electrical and electronic devices in our daily lives. With the rise of use of electrical applications, the density of artificial sources of electromagnetic fields has risen much faster than that of natural sources (Habash 2002).

In general, the non-ionizing part of the electromagnetic field can be divided into three main groups: Extremely low frequency (ELF), radiofrequency radiation (RF) and incoherent light, (Habash 2002).

ELF electric and magnetic fields (0-3 kHz).

A field of extremely low frequencies (extremely long waves) are defined as a field the frequency of which may reach values of up to 3 kHz. Wavelengths are very long at these frequencies (6000 km for 50 Hz). Electric and magnetic fields in this range are mutually independent and they are also measured independently. ELF fields are usually used to supply electric power (Habash 2002).

Radiofrequency radiation (3 kHz - 300 GHz) is a general term used to denote electromagnetic radio and television waves, radar and other microwave communications applications. The first section of the radio-frequency range is reserved for a low frequency range (long waves, LW) with frequencies from 30 to 300 kHz. This radiation is primarily used for maritime and aeronautical radio navigation beacons. Medium waves (MW) with a wavelength shorter than 200 meters are reserved for amateur radio operators. Short waves (SW) with a range of 3 to 30 MHz are suitable for worldwide communication, shortwave radio and high-frequency heating of tissues, which will be discussed later in more detail. An overview of radio radiation in each band is shown in the following Tab. 2. (Habash 2002, Kolářová 2010).

Tab. 2: Overview of non-ionizing electromagnetic field.

Wavelength	Use
Microwaves	Radar, microwave ovens, satellites
Ultra high frequencies	Television, mobile phones
Very high frequency	VHF radio
Short waves	HF radio, high-frequency heating
Medium waves and low frequencies	Radio broadcasting

Incoherent optical radiation

Optical radiation can be divided into ultraviolet (UV), visible and infrared (IR). UV rays (5 to 380-400 nm) are included in sunlight (Habash 2002).

MATERIAL AND METHODS

One of a number of experiments carried out at the Faculty of Civil Engineering, Institute of Building Structures will be described in more detail. The aim was to determine the length and cyclic measurement of microwave radiation for a successful removal of moisture absorbed by wood elements.

Description of the experiment

Spruce lumber rectangular prisms of 220 by 160 mm were the irradiated wood elements used. The irradiated wooden prisms were cut-outs from wooden ceiling beams. In total, eight prisms of identical profiles were selected. The course of the experiment is described in the table, which also includes the standard deviation or radian. Prior to start of the experiment, each prism was weighed and measured for the appropriate surface and depth moisture content. The initial moisture content varied for the pieces. The different moisture of different elements prepared for the experiments varied from a number of aspects including porosity, proper cracks or volume stability. Inner temperatures of the experimental samples were checked and measured following every single irradiation cycle, (Terebesyová et al. 2010).

Process of heating and drying

3 cycles of 15 minutes. (15 min of irradiation, 120- minute break), Microwave emitter power: 750-800 W.

RESULTS AND DISSCUSION

Following the final irradiation, the elements were left for 18 hours to allow free vaporization of accumulated water vapour. Next, moisture content and weight of the samples were analyzed and the obtained data were compared to initial values. (Ginevicius and Podvezko 2006, Baroň et al. 2012, Škramlik et al. 2012).

Throughout the evaluation process of measurements it was found out, that after the first heating cycle most of the samples had a similar termperature on their face side, which is in the range of 94.3°C - 98.9°C (Tab. 3). Sample No. 3 did reach a slightly lower temperature, only 84.2°C (Tab. 3). This was given by a smaller epoxine content. The distribution of temperature on the face side of samples acquired by a thermal imaging camera "Flir i7" after the first heating cycle is shown on (Fig. 2). It can be also stated that the temperatures on the face side are higher than on the reverse side. The values of surface temperatures are shown in detail on (Fig. 3).

The entire process is caused by the way how the radiated energy created by a generator is absorbed. The radiated energy is first absorbed by the water molecules closest to the source of radiation. Thus after the first heating cycle the temperature went up only in a certain depth, the rest of the volume is then gradually warmed up by the subsequent cycles.

Similar results were then observed in case of the internal temperature then in case of the surface ones, after several cycles of radiation exposition (Fig. 4). The values of humidity were recorded at the beginning and also by the end of ongoing measurement process. From these findings it is evident, that not all samples behaved in the exact same manner. Some samples did have a higher moisture content on the obversed side in the final stages, which may be caused by the gradual extrusion of water vapor on the surface (Fig. 4). (Fig. 5) shows the initial, mid-time (after stale) and the final weight of exposed elements. As mentioned above, sample No.3 had a higher initial mass because of the rawness of sample.

On (Fig. 6) the microwave generator is represented together with a funnel waveguide, which were used for the exposition of wooden elements.

Tab. 3: Surface and depth temperatures.

Wood elements		Surface temperatures (°C)			Inner	Temperature inside prism (°C)		
		1st heating	2nd heating	3rd heating	temperature	1st heating	2nd heating	3rd heating
Prism no. 1	front	98.9	101.0	106.0	I	27.7	62.9	86.6
	back	27.2	37.1	51.4	II	31.7	74.4	94.7
Prism no.2	front	96.5	106.0	95.1	I	27.0	58.4	95.1
	back	18.1	31.2	53.1	II	30.2	64.8	97.2
Prism no.3	front	84.2	98.0	98.9	I	16.6	37.2	48.5
	back	15.9	20.5	30.6	II	49.8	45.4	58.4
Prism no.4	front	97.2	99.8	105.1	I	26.2	57.1	93.7
	back	25.3	36.2	49.5	II	28.7	61.8	95.2
Prism no.5	front	94.3	97.5	101.7	I	23.3	54.6	91.4
	back	16.4	27.8	49.2	II	25.1	58.5	92.7
Prism no.6	front	95.1	104.6	106.3	I	27.8	59.4	96.3
	back	17.3	29.2	51.1	II	30.6	63.8	98.2
Prism no.7	front	97.8	100.5	106.2	I	26.7	58.2	94.3
	back	26.1	37.4	51.6	II	28.1	61.9	96.2
Prism no.8	front	96.2	105.1	94.9	I	27.1	58.8	95.3
	back	17.6	29.2	51.1	II	30.3	65.1	96.7
Average x	front	95.0	101.6	101.8	I	25.3	55.8	87.7
	back	20.5	31.1	48.5	II	31.8	62.0	91.2
Median	front	96.4	100.8	103.4	I	26.9	58.3	94.0
	back	17.9	30.2	51.1	II	30.3	62.9	95.7
Dispersion	front	18.6	9.4	21.1	I	12.6	54.2	227.2
	back	20.2	29.0	46.8	II	49.8	57.8	155.8
Standard deviation	front	4.3	3.1	4.6	I	3.5	7.4	15.1
	back	4.5	5.4	6.8	II	7.1	7.6	12.5

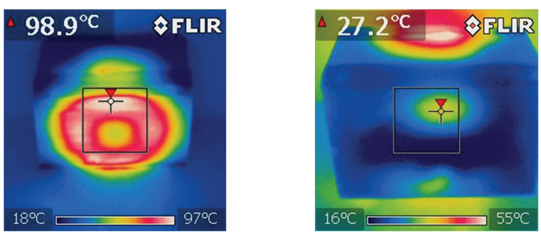
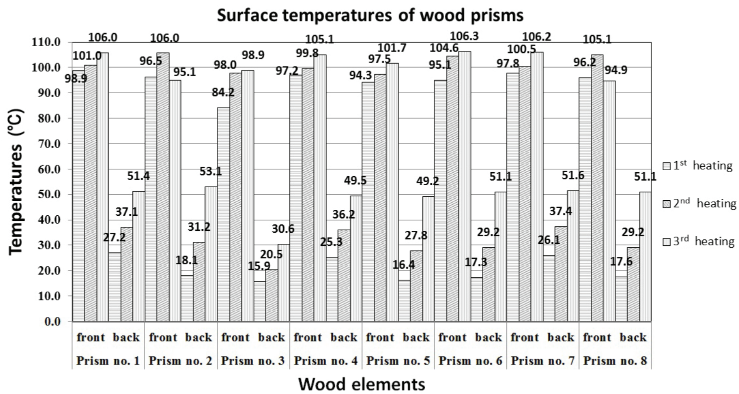


Fig. 2: Temperature field of the prism after the first heating from the back and the front.



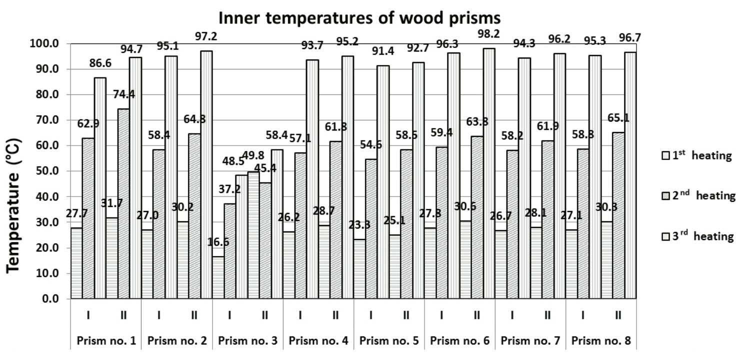


Fig. 3, 4: Charts of surface and inner temperatures.

Tab. 4: The moisture and weight values.

Wood elements		Moisture (%)		Weight (g)		
		Initial	120 minutes after heating	Initial	18 hours following heating	Weight loss
Prism no. 1	front	17.1	11.2	5754	5449	305
	back	18.1	14.9			
Prism no.2	front	17.7	19.0	5887	5428	459
	back	18.5	17.6			
Prism no.3	front	18.5	16.9	7955	7318	637
	back	22.0	20.0			
Prism no.4	front	17.5	11.8	5782	5464	318
	back	18.3	15.2			
Prism no.5	front	18.1	19.7	5927	5489	438
	back	18.9	18.3			
Prism no.6	front	17.0	19.1	5836	5417	419
	back	18.3	17.4			

Prism no.7	front	17.2	11.4	5761	5435	326
	back	18.3	15.1			
Prism no.8	front	17.9	19.3	5874	5447	427
	back	18.7	17.5			
Average x	front	17.6	16.1	6097.0	5680.9	416.1
	back	18.9	17.0			
Median	front	17.6	18.0	5855.0	5448.0	423.0
	back	18.4	17.5			
Dispersion	front	0.2	13.2	496598.0	383315.4	10166.1
	back	1.4	2.8			
Standard deviation	front	0.5	3.6	704.7	619.1	100.8
	back	1.2	1.7			

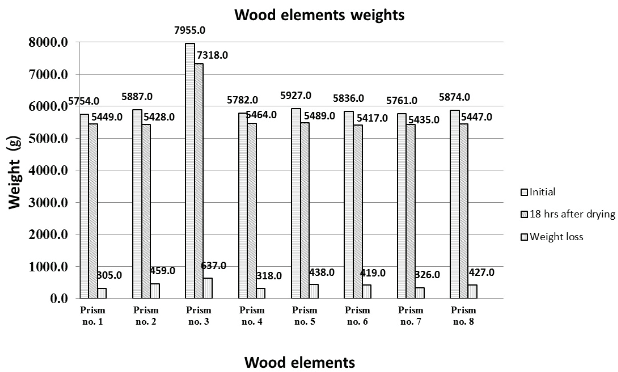


Fig. 5: Chart showing elimination of weight.

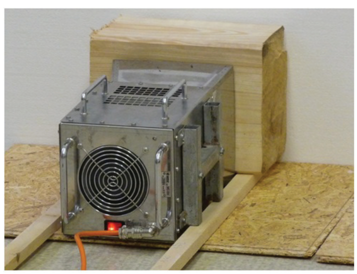


Fig. 6: Photograph of an irradiated wood element.

CONCLUSIONS

The aim of the experiment was to determine effects of higher initial moisture content of the irradiated material on the penetration of microwave energy and thus on the heating. Test specimens were taken from sawn wood in a so-called "raw" state.

As can be seen from the above tables, it has been determined experimentally that it is advantageous for the microwave drying of wood elements to use a lower microwave power and shorter irradiation cycles with longer pauses. This is due to the fact that during long irradiation cycles with higher performance and short breaks between radiation cycles large differences have been analysed between the temperatures on the front and back of the experimental prisms. Following final cooling, shape deformation and creation of additional drying cracks could be observed. With those elements that were irradiated gradually, i.e. using lower microwave power, shorter drying cycles and longer breaks the increase in temperature was gradual, evaporation of water continued in a balanced manner and basically, any deformation of the wood element has been avoided.

In conclusion, the current results of experiments have found that cyclic microwave elimination of moisture in wood elements is effective. It is essential and highly effective to apply cyclic irradiation in the elimination of moisture in wood elements than the same period of time without a cyclic repetition. It is possible to conclude that irradiation using emitters with lower microwave power is fully effective and thus absolutely sufficient. Given the results of experimental work, significant and rapid elimination of weight and moisture has been achieved as compared with the initial and final values. The method of cyclic microwave drying of wood elements appears to be one of the most effective, fastest and thus the most economical methods for local and targeted reduction of moisture content in wood elements and building structures.

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