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THE ANALYSIS AND OPTIMIZATION OF HIGH-FREQUENCY ELECTROMAGNETIC FIELD HOMOGENEITY BY MECHANICAL HOMOGENIZERS WITHIN THE SPACE OF WOOD MICROWAVE HEATING DEVICE

Andrea Nasswettrová, Květoslav Nikl, Jiří Zejda
Mendel University in Brno, Faculty of Forestry and Wood Technology
Department of Wood Science
Brno, Czech Republic

Jan Klepárník
Mendel University in Brno
Faculty of Forestry and Wood Technology, Department of Forests and Forest Products Technology
Brno, Czech Republic

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ABSTRACT

The paper deals with an experimental verification of the homogeneity of the electromagnetic field of the microwave band (2.45 GHz) in the operational space of a microwave device MIA–4K with an applied output of 3.6 kW and mechanical rotational homogenizers designed by the authors. The verification of homogeneity consists in experimental measuring of the temperature distribution within the medium – water – in the operational space of the device. The method is based on heat exchange in an isolated system where water serves as an absorber of the irradiated energy. Grids with test tubes with a predefined volume of water were placed inside the device at three different height levels. The grid was designed with respect to the used wavelength of the sources. The temperature of water in the test tubes was measured both with and without using the homogenizers. The results show that by placing homogenizers in front of waveguides we can achieve a higher homogeneity of temperature within the operational space. The higher homogeneity of temperature comes hand in hand with a higher homogeneity of the electromagnetic field. The proposed solution of homogenizers increases the HFF homogeneity, which directly affects the quality of the wood drying or wooden material modification processes using high-frequency electromagnetic energy.

KEYWORDS: Microwave heating, electromagnetic field homogeneity, rotational mechanic homogenizers, wooden material.

INTRODUCTION

Many technological operations in wood processing industry are connected with material heating for the purpose of temporary plasticization. This intentional modification of physical and mechanical properties of wood is usually achieved by means of a temperature increase brought about by convectional or contact thermal energy transfer. These technologies are mostly suitable; however, they are not often used for a locally limited modification of material. In these cases it is more suitable to use a directed flow of energy from the spectrum of electromagnetic (EM) waves. This energy could be various forms of EM radiation, most often the narrow band of microwaves. For wood drying and local change of wood properties in the wood-processing industry, the technology of dielectric heating is used, both microwave (MW) and high-frequency (HF). In contrast to conventional heating, the EM energy heats the material in its entire volume. Only dielectric heating is able to induce a higher temperature inside material than on its surface.

The effect of the EM energy on wood is not only drying but also the modification of wood properties. The high-frequency and the microwave technologies within dielectric heating provide solutions for drying of hard woods (Torgovnikov and Vinden 2009), production of wood-resin composites (Torgovnikov and Vinden 2000), further it works in the field of the stabilization of tension in logwood (Torgovnikov and Vinden 2007), impregnation of wood with preserving agents based on increased permeability (Sugiyanto et al. 2008), in the production of paper and pulp, etc. Torgovnikov and Vinden (2004) uses the high radiation intensity and moisture content (35–300 %) for an easy absorption of the EM energy, which leads to wood destruction and better permeability for liquids and gases. Vinden et al. (2011) used this property of wood for the modification of the permeability of pine railway sleepers for an easier distribution of preservatives.

However, such a change in wood structure demands well designed parameters of the MW applicator and a technological procedure ensuring all the required parameters of the resulting product. Among significant parameters of the device for MW heating there are the used frequency, the high-frequency output, the applicator configuration, the distribution of the high-frequency electromagnetic field (hereinafter HFF), the amount of energy absorbed by the inserted material, and the protection against MW radiation leaks outside the operational space of the device.

What seems to be the most significant for industrial applications is the distribution of the HFF, which is dependent on the configuration of the applicator. The first studies dealing with the technological solution of the device were published at the end of the 1950s (Jagfeld 1963, Egner and Jagfeld 1964, Gillwald 1964, Gefahrt 1966, Resch 1968), other research into the HFF heating was conducted by Metaxas and Meredith (1983), Torgovnikov (1993), Makovíny (1995), Perre and Turner (1997), Zhou and Avramidis (1999) and others. The majority of these pointed out the problems with the distribution and control of the process. Antti in 1990 experimentally proved that it is possible to MW dry wood during several hours with a corresponding quality (Antti and Perré 1999). Besides this, he presented the data on the moisture and temperature of wood during the heating and thus laid the foundations for the solution of the MW field distribution problem during drying. His data showed a reverse gradient of moisture in the dried material when compared with a conventional heating, and at the same time a high temperature near the surface layers of the material. These results were confirmed by Resnik et al. (1997)

and Zielonka et al. (1998 and 1999), who were concerned with studying the distribution of temperatures and moisture gradients during drying. Studies into the issue of local heating as a consequence of the inhomogeneity of the HFF or the material itself can be found in papers of other authors as well (Hanson and Antti 2003, Leiker and Aurich 2003, Leiker et al. 2004). One of the main goals in MW applicator design is to find out a set-up/arrangement that provides a homogeneous distribution of EM energy in a chamber and thus overcome the issue of non-uniform heating of the material. The essential drawback of current multimode applicators for industrial use is the interference of direct and reflected EM waves, which leads to the occurrence of places with differing intensity of HFF – "hot and cold spots". These places are static and non-variable in time, therefore an efficient heating of the material is impossible. To eliminate this undesirable phenomenon, mechanical rotational homogenizers were placed in the MW oven to decrease the HFF inhomogeneity.

The aim of this study is to verify the HFF homogeneity experimentally in the operational space of the laboratory microwave device MIA–4K designed by the authors. The principle of inhomogeneity reduction is a mechanical stochastic change of reflection conditions in the operational space of the applicator, which is achieved by the rotational movement of individual "blades" of the EM field homogenizers (hereinafter only homogenizers). These are made from a thin power conductive material and when they are moving they vibrate mechanically (Nikl and Nasswettrová 2011a). The mechanical movement of the homogenizers changes the reflection conditions unidentifiably; therefore, the presented solution decreases the occurrence of the spots with different power density. The study examines the proposed hypotheses in compliance with the established methodology to identify the HFF homogeneity in the operational chamber based on the heat exchange in the insulated series.

MATERIAL AND METHODS

Experimental verification of the HFF distribution in the operational space of the laboratory MW device MIA–4K consisted in the heat exchange in the insulated series. All measuring was conducted at a total output of magnetron generators of 3.6 kW (4 x 900 W) and a frequency of 2.45 GHz. As an absorber of the irradiated energy we used a grid of 64 test tubes 100 mm far from each other with a predefined volume of distilled water (Fig. 1). The ability of water to absorb MW energy through which heat originates enabled us to monitor the temperature distribution in the chamber and thus verify the HFF homogeneity. At a frequency of 2.45 GHz water is a good MW energy absorber. The test tubes were filled with water up to 10 ml water column. The test tubes from soda-potash glass had a flat rim and a round bottom, dimensions 15 x 100 mm. For the base of the test tube grid a constructional polystyrene (EPS 70Z) was used composed from two parts – one part of the dimensions 50 x 500 x 900 mm and the second one 50 x 400 x 900 mm. The initial temperature of water in the test tubes was 15 ± 2°C and new liquid was used for each measuring. The distribution of temperatures in the space of the chamber was monitored at three height levels. The first (Bottom Level) was 125 mm above the chamber bottom. The second (Middle Level) was placed on the level of the magnetron generators, 250 mm above the bottom. The third (Top Level) was 375 mm above the bottom, see Fig. 1. To identify the spots with different power density, measured by means of temperature, non-contact thermography was used. Temperatures were measured till 1 min. after the heating. The analysis of the experimentally measured values of temperature distribution within the chamber of MIA–4K was conducted for two versions of the process (Experiment I and Experiment II).

The first experiment was conducted by measuring the temperatures in the operational space of the MW device without the rotational movement of the homogenizers. The distribution of temperatures at the three height levels (Fig. 1) was monitored for 60 s. After the examination of the distribution within the entire chamber, the middle part of the chamber, the middle level, was examined again to be compared with experiment II. Due to the symmetrical design of the chamber only a half of the test tubes could be used in a grid of 50 x 500 x 900 mm.

The second experiment was conducted in the space of the chamber with the rotational homogenizers being active. The specimen was placed at the axis height of the magnetron generators with fitted homogenizers and it was exposed to EM energy for 60 s. The specimen was a half of the polystyrene base 50 x 500 x 900 mm with a half of the test tubes (32), Fig. 1b).

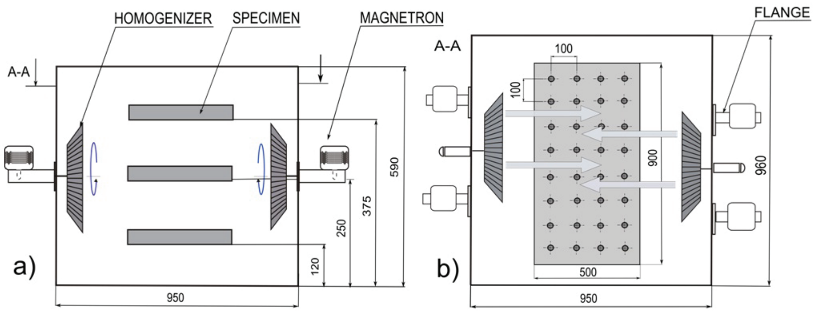

Fig. 1: Diagram of microwave device MIA–4K and the layout of samples in the chamber.

Technical description of the device used in the experiment

Experimental microwave device for dielectric heating of wood

All measuring was carried out using the microwave device we designed and called MIA–4K (Fig. 2); it was primarily designed for the research into the effects of EM energy on wood, wooden and wood-based materials (Nikl and Nasswettrová 2011b).

The operational space of MIA-4K is conceived as a multimode resonator with four magnetron generators. Their total output is 3.6 kW (4 x 900 W) and power density is 346 $W.m^{-2}$. Magnetrons work in the CW (continuous wave) mode at 2.45 GHz frequency and they are air-cooled. Both pairs of magnetron generators are fixed to the body of the operational chamber with choking quarter-wave flanges and they are horizontally shifted to each other by a distance which equals a double of the used wave length (λ = 12.25 cm) of the magnetron generators. To reduce the formation of spots with different power density, there are mechanical rotational homogenizers in the chamber. They are connected with a rotational shaft by their fixed part and they are made of hard power conductive material. The outer part is divided into segments which are in an angle 40–60 ° to the plane of the inner part (Fig. 2). Thus created angled segments efficiently reach into the operational space of the neighbouring magnetron generators. During the rotational movement of the homogenizers, the differently oriented thin segments vibrate irregularly and according to our hypothesis they eliminate the interferential combination of reflected waves occurring in a closed application chamber.

The HFF energy is brought to the operational space from magnetron generators by impendence adapted quarter-wave waveguide plates. To prevent moisture entering into the waveguides, the application openings of waveguide plates are equipped with a protection board from Teflon® PTFE material, which does not represent a loss dielectric for the used frequency of 2.45 GHz. The arising moisture is exhausted from the operational space (using a mode or manually) by an exhaustion fan, which is located at the back of the chamber.

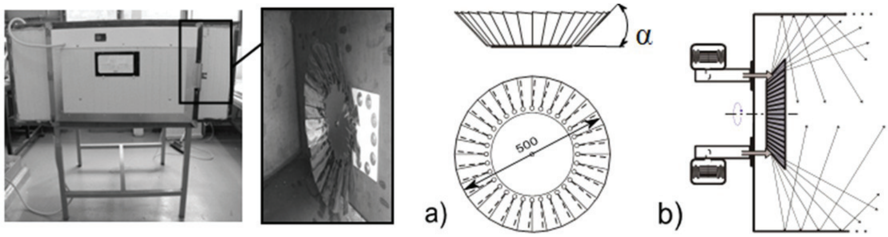

Fig. 2: MIA–4K (left), homogenizers, a) a drawing and b) the principle of a rotational homogenizer.

Thermovision camera ThermaCAM^{TM} P65 for imaging of temperature fields

Scanning of temperature distribution in the samples in the operational space was conducted using infrared thermovision camera ThermaCAMTM P65 (Fig. 3), with heat sensitivity of 0.08°C and image quality of 320 x 240 pixels. The camera captures the thermal images, the thermograms, as 14-bit pictures in JPEG. The tool used for saving and processing of thermograms was ThermaCAMTM ResearcherTM Pro 2.9., which makes an analysis of temperatures possible, see Fig. 3. The camera was calibrated for direct reading of temperatures on the outside of samples.

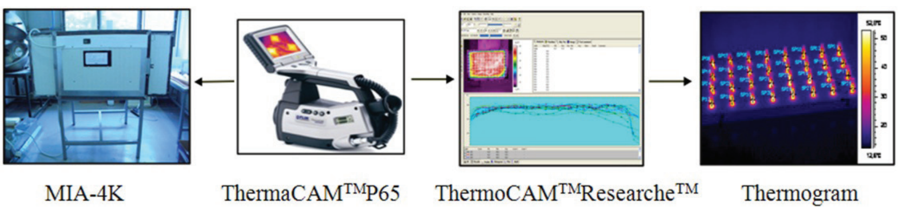

Fig. 3: Temperature scanning by ThermaCAMTM P65.

Experiment verification by analytical calculation

We can use a theoretical formula to calculate the temperature of water in the test tubes provided that we know the input data of the equipment and the properties of the heated substance. Assuming that the walls of the operational space are perfectly reflecting for microwaves and that the radiation cannot return to the magnetron, after more or less reflections the supplied radiation will be finally absorbed by the substance. Therefore, the specific heat capacity equation is valid and we can theoretically derive the value of the temperature to which the water in the test tubes will be heated.

$$c = \frac{P \cdot t}{m \cdot (T_2 - T_1)} \quad \Rightarrow \quad T_2 = \frac{P \cdot t}{c \cdot m} + T_1$$

where: c - specific heat capacity ($J.kg^{-1}.K^{-1}$),
P - output (W),
m - weight (kg),

t - time (s),

T_2–T_1 - temperature difference (K).

Using our parameters (P = 3600 W, t = 60 s, m = 0.640 kg, c = 4186 J/(kg.°C), T_1 = 15°C) for eq. (1), we get the temperature of water after heating T_2, which is 95.6°C.

With respect of the HFF inhomogeneity, we can expect that temperature T_2 will not be the same in all test tubes. In some spots (hot spots), where the intensity of the EM field is very high the water can even reach the boiling point.

RESULTS AND DISCUSSION

Experiment I (chamber without homogenizers)

In this version, the temperature distribution along the entire width and depth of the resonator without homogenizers was measured. The temperatures of the water grid were recorded before and after the exposure to heating which took 60 s.

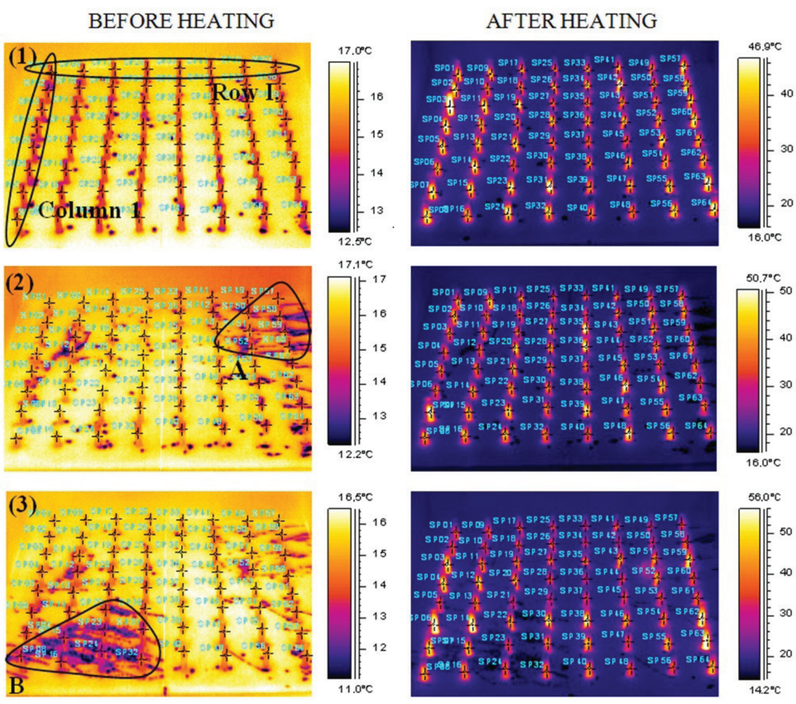

Fig. 4: Thermograms showing the temperature distribution of water in the test tubes, in the individual height levels: 1) – the bottom level; 2) – the middle level; 3) – the top height level; before heating and after heating.

Fig. 4 shows the thermograms of the temperature distribution in the space of the chamber and Tab. 1 presents the basic statistical characteristics of the measured temperatures in all the 64 test tubes in the grid. The results show that water was heated to a temperature of 40.5–65.5°C at the bottom level, 30.2–54.8°C at the middle level, i.e. at the height of magnetron generators axis, and 29.4–64.2°C at the top level in the upper part of the resonator. The thermograms (Fig. 4) and the measured values (Tab. 1) prove that the maximum value is 16.6°C before heating and 65.5°C after heating. In the exposition time of 60 s the temperature of water in the test tubes increased by 48.9°C on average. The analytical calculation (eq.) set the water temperature in the test tubes to 95.6°C. However, the maximum measured temperature of the water grid was 65.5°C, i.e. 30.1°C lower than the calculated value. Yet, the theoretical temperatures were reached as can be demonstrated in Fig. 4. There we can see spots where the water boiled out (spots A and B). These spots confirm the hypothesis that water temperature was not identical due to HFF inhomogeneity and that water reached the boiling point in the spots where the intensity of the EM field was considerable. The temperature measured in these spots after heating and extracting from the chamber space was much lower because the test tubes and the water itself cooled down after the water had boiled out. That is the reason why the maximum temperature measured was lower than the theoretical temperature. The difference can be partially accounted to the losses caused by the HFF and partially to the properties of the inserted substance which decreased the intensity of radiation. However, these are temperature maxima, the average temperature of the water in test tubes after heating ranged between 41.0°C and 47.5°C (Tab. 1). This fact only confirms the hypothesis about unequal distribution of the HFF and the existence of "hot and cold spots".

Tab. 1: Descriptive statistics of temperature distribution at individual height levels.

Level	–	$\overline{X}$ (°C)	S (°C)	V (%)	Min (°C)	Max (°C)
Bottom	before MW	14.800	0.298	2.011	14.300	15.300
	after MW	47.570	6.694	14.072	40.500	65.500
Middle	before MW	15.452	0.573	3.712	13.700	16.600
	after MW	41.083	5.262	12.809	30.200	54.800
Top	before MW	14.530	0.609	4.189	13.000	16.000
	after MW	41.716	8.521	20.425	29.400	64.200

$\overline{X}$ = mean value, S = standard deviation, v = coefficient of variation, min = minimum, max = maximum, MW = microwave heating

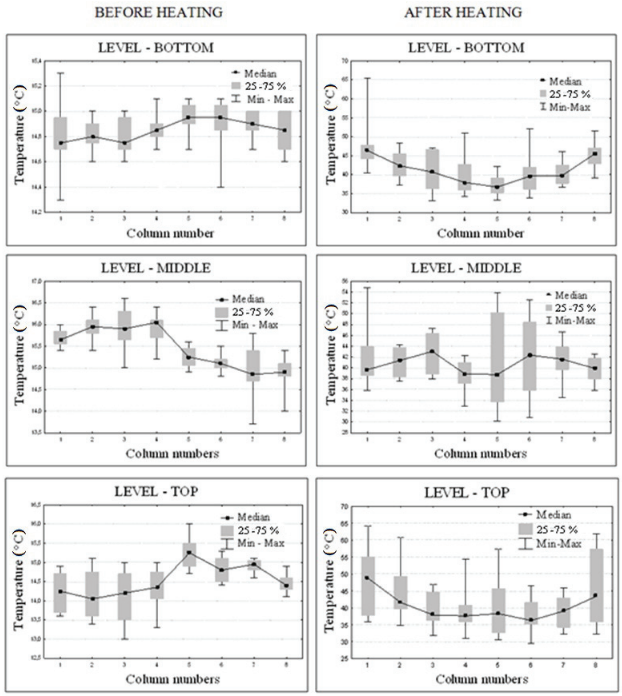

Fig. 5: Statistical evaluation of water temperature distribution at individual height levels, before and after heating.

The basic statistical evaluation of temperature distribution in each column before and after heating is presented in Fig. 5. It shows the differing tendencies at each height level. The results of the analysis of variance (ANOVA) indicate that at the middle and the top height levels (Fig. 6) the mean values agree with the level of significance alpha 0.05. This is based on the comparison of test criterion and the critical value. The differences between the selection means can be considered random (insignificant) and we assume that zero hypothesis is valid. The evaluated factor, the position of the water grid, has therefore no significant influence on the temperature distribution at the middle and the top levels. As regards the bottom level, the zero hypothesis on the agreement of mean values was rejected. The multiple comparison test (Tukey's HSD test) indicated that the mean value of column 1 is statistically significantly different, see Fig. 5. However, the highest degree of variability was measured at the top height level – 20.4 %. At the bottom level, the variability of measured temperatures in the test tubes was 14.07 %. The lowest degree of variability was found at the middle level, in the axis of magnetron generators - 12.8 %, see Tab. 1. It follows that at the bottom and the top height levels, there is the highest dispersion of energy and the middle level seems to be the optimum.

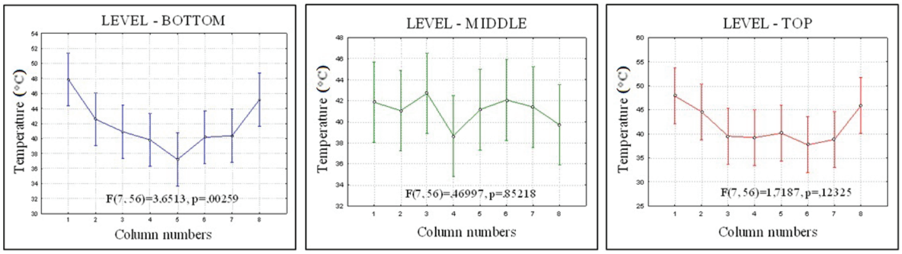

Fig. 6: Graphs of 65 % reliability intervals picturing the influence of the position of the water grid on the temperature of water in the test tubes.

The second part of the experiment concentrated on this area to investigate the effect of the rotational movement of the proposed homogenizers. Due to the symmetrical design of the application space of the microwave device MIA–4K, a half number of the test tubes in the grid (32 pieces) was used for the following measuring. The grid was placed at the axis level of the magnetron generators (Fig. 7).

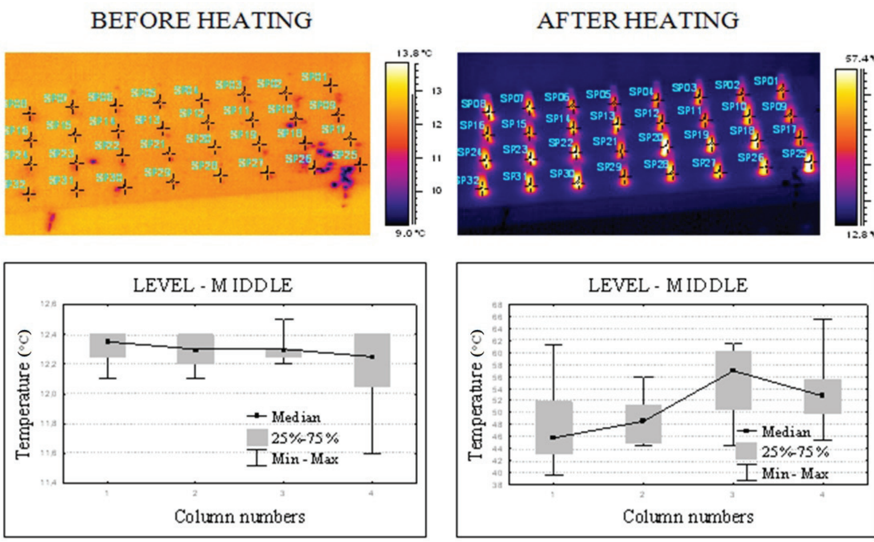

Fig. 7: Thermograms capturing the temperature distribution in the grid at the middle level and its statistical evaluation.

The time of HFF energy exposition was again 60 s, without the rotational movement of mechanical homogenizers. The results presented in Tab. 2 show that the maximum value of water temperature is 12.5°C before heating and 65.6°C after heating: in 60 s heating the water temperature increased by 53.1°C. The maximum temperature of water at the same height level with the full number of test tubes (64) was 54.8°C (Tab. 1). The difference is 10.8°C in comparison with the results of the first measuring. This fact can be accounted for by the smaller dimensions of the absorber of radiated energy, which means an increase in radiation absorption and thus also the resulting temperature. The total temperature range in the grid with a half number of test tubes was 39.6–65.6°C (Tab. 2). The coefficient of variation was again 12.8 %, so we can see that the size of the absorber has no effect on the variability. The average water temperature was 12.3°C before heating and 51.3°C after heating (Tab. 2). Fig. 7 shows the trends of curves and the distribution of temperatures before and after heating.

Tab. 2: Descriptive statistics of temperatures in the test tubes at the middle height level.

Level	–	$\overline{X}$ (°C)	S (°C)	V (%)	Min (°C)	Max (°C)
Middle	before MW	12.269	0.167	1.364	11.600	12.500
	after MW	51.278	6.583	12.839	39.600	65.600

Experiment II (chamber with homogenizers)

For the second experiment we used a grid of 32 test tubes. We only examined the middle height level – the axis height of the magnetron generators and mechanical homogenizers. The time of exposure to MW energy was 60 s. The results are presented in Fig. 8; Tab. 3 shows the basic descriptive statistics.

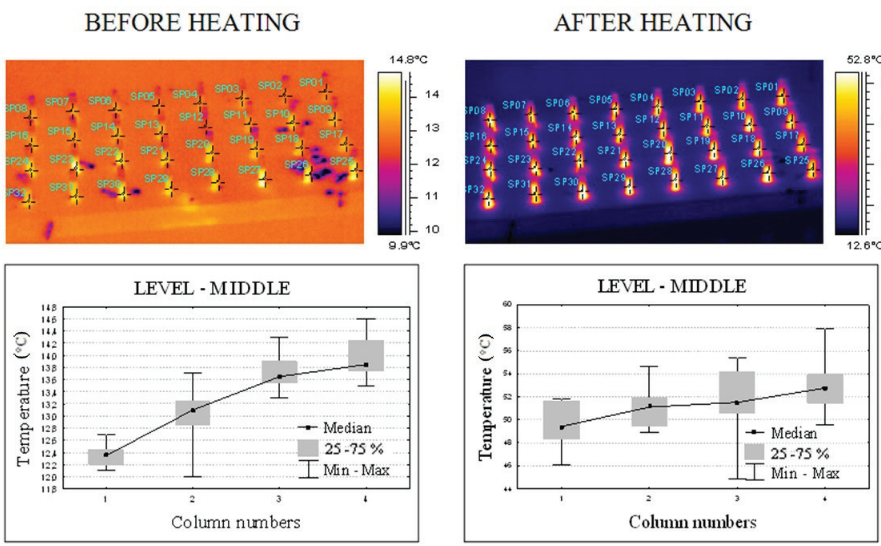

Fig. 8: Thermograms capturing the temperature distribution in the test tubes and its statistical evaluation.

Tab. 3: Descriptive statistics of temperatures in the test tubes with the homogenizers.

Level	–	$\overline{X}$ (°C)	S (°C)	V (%)	Min (°C)	Max (°C)
Middle	before MW	13.266	0.729	5.495	12.000	14.600
	after MW	51.294	2.687	5.238	44.800	57.900

In general, the electromagnetic radiation can be divided into non-ionizing and ionizing. Non-ionizing radiation is a general term for a portion of the electromagnetic spectrum where radiationsuch a low energy photon that cannot break the bonds between atoms in the irradiated material, but still has a marl effect, which is heating. Region of the spectrum for non-ionizing radiation includes ultraviolet and infrared radiation, visible light radiation and higher wavelengths (microwaves, radio waves), whose effect is especially heat, thus does not have a destructive effect on the human organism.

The results presented in Fig. 8 and Tab. 3 show that the maximum temperature of water was 14.6°C before heating and 57.9°C after heating. The temperature of the water in the test tubes increased by 43.3°C in 60 s. The maximum temperature of water at the same level in the same sample without rotational homogenizers was 65.6°C (Tab. 2). It means the maximum temperature of water was 7.7°C lower in comparison with the results of experiment I. The total temperature range was 44.8–57.9°C (Tab. 3). The difference in the value of the coefficient of variation between experiment I (Fig. 7, Tab. 2) and experiment II (Fig. 8, Tab. 3) is significant. The degree of variability in the sample heated with rotational homogenizers working (experiment II) was 5.2 % (Tab. 3), while the coefficient of variation when the homogenizers were not working (experiment I) was 12.8 % (Tab. 2). The degree of variability in the temperature distribution in the application space of the chamber was considerably lower when the rotational homogenizers were working, in contrast to the first experiment in which the degree of variability was the same for two differently sized radiation absorbers. The factor which changed the variability was not the size of the sample but the change in the reflection of EM waves within the space of the resonator due to the rotational movement of homogenizers. Based on the presented statistical evaluation, we can conclude that the proposed technical solution of homogenizers confirms the hypothesis of stochastic reflection of EM radiation and thus increases the homogeneity of the HFF in the application space of the device. The statistical evaluation of temperature distribution in each column for experiment I and experiment II can be seen in the trends of the curves (Fig. 7, Fig. 8).

The proposed methodology is suitable for the examination of HFF distribution in the application space of MIA–4K and for the verification of the effect of the homogenizers. The results of the experimental measuring lead us to the conclusion that the rotational movement of the proposed homogenizers has a substantial influence on the homogeneity of the HFF distribution in the chamber. This fact has been confirmed by the statistically significantly lower value of the variability in the sample heated in the chamber while the rotational homogenizers were working in comparison with the sample of the same size heated up without the movement of rotational homogenizers. On the other hand, the size of samples seems to be statistically insignificant. Further, the results show that the optimum place for locating samples during heating in the space of the chamber is the axis level of magnetron generators and HFF mechanical homogenizers. The optimization of the chamber space by means of homogenizers confirmed the hypothesis on the elimination of HFF inhomogeneity; Although the presented solution reduces the available space of the device, the homogeneity of the power density within the operational space of the proposed application chamber MIA–4K increases.

CONCLUSIONS

The paper dealt with the experimental verification of HFF homogeneity in the operational space of laboratory microwave device MIA–4K and the effect of the proposed rotational homogenizers. A methodology for the verification of HFF homogeneity inside the resonator based on the distribution of temperature of water in a sample grid was proposed. The temperature distribution of water in the operational space of the device was measured at three height levels. The results showed an inhomogeneous distribution of temperature along the height and width of the space manifested by the occurrence of two extremes: spots with a weak and strong intensity of the field – "hot and cold spots". The highest HFF inhomogeneity was found at the top and the bottom of the chamber with the highest variance of energy. The variability of the measured temperatures was 20.4 % at the top of the chamber and 14.07 % at the bottom. The lowest degree of variability (12.8 %) was found at the axis level of the magnetron generators. Using the proposed homogenizing device a more equal distribution of temperatures and thus HFF in the space was achieved. This is proved by the coefficient of variability (5.2 %) of the sample heated in the middle of the chamber while the homogenizers were working, which is statistically significantly lower than the variability of temperatures (12.8 %) of the sample with the same size heated in the middle of the chamber without the homogenizers. On the basis of the results, we can conclude that the size of the radiated energy absorber has no effect on the coefficient of variability but it affects the degree of heat created by the absorption of the MW energy into the material. This was confirmed by the 10.8°C increase in water temperature when the size of the radiation absorber decreased from 64 to 32 test tubes. Further, the measuring proved that the most suitable place to locate the sample during microwave heating is the axis level of magnetron generators and mechanical homogenizers. In conclusion, we can state that the proposed solution of homogenizers increases the HFF homogeneity, which directly affects the quality of the wood drying or wooden material modification processes using high-frequency electromagnetic energy.

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Andrea Nasswettrová, Květoslav Nikl, Jiří Zejda
Mendel University in Brno
Faculty Of Forestry and Wood Technology
Department of Wood Science
Zemědělská 1
613 00 Brno
Czech Republic
Corresponding author: andrea.nasswettrova@gmail.com

Jan Klepárník
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Forests and Forest Products Technology
Zemědělská 1
613 00 Brno
Czech Republic