Journal of Materials Science and Engineering with Advanced Technology
Volume 17, Number 2, 2018, Pages 63-90
Available at http://scientificadvances.co.in
DOI: http://dx.doi.org/10.18642/jmseat_7100121923

EXPERIMENTAL STUDY OF MICROWAVE SLOW WAVE COMB APPLICATORS FOR TIMBER TREATMENT AT FREQUENCIES 2.45 AND 0.922GHz

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Keywords and phrases: comb applicator, microwave, microwave wood treatment, slow wave applicator, timber.

Received January 23, 2018; Revised February 13, 2018

Abstract

Slow wave comb applicators for timber (and other materials) treatment at frequencies 2.45GHz (Comb1) and 0.922GHz (Comb2), designed for surface layer heating, modification and sterilization, were experimentally studied. Experiments showed that the Comb1 applicator released 83-88% of applied MW energy in wet wood on the depth up to 30mm, in zones with maximum energy application. In other zones, energy application efficiency is higher. The Comb2 applicator releases about 60% of the applied energy on the depth up to 30mm in the zones of maximum energy release. Energy distribution from the comb applicators, in the wet wood, allows the most significant part of the energy to be released in surface layers and increases efficiency of energy use, compared to other MW radiators. Comb1 and Comb2 are recommended for practical use in wood heating, MW modification and sterilization processes. They can be used for soil, concrete, plaster, bricks, plastics and other materials were required heating of surface layers.

1. Introduction

Microwave (MW) processing technologies are developing rapidly in all industries. This arises from: the high efficiency of converting electricity into microwave energy, energy savings associated with rapid in-depth heating of materials, specific interactions that can be achieved between microwaves and materials, radical acceleration of technological processes, reductions in MW equipment costs and improvements in the reliability of industrial MW equipment. In the timber industry, MW wood processing is used for wood heating, drying [1, 2], bending [4], and modification for increasing wood permeability for liquids and gases [12] to allow better impregnation with preservatives [8, 10, 13, 16], resins, plastics, and alloys [11].

A number of wood species have a very low permeability causing problems during timber processing. These processing problems include, very long drying times, large material losses after drying, expensive drying processes and difficult impregnation with preservatives and resins. In the wood pulping industry low wood permeability results in shallow chemical penetration of pulping liquids into wood. This requires the use of small sized chips, high chemical usage and high energy consumption. MW wood modification can provide an increase in wood permeability, that solves many wood processing problems [14]. Intensive MW power applied to green wood generates steam pressure within the wood cells. Under high internal pressure, the pit membranes in cell walls, tyloses in vessels and weak ray cells are ruptured to form pathways for easy transportation of liquids and vapours [15]. A several thousand-fold increase in wood permeability in the radial and longitudinal directions can be achieved in species previously found to be impermeable to liquids and gases.

For timber modification, it is required to supply to wood with very high intensity MW power and maximum possible uniformity, which traditional MW devices (chambers, resonators, antennas) cannot provide. In many cases in industry it is required to heat or treat only the surface layers of different material (timber, soil, concrete and so on) using MW. For example, for soil sterilisation (weed killing) it is required to treat soil only to a depth of 25mm [3]. Traditional MW irradiators (antennas) cannot provide only surface heating and energy penetrates deep into the material, where the energy decays exponentially due to absorption into the material. Energy losses, if the application requires heating only to a depth 20-60mm (for example, to modify only wood surface layers by MW for preservative treatment or impregnation with resins), is very significant. Therefore, special MW radiators are required for surface treatment to increase process efficiency.

To achieve good surface heating efficiency the slow wave (which are often called "surface waves") comb (SWC) structure was studied. The main property of slow waves is the energy concentration near the impedance electrode, – i.e., the comb surface. Previously, slow wave structures (SWS) were used mostly as delay lines [17] and as interaction circuits in MW vacuum devices, and their properties were explored for these specific applications [7]. Adapting MW technologies to industry, medicine, and military applications initiated a study of slow wave structure properties and peculiarities which can be used for developing novel technologies [5, 18]. It was shown by the full-wave analysis as well as by experiments and practical realization [19] that the SWSs have many previously unknown peculiarities, which can be used for creating novel technologies for industrial heating.

Usually in wood technology, MW radiators (for example, horns or slot radiators) form heating zones with high nonuniformity, which leads to overheating in some surface zones. Also, energy penetration into the material is too deep, which leads to significant energy losses. Comb applicators can provide effective MW energy release in the wood surface layers by keeping energy close to the comb surface and limiting energy penetration into the material. This leads to significant energy savings.

The research and development objectives were to: design and manufacture slow wave comb structures – irradiators (applicators) for wood treatment at frequencies of 2.45GHz and 0.922GHz; study the opportunities to use these slow wave comb structures for surface wood layers heating; experimentally study the energy distribution from the slow wave comb applicators in wood; and develop recommendation for practical use of the slow wave comb applicators.

2. Design of Slow Wave Comb Applicators

The operational limits of slow-wave applicators depend on the geometry of the comb, especially the comb's depth. When the comb's depth approaches zero, the comb appears like a short circuit and behaves like the wall of a wave guide. When the comb's depth approaches $\frac{\pi}{k'}$, where k' is the wave number of the electromagnetic field, the impedance of the comb approaches infinity and wave propagation is prevented. Within these limits, as the comb's depth increases the electromagnetic wave's propagation speed slows and the heating depth decreases.

On the base of the theoretical study and modelling of slow wave structures described in [6], the slow wave comb (SWC) applicators for frequency 2.45GHz (Comb1) and 0.922GHz (Comb2) were designed for treatment of wet materials including wood. Comb applicators, which are shown in Figure 1, were fabricated from aluminium. The main dimensions of the Comb1 and Comb2 applicators are displayed in Table 1.

Table 1. Applicator parameters

Parameters	Comb1 (2.45GHz), mm	Comb2 (0.922GHz), mm
Working length	356	346
Applicator thickness	23	37
Applicator width	150	264
Comb electrode width	100	150
Comb electrode thickness	16	28
Comb electrode conic length	90	120
Grove depth	6	13
Grove width	3	8
Comb tooth thickness	3	8
Ceramic plates	Alumina (99%) ceramic plate size 3 × 84 × 146mm (4 pieces), (DC = 9.8, loss tangent 0.0002)	Alumina (99%) ceramic plate size 4 × 86.5 × 182mm (4pieces), (DC = 9.8, loss tangent 0.0002)

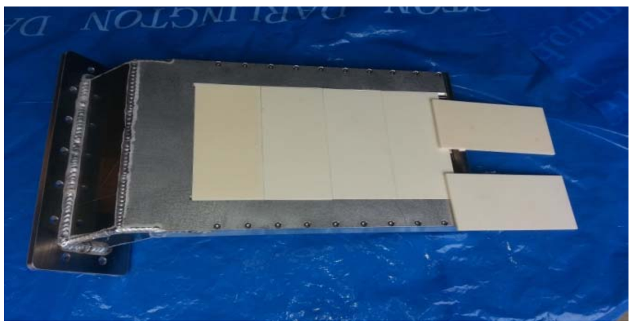
In the experiments, the surface of Comb1 was covered by 3mm thick alumina plates (Figure 1), while Comb2 was covered by 4mm thick alumina plates (Figure 2).

(a)

(b)

Figure 1. Comb1 applicator (2.45GHz) without ceramic plates (a) and with ceramic plates (3 × 84 × 146mm – 4pc) (b).

(a)



(b)

Figure 2. Comb2 applicator (0.922GHz) without ceramic plates (a) and with ceramic plates ($4 \times 86.5 \times 182$mm – 4pc) (b).

3. Experimental Study: Material and Methods

3.1. Material

Green Radiata pine (*Pinus radiata*) sawn timber $50 \times 310 \times 450$mm (MC = 148%, green density 1130kg/m^3) was used for these tests. Five boards, of 50mm thickness, were connected together to form a sample block of 250mm thickness (Figure 3). Holes, with a diameter of 2mm for temperature measurements by thermocouples, were drilled at distances of 5, 15, 30, 45, 95, 115, 135, 165, and 195mm from the beginning of the ceramic plate surfaces of the applicator. The distribution of the holes covered the whole volume of the samples along and across the samples. The distances between the rows of holes along the samples were 30mm and across the sample was 37.5mm.

(a)

(b)

Figure 3. Samples for tests (a) and $250 \times 310 \times 450$mm sawn timber block on Comb applicator in leakage protection box.

Dielectric parameters (dielectric constant and loss tangent) of Radiata pine wood, used for experiments, are presented in Table 2. They depend on frequency, temperature and electric field strength vector E orientation relative to the wood fibres [9]. In experiments the electric field strength vector E was orientated perpendicular to the fibres.

Table 2. Dielectric parameters of Radiata pine wood (MC = 148%, green density 1130kg/m^3, electric field strength vector E orientation is perpendicular to fibres)

Tempe rature, °C	F = 2.45GHz		F = 0.922GHz	
	Dielectric constant	Loss tangent	Dielectric constant	Loss tangent
20	20.5	0.15	19.8	0.14
50	20.5	0.14	19.8	0.13
90	20.5	0.12	19.8	0.12

A scheme of the timber, placed on the applicator, is shown in Figure 4.

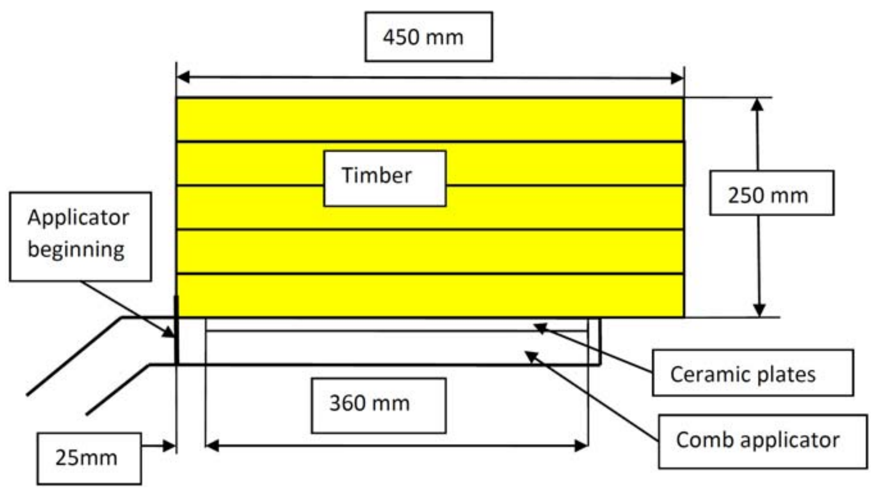


Figure 4. Scheme of comb applicator with wood.

3.2. Experimental installations and procedure

The Comb1 applicator (Figure 1) was connected to a 2.45GHz 30kW MW generator (Figure 5) and placed to a metal box $(400 \times 500 \times 1120\text{mm})$ for leakage protection.

Figure 5. Comb1 applicator (inside of metal box) connection with 30kW MW generator 2.45GHz.

The Comb2 applicator was connected to a 0.922GHz 60kW MW generator (Figure 6) and placed into a metal box for leakage protection.

(a)

(b)

Figure 6. Comb2 applicator (inside of metal box, (a)) connection with MW generator 60kW, 0.922GHz.

Auto tuners were used in MW systems to provide good matching of the generators and the applicators (with wood). There was practically no power reflection as a result.

Values of MW power and time of the treatment were determined during preliminary tests to provide wood heating at a depth of 10mm with no more than 80°C, to prevent water in the wood from boiling. After the timber was placement on the applicator and leakage protection box was closed, MW energy was supplied to the applicators according following schedules:

(1) Applicator Comb1 (2.45GHz)

MW applied power	3.7kW
Time	15 sec
Energy	56kJ

(2) Applicator Comb2 (0.922GHz)

MW applied power	9kW
Energy	180kJ
Time	20 sec

After MW heating, temperatures in the wood were measured in the holes using thermocouples. Errors in experiments have the following nature: variability of wood structure and properties, accuracy of temperature measurements, accuracy of MW power measurements, accuracy of time measurements, and accuracy of distances measurements. Preliminary tests showed that temperature variation during 4-5 repetitions at similar conditions was mainly +/− 2^{o}C. This is acceptable for Comb1 and Comb2 applicator assessment and comparison.

4. Results of Experiments and Discussion

4.1. Temperature distribution in wood by Comb1 applicator (2.45GHz)

We assume that the temperature distribution in the wood reflects energy release in wood volume and allows us to assess energy distribution from the MW applicators. Figure 7 shows typical temperature distribution in the wood volume, at a depth of 5mm, after applying MW power of 3.7kW for 15 sec.

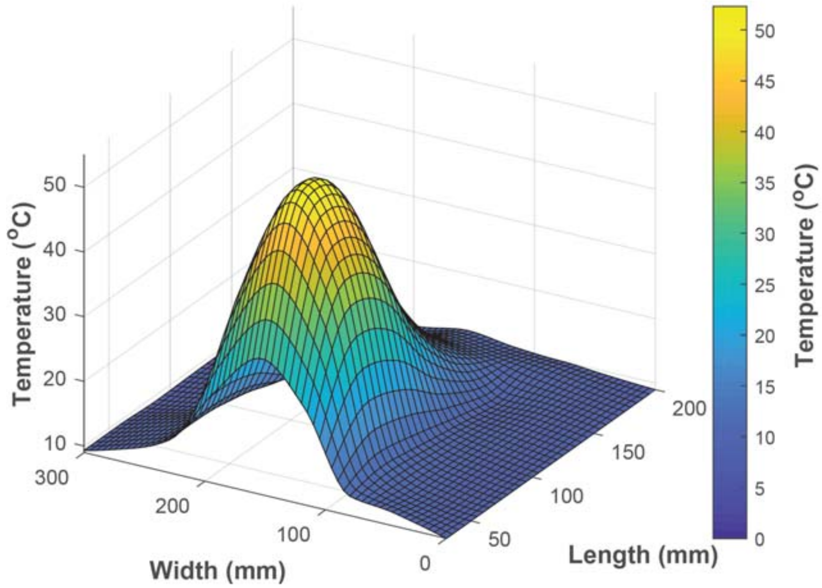


Figure 7. Temperature distribution in wood on the depth 5mm by Comb1 applicator at F = 2.45GHz, P = 3.7kW, time of MW heating 15 sec, To = 9ºC, applied energy 56kJ. Wood moisture content 148%, green density $1130 \mathrm{kg/m}^3$.

Temperature distribution after MW heating in timber, at initial temperature To = 12ºC, along the central vertical plane of the Comb1 applicator, is shown in Figure 8.

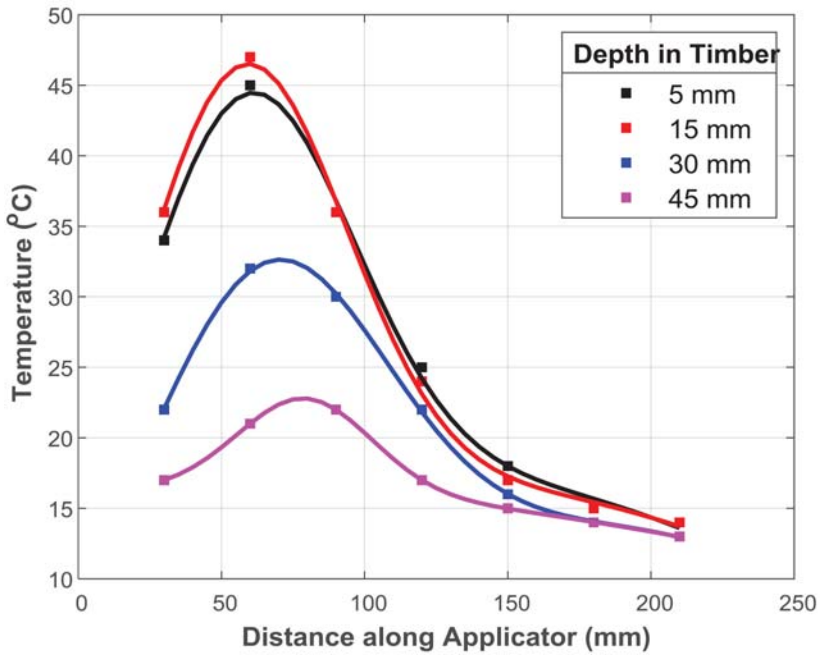


Figure 8. Temperature distribution in the wood sample along the applicator central vertical plane. Sample 12 Radiata pine: MC = 148%, density 1130kg/m^3. F = 2.45GHz, P = 3.7kW, time of MW heating − 15 sec, To = 12ºC. Applied energy 56kJ.

The maximum energy release take place at about 60mm from the beginning of the applicator. Almost all the applied MW energy was absorbed after about 140mm from applicator's beginning.

Temperature distribution in the wood sample, across the Comb1 applicator, is displayed in Figure 9.

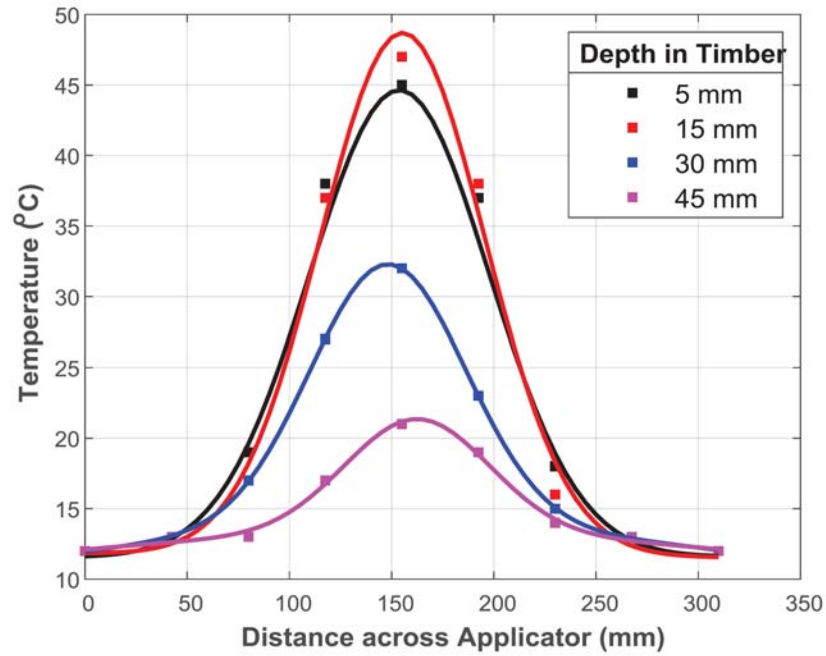


Figure 9. Temperature distribution across the wood sample at the distance 60mm from applicator beginning. Sample 12 Radiata pine: MC = 148%, density 1130kg/m^3. F = 2.45GHz, P = 3.7kW, time of MW heating – 15 sec, To = 12°C. Applied energy 56kJ.

Almost all applied MW energy is absorbed in a width of about 140mm.

The temperature distribution as a function of depth in central vertical plane of the wood sample is displayed in Figure 10.

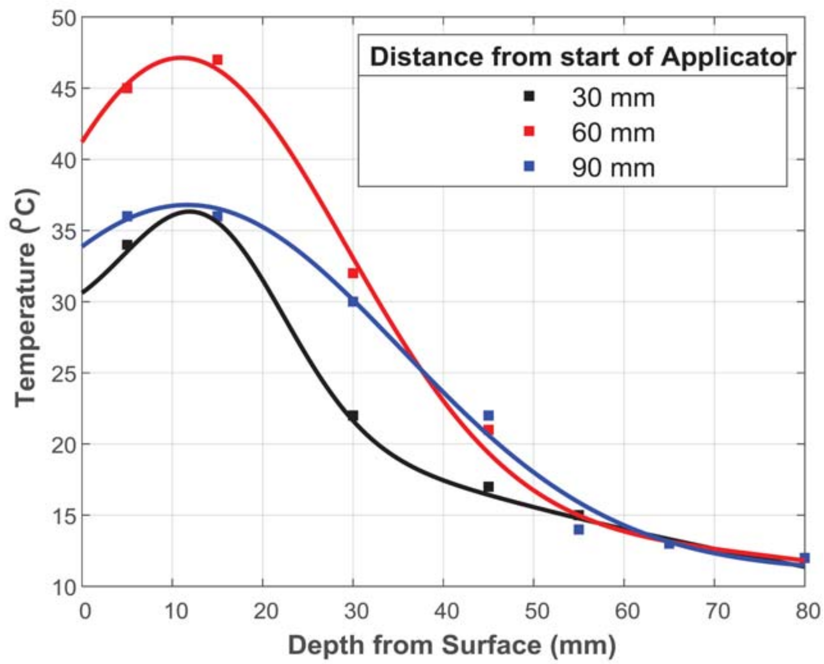


Figure 10. Temperature in depth of the sample in applicator central plane. Wood MC = 148%; F = 2.45GHz, P = 3.7kW, time of MW heating − 15 sec, To = 12°C. Applied energy 56kJ.

The most significant part of energy in the zone of maximum power release (30-90mm from applicator beginning) was absorbed on the depth up to 50mm. In other zones the depth of heating is much lower.

Temperatures at a depth of 5mm (curves in Figures 8-10), after MW treatment, are lower compared to temperaure at a of depth 15mm. This is explained by the influence of more intensive cooling of surface layers during MW processing and during temperature measurement.

Percentage of MW energy absorption, as a function of timber depth (in zone of maximum power release) in the central vertical applicator plane, is shown in Figure 11.

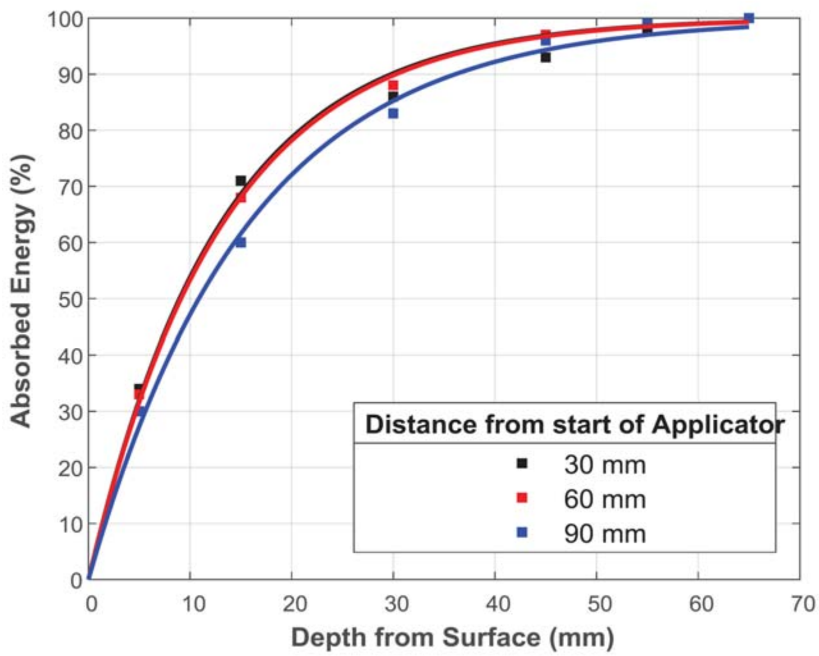


Figure 11. Percentage of MW energy absorption on timber depth in the central vertical Comb1 applicator plane in zone of maximum power release (2.45GHz).

In the wood sample, with MC = 148%, the main part of the MW energy was absorbed within about 140mm from applicator beginning. Across the sample, almost all the MW energy was absorbed in the central zone width of about 140mm (+/− 70mm from central plane of the applicator). The average MW specific power, applied by the Comb1 applicator, to wood surface was: 3700(W): $14(\text{cm}) \times 14(\text{cm}) = 18.9\text{W/cm}^2$ and the average MW energy absorbed was 0.29kJ/cm^2.

In the central Comb1 applicator zone (30-90mm from applicator beginning), at a depth up to 30mm, 83-88% of the applied MW energy was absorbed, in all other zones the absorbed percentage of MW energy was higher.

4.2. Temperature distribution in wood by Comb2 applicator (0.922GHz)

Figure 12 shows the typical temperature distribution in wood volume at a depth of 5mm after applying 9kW of MW power for 20 sec using the Comb2 applicator.

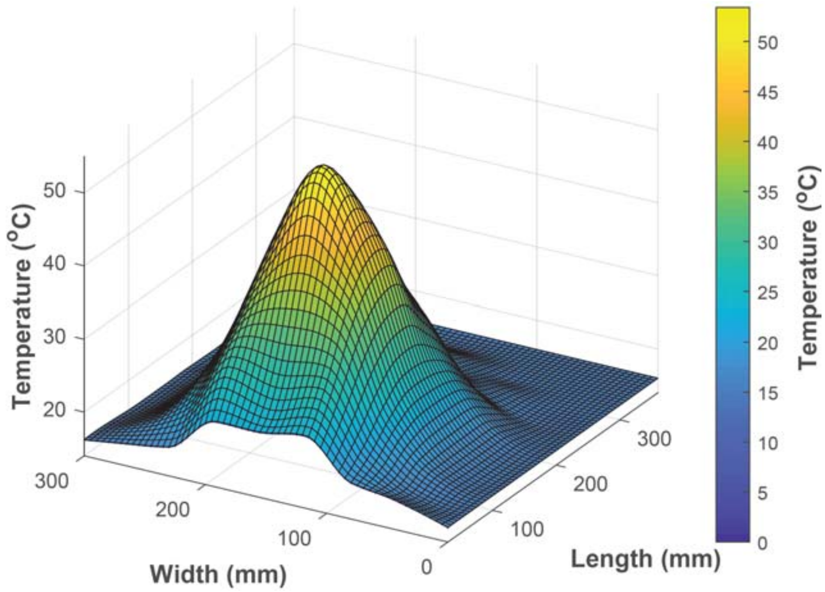


Figure 12. Temperature distribution in the wood sample at 5mm depth from the Comb2 applicator at F = 0.922GHz, P = 9kW, time of MW heating 20 sec, To = 12ºC, applied energy 180kJ. Wood moisture content MC = 148%, density 1130kg/m^3.

Temperature measurement results of wood MW heating, using Comb2 at initial timber temperature 15ºC-16ºC and applied energy 180kJ, are displayed in Figures 13, 14, 15.

Experiments showed that practically all the MW energy was absorbed within about 300mm from applicator's beginning (Figure 13).

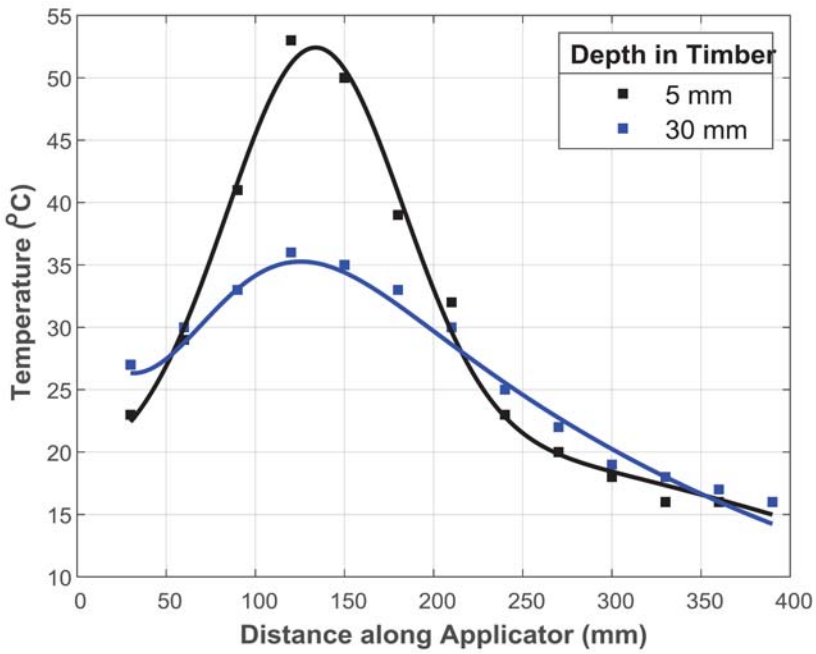


Figure 13. Temperature distribution in the sample along the applicator central vertical plane. Wood thickness 250mm (dimensions $250 \times 310 \times 450$mm) MC = 148%; F = 0.922GHz, P = 9kW, time of MW heating – 20 sec, To = 16°C. Applied energy 180kJ.

Most of the energy was absorbed within 260mm of applicator beginning, with the maximum energy release taking place at a distance of 120mm from applicator's beginning.

Temperature distribution across the sample after MW heating is shown in Figures 14 and 15.

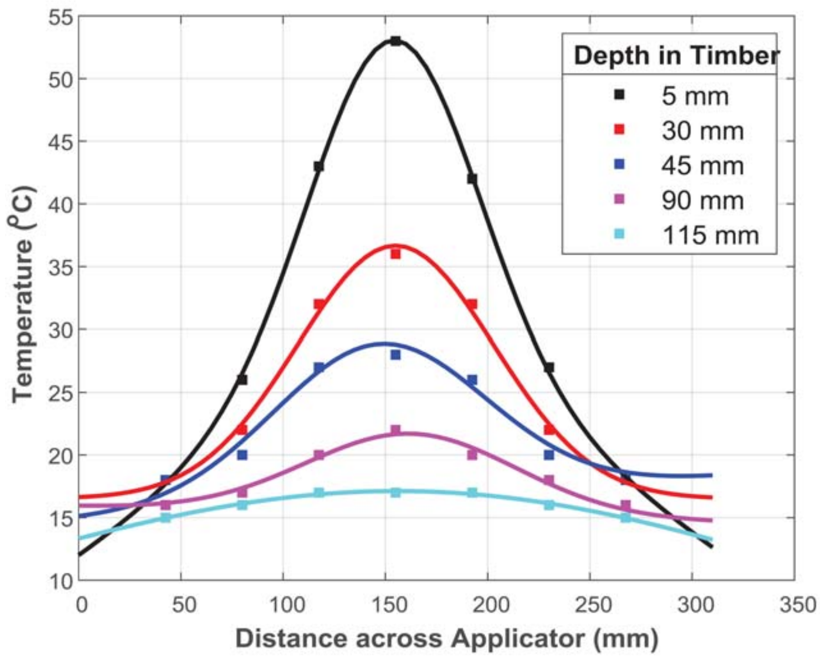


Figure 14. Temperature distribution across the sample at the distance 120mm from applicator beginning. Sample of Radiata pine: thickness 250mm $(250 \times 310 \times s450)$, MC = 148%; F = 0.922GHz, P = 9kW, time of MW heating – 20 sec, To = 16°C. Applied energy 180kJ.

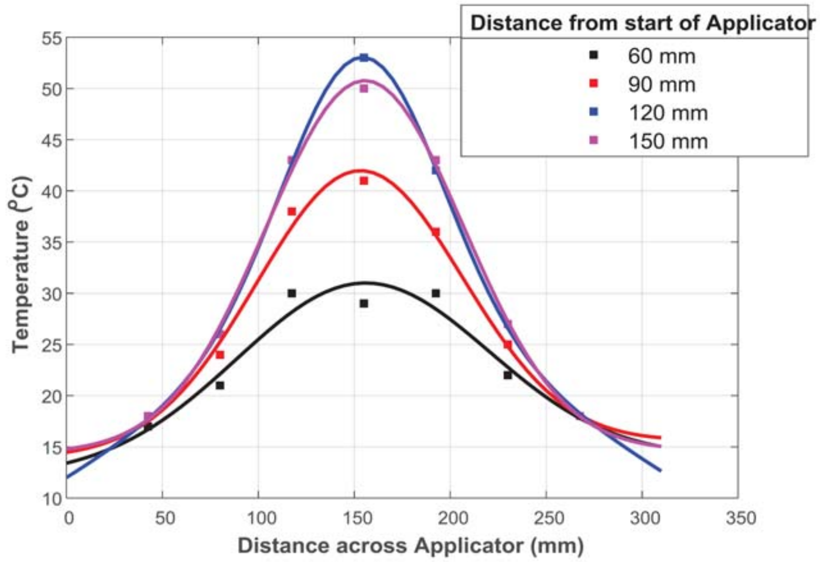


Figure 15. Temperature distribution across the sample at different distances from applicator beginning on the depth 5mm. Sample of Radiata pine wood: thickness 250mm $(250 \times 310 \times 450\text{mm})$, MC = 148%; F = 0.922GHz, P = 9kW, time of MW heating − 20 sec, To = 16°C. Applied energy 180kJ.

Experiments showed that almost all of the 180kJ of applied energy was absorbed in the sample width of 160mm in the zones of maximum energy release (for the Comb2 applicator, between 60mm-180mm from the beginning of the applicator). In all other zones the energy distribution in the sample width at any depth was very low.

The average MW specific power, applied by the Comb2 applicator, to the wood surface was 9000(W): 26(cm) $\times$ 16(cm) $= 21.6\text{W/cm}^2$ and the average MW energy absorbed was 0.43kJ/cm^2.

Figure 16 displays the temperature distribution as a function of depth in the wood from the Comb2 applicator along the central vertical plane in the zones of maximum energy release (60-180mm from applicator beginning).

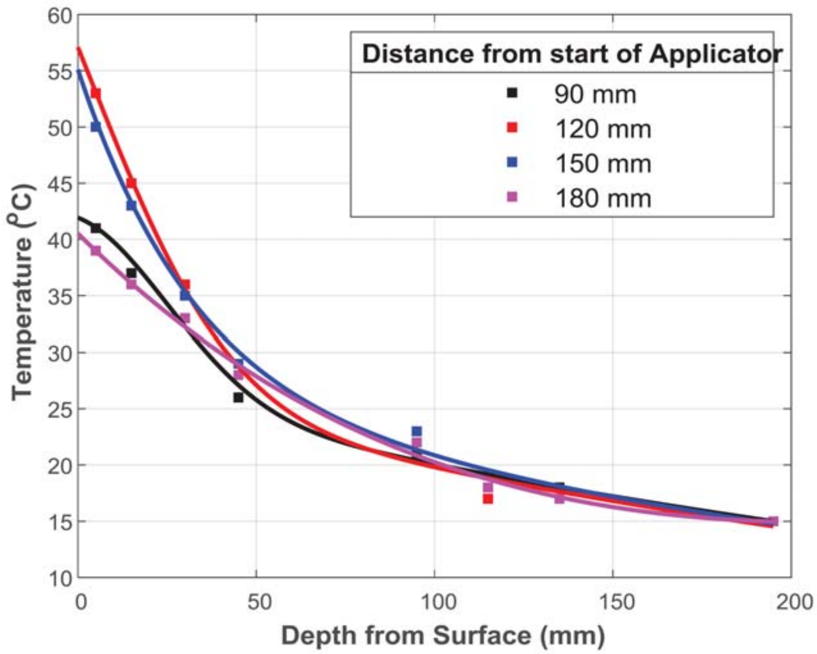


Figure 16. Temperature distribution as a function of depth in the wood from the Comb2 applicator along the central vertical plane. Radiata pine sample: thickness 250mm $(250 \times 310 \times 450\text{mm})$, MC = 148%; F = 0.922GHz, P = 9kW, time of MW heating 20 sec, To = 16ºC. Applied energy 180kJ.

At the applied energy of 180kJ, practically all the energy was absorbed within 135mm from the timber surface, in the zones of maximum energy release. In all other zones the depth of energy penetration was lower.

In the wood sample with MC = 148% the main part of the MW energy was absorbed within about 260mm from the beginning of the Comb2 applicator. Across the sample almost all the MW energy was absorbed in the central zone, which was about 160mm wide (+/− 80mm from central plane of the Comb2 applicator). The average MW specific power applied by the Comb2 applicator to wood surface was 9000(W): 16(cm) × 26(cm) $= 21.6\text{W/cm}^2$ and average MW energy absorbed was 0.43kJ/cm^2.

4.3. Comparison of energy distribution by applicators Comb1 and Comb2

Comparison of percentage of energy release in timber as a function of depth by applicators Comb1 and Comb2 in the zones of maximum energy release (on distance 30-90mm for Comb1 and on distance 90-180mm for Comb2 from applicator beginning) is displayed in Figure 17.

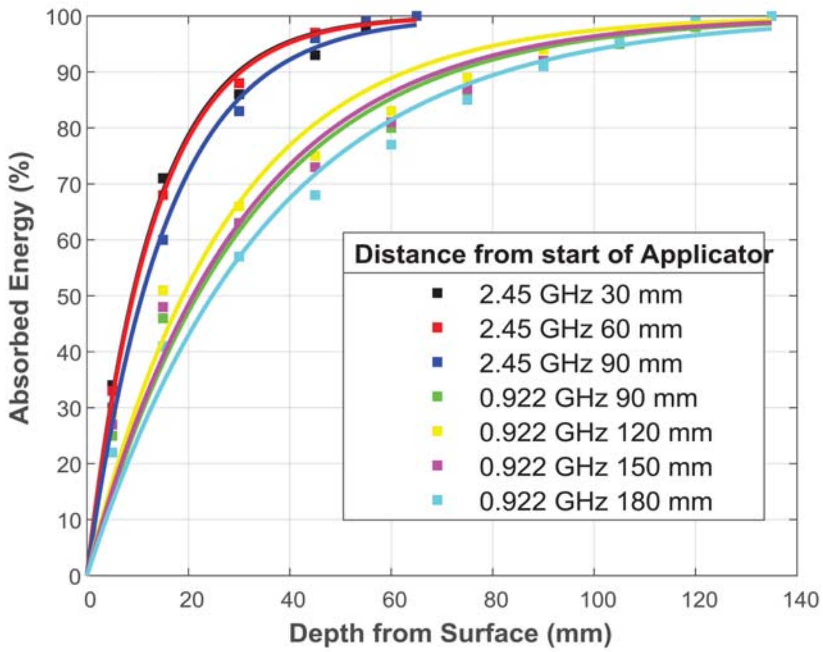


Figure 17. Comparison of percentage of energy release on timber depth applied by applicators Comb1 and Comb2 in zones of maximum energy release (on distance 30-90mm for Comb1 and on distance 90-180mm for Comb2 from applicator beginning).

Dimensions and energy distribution parameters of applicators Comb1 and Comb2 are displayed in Table 3.

Table 3. Comparison of sizes and energy distribution parameters of applicators Comb1 and Comb2 in wood with moisture content 148% and density 1130kg/m^3

Parameters	Comb1 (2.45GHz)	Comb2 (0.922GHz)
Applicator working length, mm	356	346
Applicator width, mm	150	264
Comb electrode width, mm	100	150
Average MW specific power applied, W/cm^2	18.9	21.6
Average MW specific energy applied, kJ/cm^2	0.29	0.43
MW energy distribution zone width, mm	140	160
MW energy distribution zone length, mm	140	260
Length of zone of high intensity heating along applicator, mm	60-90	180-200
Depth of full MW energy absorption in zones of maximum energy release, mm	50	135
Percentage of energy release on timber depth up to 15mm in zone of maximum energy release, %	68-71	41-51
Percentage of energy release on timber depth up to 30mm in zone of maximum energy release, %	83-88	57-66

Experiments with different moisture content materials showed the energy distribution on applicators Comb1 and Comb2 width depends not significantly on moisture content and density in MC range 40 to 140% and density 600-1100kg/m^3. Energy distribution along the applicator Comb1 length, at a frequency of 2.45GHz at low moisture content and wood density can be more than 140mm from the start of the applicator; therefore, for practical purposes it is better to have the applicator length not less than 250-280mm. For Comb2 applicator a minimum length 350mm is recommended.

Applicator Comb1 provides very high efficiency of energy release at depths up to 30mm-83%-88% in zones with maximum energy application. In other zones energy application efficiency is higher. Comb2 applicator, due to longer MW wave length, provides a deeper energy penetration. Efficiency of energy absorption in the zones of maximum energy release at depths up to 30mm is about 60%.

There are two main advantages in energy distribution from comb applicators compared with horn applicators. These include: more uniformity of energy distribution along the applicators and significant energy concentration near the applicator's surface (ceramic plates). In MW surface heating systems, the timber (logs, boards) moves along the applicator, which improves the uniformity of energy distribution along the log. Non-uniformity of energy distribution across the log can be compensated by using several applicators, positioned with displacement along the log for overlapping zones with low MW intensity.

Comb applicators can provide required wood top layer treatment (sterilization) with good efficiency and can be recommended for practical use. The Comb1 applicator (2.45GHz), due to its higher frequency, provides better efficiency for energy release in the top layers of wood, compared to Comb2 (0.922GHz). But at a frequency of 0.922GHz, the efficiency of electric energy transformation to MW energy is much higher and the price of generators is significantly lower; therefore, the choice of frequency for industrial wood heating use needs to be done from an economic assessment.

5. Conclusion

Experiments showed that the Comb1 applicator (2.45GHz), with alumina ceramic plates, provides the following energy distribution in wood with moisture content of 148% and density of 1130kg/m^3 in the tested conditions: along the applicator length 140mm, on applicator width −140mm and full energy absorption in depths up to 50mm. The Comb2 (0.922GHz) applicator, in the tested conditions, provides energy release along the applicator length to 260mm, on the applicator width −160mm and full energy absorption to depths up to 135mm.

The Comb1 applicator provides high efficiency of MW energy release in depths up to 30mm – 83-88% of applied energy in zones with maximum energy application. In other zones energy application efficiency is higher. The Comb2 applicator, due to its longer MW wave length, provides a deeper energy penetration. The efficiency of energy absorption in the zones of maximum energy release to depths up to 30mm is about 60% of applied energy. Energy distribution by comb applicators in the wet wood allows the release of the most significant part of the energy in the surface layers and increases efficiency of energy use compared to other typed of MW radiators. Comb1 and Comb2 applicators are recommended for practical use in wood heating, MW modification and sterilisation processes.

The experimental study of slow wave comb structures, designed for heating surface layers of timber (and other materials: soil, concrete, plaster, bricks and so on), provides effective MW energy release in the wood surface layers by keeping the energy close to the comb surface, spreading energy along applicator and limiting energy penetration into the material. Comb MW applicators are more effective for heating surface layers compared to horn or slot radiators.

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