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Developing treatment protocols for disinfesting pine wood product using radio frequency energy

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Abstract Numerous non-native insect pests are moved around the world via international trade and have caused major forestry losses, especially for pine trees. The purpose of this research was to study a potential application of radio frequency (RF) heating for disinfesting pine wood products to reduce forestry damage caused by exotic pests. A pilot-scale 6 kW, 27.12 MHz RF system was used to develop a treatment protocol for disinfesting pine wood products based on the heating uniformity studies. The results showed that the heating time needed was only 6.7 min to heat the wood blocks ($250\times400\times60$ mm^3) with moisture content of 13.3% d.b. from 25 to 60 °C using RF energy, but 320 min to reach 56.2 °C using hot air at 60 °C with 1.6 m/s. Based on the heating uniformity study, the best condition occurred when the lower wood moisture content was used and the wood width approached the RF electrode one. The RF treatment protocol was finally developed to combine RF energy with forced hot air at 60 °C, movement of conveyor at 7.4 m/h and holding at 60 °C hot air for 1 min. Wood quality was not affected significantly by the RF treatments because quality parameters of treated wood samples were similar to those of controls. The RF treatment may provide a rapid, effective and environmentally friendly method to disinfest wood products.

Keywords Radio frequency · Wood product · Heat treatment · Uniformity · Quality

1 Introduction

The international trade of wood materials associated with non-native forest insects is a threat to the security and sustainability of forests worldwide (Chornesky et al. 2005). Increasing speed, volume and number of trading result in frequent invasions of non-native insects across countries. More than 400 insect species, which feed on trees and shrubs, have been introduced into US during the 1900s (Haack 2006). Wood-boring insects are oftentimes transported on wood products, such as wood packing materials, logs and lumbers (Dobbs and Brodel 2004). Asian long-horned beetles (ALB) were accidentally introduced into the US from China in wood packaging materials during the mid-1990s (Fleming et al. 2003). After that, the beetle infestation on trees in many states has led to large economic losses (APHIS 2011).

Since wood materials infested by internal-feeding pests are not easily detected by external inspection, regulatory agencies in many countries have established quarantine protocols intended to prevent the introduction of exotic pests. The most common method for quarantine control of ALB in wood is chemical fumigation with methyl bromide (Barak et al. 2009, 2011; Moffitt et al. 1992). Due to its negative impact on ozone layer and human health, however, Montreal protocol (UNEP 1992) has proposed to phase out fumigation disinfestation methods with methyl bromide (CH_3Br), which is becoming unavailable (Lazarescu et al. 2009, 2011). Thus, it is urgent to develop non-chemical alternative methods to replace methyl bromide fumigation for disinfesting wood.

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Non-chemical methods include conventional heating, irradiation (Kunstadt 1998), vacuum technology (Chen et al. 2006, 2008), microwave (Fleming et al. 2003; Hoover et al. 2010) and radio frequency (RF) (Lazarescu et al. 2011, 2012, 2015; Uzunovic et al. 2012; Watanabe et al. 2011) treatments for disinfesting wood products. Conventional heat treatment is costly due to its low energy efficiency and lengthy exposures (Watanabe et al. 2011). Irradiation is effective for postharvest pest control of many commodities, but few dedicated irradiation facilities are available and a number of export markets (Japan, Taiwan, or EU) do not allow irradiated products. Vacuum requires lengthy treatment times for disinfestations (Chen et al. 2008). Microwave provides fast and volumetric heating as RF energy but has limited penetration depths and difficulties for large-scale applications (Zhang et al. 2006).

RF treatment as an electromagnetic wave heating method can rapidly penetrate thick material and be easily scaled up for industrial applications. Therefore, RF treatments are a potential alternative for phytosanitary and quarantine treatments of wood products. Previous research using RF energy for disinfestations has focused on controlling insect pests in agricultural products, such as codling moth in apples (Wang et al. 2006a), and naval orangeworm in walnuts (Wang et al. 2001, 2002, 2007), Mexican fruit fly in mangoes (Sosa-Morales et al. 2009), yellow peach moth in chestnut (Hou et al. 2015), and rice weevil in milled rice (Zhou and Wang 2016). Comparatively, there are a few reports on using RF heating to sanitize wood products from invasive pests. Evaluating RF heating for disinfesting pinewood nematode (PWN) and mountain pine beetle (MPB) has been reported by Dwinell et al. (1994), Lazarescu et al. (2011, 2015) and Uzunovic et al. (2012). Their studies confirm that the RF heating disinfestations are feasible and effective methods but lack studies on RF heating uniformity for developing effective treatment protocols in wood products. Further applications of RF treatments for disinfesting wood products are limited probably due to lack of RF heating uniformity studies. It is urgently needed to study RF heating uniformity in developing a successful treatment protocol for disinfesting wood products.

The objectives of this research were (1) to compare the heating rates in pine wood samples when subjected to RF and hot air heating; (2) to study the RF heating uniformity in wood products with different moisture content (MC) and width using hot air surface heating and sample moving on a conveyor belt and explore an optimum RF treatment protocol for disinfesting pine wood products, and (3) to evaluate the effects of RF treatments on quality parameters (moisture content, color, and checking) of the wood samples.

2 Materials and methods

2.1 Hot air assisted RF heating system

A pilot-scale, 6 kW, 27.12 MHz free running oscillator RF system (S06B, Strayfield International, Wokingham, UK) with an additional hot air system (6 kW) was used to study heating uniformity of wood samples as the reliable first step in determining optimal RF heating conditions for pine woods (Fig. 1). Details of the RF and hot air systems were described in Wang et al. (2010). Moving the top electrode (400×830 mm^2) was used to change the electrode gap, and thus adjust RF power. Wood samples were placed on a conveyor belt between the two electrodes. The speed of the conveyor belt can be adjusted from 1.0 to 60 m/h during RF heating to simulate continuous processes. Hot air produced by electric heating strips was blown into the RF cavity between the electrodes through the holes distributed on the bottom plate (Fig. 2). The hot air flow rate and temperature in the RF cavity were controlled by the fan speed and the input electric power.

2.2 Materials

Pinewood (*Pinus sylvestris*) harvested in Russian Far East and imported to Xianyang, Shaanxi Province, China was chosen as the test species in this research. The boards were then processed into samples with 20 mm-thickness, and a length of 250 mm and three widths of 200, 300, and 400 mm. The initial moisture content (MC) of the specimens was $13.3 \pm 2.0\%$ on dry basis (d.b.). Then all wood samples were immediately stored in polyethylene bags in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 4 ± 1 °C prior to the experiment to

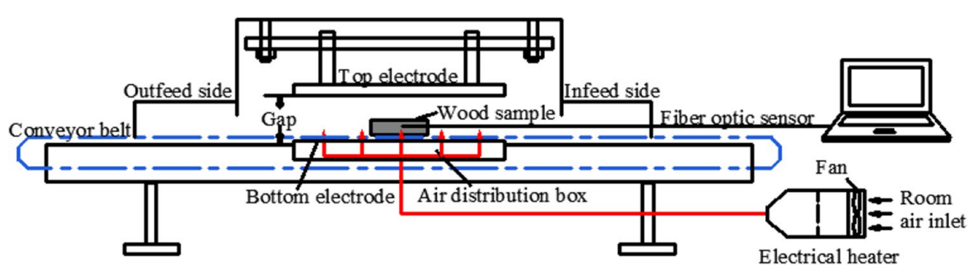

Fig. 1 Schematic view of the 6 kW, 27.12 MHz radio frequency system showing the plate electrodes, conveyor belt, the hot air system and the fiber optic sensor. Adapted from Wang et al. (2010)

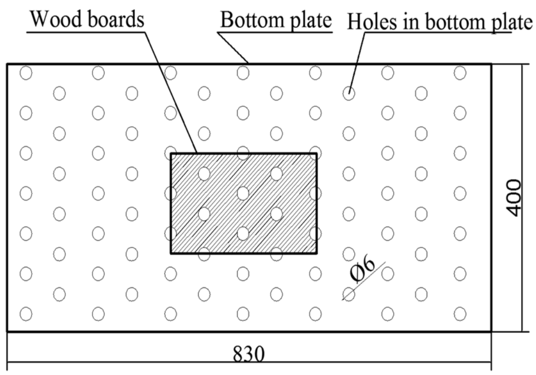

Fig. 2 Distribution of holes for hot air outlets in bottom electrode (all dimensions are in mm)

prevent moisture loss. Prior to experiment, they were taken out from the refrigerator and put in an incubator (BSC-150, Boxun Industry & Commerce Co., Shanghai, China) to equilibrate at 25 ± 0.5 °C for more than 20 h.

2.3 Wood sample moisture content (MC) measurement

Wood sample MCs were determined by using the oven drying method following the National Standard of China described in GB/T 1931–2009 (2009) issued by China State Bureau of Standard. Treated wood samples were first cut into 20 mm-thick cubes, placed in aluminum dishes, and then dried in vacuum oven (DZX-6020B, Nanrong Laboratory Equipment Co., Ltd., Shanghai, China) at 103 °C for 8 h. Weighing the samples every 2 h was carried out until the difference was less than 0.5% as compared to the previous weight of samples. The samples were placed in desiccators with $CaSO_4$ and cooled to room temperature before weighing.

2.4 Electrode gap selection

Different electrode gap in the RF system results in various anode currents and RF powers. The electric current (I, A) shown on the console of the RF unit was used to calculate the output power (P, kW) of the RF system with a corresponding relation ($P = 5 \times I - 1.5$) provided by the manufacturer (Jiao et al. 2012). To select the appropriate electrode gap, pine wood samples with 13.3% d.b. MC ($250 \times 300 \times 60$ mm^3) were placed in the center of the bottom electrode. After turning on the RF system without hot air and movement, the anode current with or without samples was recorded when the electrode gap was regulated from 90 to 190 mm with a distance interval of 10 mm. All the tests were repeated three times. According to the estimated RF power, three electrode gaps of 110, 120, and 130 mm were selected for next heating rate tests.

To determine the best one from the three suitable electrode gaps for studying RF heating uniformity and the final treatment protocol, the sample temperature was measured at the geometrical center of the sample using a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. The probe was inserted into the center of the wood sample through predrilled holes. The central sample temperature was recorded every 1 s when RF heating of the woods was conducted from ambient room air (25 °C) to target temperature (60 °C). The target temperature was selected based on the dialectic heating for wood packaging material (ISPM-15-IPPC 2011). The tests were also replicated three times. The final electrode gap was determined based on the optimal heating rate (6–8 °C/min) of samples (Hou et al. 2014) and applied to further tests.

2.5 Comparisons of wood temperature profiles between RF and hot air heating

The preconditioned wood samples ($250 \times 400 \times 60$ mm^3) with 13.3% d.b. MC. and initial temperature of 25 °C were placed at the center of the bottom electrode for hot air and RF heating. The sample temperatures at the geometric center were recorded every 60 s by the fiber optic temperature sensor system. The experiment was stopped when the sample temperature reached 60 °C or the temperature of the sample geometric center increased less than 0.1 °C within 30 min using hot air. The tests were repeated three times for each heating method.

2.6 Heating uniformity tests

The heating non-uniformity is an important problem in developing a large-scale RF treatment protocol since it influences insect mortality and sample quality. Wang et al. (2005, 2008) used a heating uniformity index (λ) to evaluate RF heating uniformity in agricultural products, such as walnut (Wang et al. 2007), almond (Gao et al. 2010), legume (Wang et al. 2010), lentil (Jiao et al. 2012), chestnut (Hou et al. 2014), and milled rice (Zhou and Wang 2016). It is defined as the ratio of the rise in standard deviation of sample temperatures over the treatment time and can be calculated by the following equation:

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \tag{1}$$

where μ and μ_0 are initial and final mean wood sample temperatures (°C), σ and σ_0 are initial and final standard deviations (°C) of wood sample surface temperatures over treatment time. The smaller λ values result in the better heating uniformity.

The surface temperatures in the three layers of the wood sample (Fig. 3) were mapped using a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd, Hangzhou, China) with an accuracy of ±2 °C. Before and immediately after RF treatment, the sample surface temperatures on the top, middle or bottom layer were measured by the thermal imaging camera. Each thermal imaging took less than 2 s. Details of the infrared imaging system to measure product surface temperature after RF treatment can be found in Wang et al. (2006b). The surface temperature data in the treatment area were obtained and used for estimating the average and standard deviation temperatures. The mean and standard deviation (SD) values of the surface temperatures for each test were used for evaluating the RF heating uniformity using Eq. (1). The appropriate level of the sample moisture content and width corresponding to the best RF heating uniformity was used for next tests.

2.6.1 *Comparison of the RF heating uniformity for wood with different MCs and widths*

To determine the effects of MC on RF heating uniformity, $20\times300\times250$ mm^3 blocks were cut from the pine wood boards. Wood samples with MCs of 13.3 ± 2.0, 23.1 ± 2.5, and 35.6 ± 2.3% d.b. were selected in this study. To achieve various specimen MCs, the relationship between MC and soaking time of wood samples was obtained as shown in Fig. 7. The soaked samples were equilibrated in a plastic bag for 4 days to achieve relatively uniform moisture distributions prior to RF heating. To study the effects of width on RF heating uniformity, pine wood samples with three widths of 200, 300, and 400 with 250 mm-length and 13.3% d.b. MC were used. Temperature measurements were made according to the abovementioned methods. The tests were repeated three times for each MC and width.

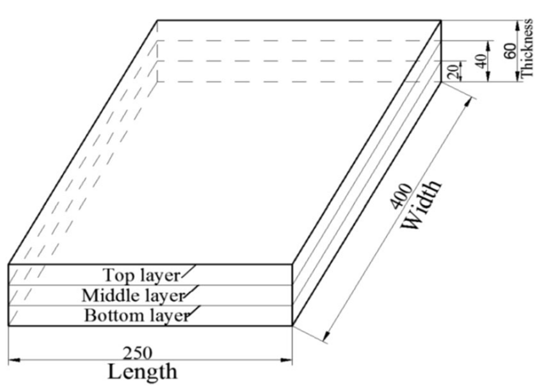

Fig. 3 Wood sample with three layers for surface temperature measurement using thermal imaging camera (all dimensions are in mm)

2.6.2 *Comparison of RF heating uniformity under different process conditions*

After determining the effects of sample moisture content and width, RF heating uniformity still depends on different treatment conditions, such as with or without forced hot air, and with or without movement of samples on the conveyor belt. It is essential to improve the RF heating uniformity before determining an optimized RF treatment protocol for pine wood. So full loads of wood samples at predetermined 13.3% d.b. MC with a width of 400 mm were placed in the middle of two electrode gaps and heated in the RF unit to compare the sample temperature distribution under five conditions: RF heating only, RF heating with hot air assisted, RF heating with conveyor belt speed of 7.6 m/h, forced hot air of 60 °C assisted RF heating with conveyor belt movement, and hot air assisted RF heating with conveyor belt movement and holding in 60 °C hot air for 1 min. The sample movement started from the right edge (in-feed side) to the left edge (out-feed side) of the top electrode (Fig. 1). The forced hot air at 60 °C was provided through the air distribution box at the bottom electrode (Figs. 1, 2). The tests were conducted in triplicate for each treatment.

2.7 Treatment protocol development

The RF treatment protocol was developed based on achieving complete control of the target insects with the temperature of 60 °C and holding time of 1 min (ISPM-15-IPPC 2011). The optimal electrode gap (120 mm) with the conveyor belt movement at the speed of 7.4 m/h was used for heating 60 mm thick wood samples with 13.3% d.b. MC in the RF system together with hot air heating at 60 °C. Then the RF system was turned off and the wood samples in polyethylene plastic bag were held in hot air for 1 min. The untreated samples were considered as controls. Each treatment was repeated three times.

2.8 Quality evaluation of wood products

Before and after RF treatments, the quality attributes of wood products were evaluated immediately. Moisture content, checking, and bending properties were selected as major quality parameters. The wood samples MC measurements were made according to the abovementioned methods. Wood checking is an important appearance factor for wood quality in practical use and market. RF treatments may provide some drying effects and vapor pressures from inside to outside of the wood samples, resulting in possible checking. The surface checking numbers in each sample layer were visually inspected and counted before and after

RF treatment according to the method reported by Brischke and Melcher (2015). Checking with a length of less than 5 mm was neglected.

Wood bending properties including modulus of elasticity (MOE) and modulus of rupture (MOR) were measured with a static 3-point bending test (load speed of 2 mm/min with span of 120 mm) as previously described by Surini et al. (2012), and only sapwood samples were selected to be evaluated. The specimens of bending test were cut to $20\times20\times250$ mm^3, which was shorter than the standardized length (300 mm) due to the technical requirements of the measurement system. Six replicates were performed for each test.

3 Results and discussion

3.1 Electric current under different electrode gap

Figure 4 shows the relationship between the electric current and electrode gap with or without wood samples at 13.3% d.b. placed on the RF bottom electrode without hot air and movement of conveyor belt. With wood samples, electric current rapidly decreased from 0.36 to 0.30 A when the electrode gap increased from 110 to 130 mm. However, the electric current decreased slowly when the electrode gap increased from 130 to 190 mm. When the electrode gap was smaller than 110 mm, the electric current was large with bigger SD. Without wood samples, the electric current was almost constant, around 0.27 A, which was not affected by the electrode gap changes. Similar trends were also found by Zhou et al. (2015) and Wang et al. (2007). Thus, three electrode gaps (110, 120, and 130 mm) were chosen for further tests.

3.2 Determining the electrode gap

Figure 5 shows the sample temperature–time histories at the center of the wood sample with the electrode gaps of 110, 120, and 130 mm during the RF heating. The sample temperature increased almost linearly with the heating time under the three gaps. The heating rate increased with decreasing electrode gap when the wood sample temperature was raised from 25 to 60 °C. About 4.4, 6.7, and 9.8 min were needed to heat the sample with the heating rates of 7.89, 5.17, and 3.57 °C/min for the electrode gaps of 110, 120, and 130 mm, respectively. Faster heating rates led to higher throughput, but might have an adverse effect on RF heating uniformity. To obtain a better balance between heating uniformity and throughput, the electrode gap of 120 mm was selected for wood sample to achieve the heating rate of 5.17 °C/min and used for further RF heating uniformity tests.

3.3 RF and hot air heating profiles

Figure 6 shows the temperature–time history comparisons of the 400 mm-wide wood samples with 13.3% d.b. between RF heating with electrode gap of 120 mm and 60 °C forced hot air with 1.6 m/s. The RF treatment resulted in faster heating as compared to conventional hot air heating, since it needed only 6.7 min for RF heating of the wood sample the center temperature to 60 °C, as compared to 320 min for hot air heated samples to reach only 56.2 °C. The slow hot air heating could be caused by the poor heat transfer through wood samples with 60 mm thickness due to small heat conductivity. The advantage of rapid RF heating is similar to the results observed with milled rice (Zhou

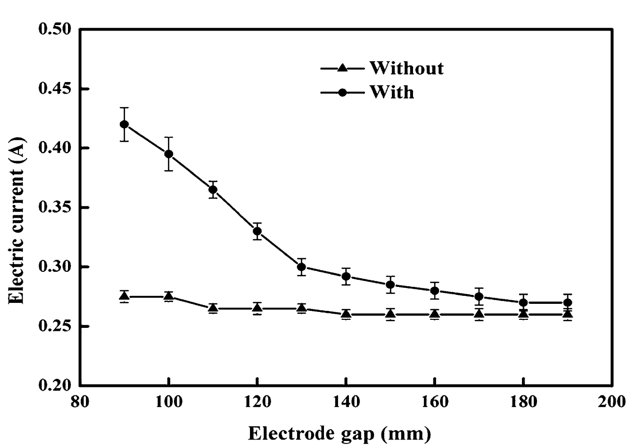

Fig. 4 Electric current of the radio frequency system as a function of electrode gap with or without samples ($250\times300\times60$ mm^3 and moisture content with 13.3% d.b.)

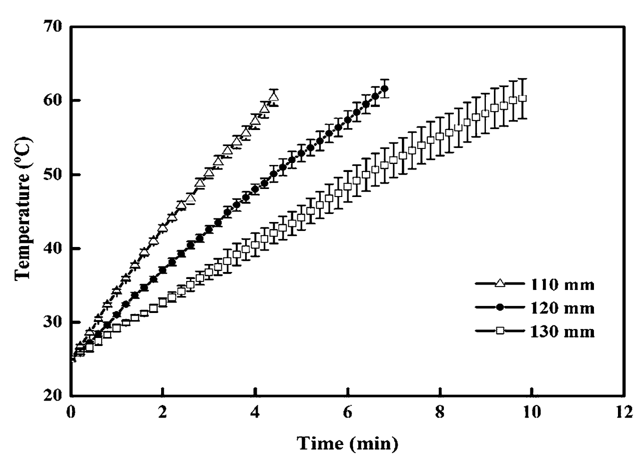

Fig. 5 Temperature–time histories of the RF heated pine wood ($250\times300\times60$ mm^3 with 13.3% d.b. MC) in the center as a function of the electrode gap

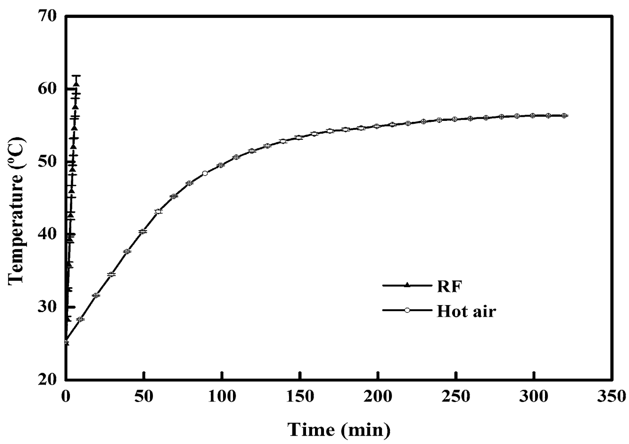

Fig. 6 Comparison of temperature–time histories of pine wood samples ($250\times400\times60$ mm^3) between RF heating (gap = 120 mm) and hot air heating at 60 °C (1.6 m/s)

et al. 2015), chestnut (Hou et al. 2014) and lentil (Wang et al. 2010).

3.4 Heating uniformity analysis

3.4.1 Effect of wood moisture content

Figure 7 shows the moisture content of the wood sample as a function of soaking time at room temperature of 25 °C. The moisture content of the wood sample increased from the initial value of 13.3% to final 60.0% d.b. for a soaking time up to 18 h. There was almost no change of moisture contents in the sample between 16 and 18 h soaking. Based on moisture content-time histories, the soaking time of 1.2 and 3.5 h were selected for the wood RF heating uniformity test to achieve the sample moisture content of about 25.0 and 35.0% d.b., respectively.

The initial sample temperature distribution was relatively uniform with 25 ± 0.1 °C before RF treatment. Figure 8 shows a comparison of surface heating uniformity index of wood samples in top, middle and bottom layers with three moisture contents after RF treatment. The lower moisture content resulted in the better heating uniformity. For all wood samples, the heating uniformity indexes in high-moisture samples were higher than those in low moisture products. The result might be caused by the different dielectric properties of samples. That is, lower moisture sample had smaller dielectric loss factor, resulting in less RF power absorbed and thus low heating rates (Jiao et al. 2014).

3.4.2 Effect of wood width

Figure 9 shows the comparison of heating uniformity index of the pine wood samples at 13.3% d.b. in top, middle and bottom layers with three wood widths after RF treatment. Increasing sample width reduced the heating uniformity index. The best heating uniformity was obtained when the sample width was close to that of the top electrode. This finding was in good agreement with results reported by Tiwari et al. (2011) and Huang et al. (2015).

3.4.3 Effect of treatment conditions

Figure 10 and Table 1 show a detailed comparison of the temperature distribution and heating uniformity index of wood samples at 13.3% d.b. with 400 mm width in top, middle and bottom layers after RF heating under different treatment conditions. The initial sample temperature

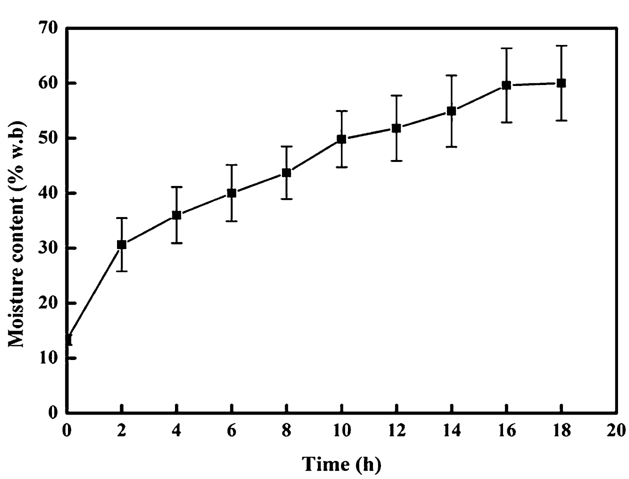

Fig. 7 Moisture content of woods test cube ($2\times2\times2$ mm^3) as a function of soaking time at room temperature (25 °C)

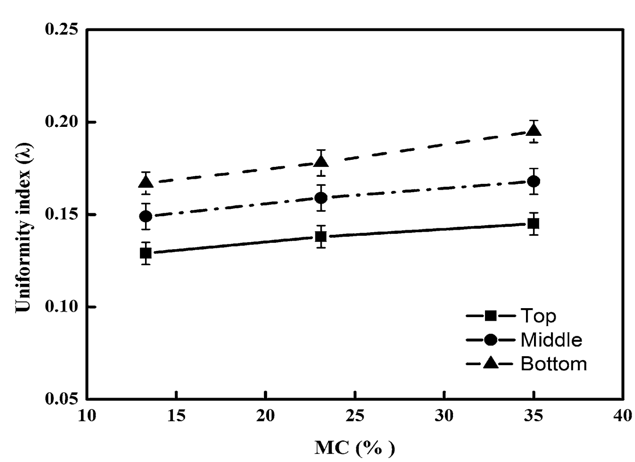

Fig. 8 Typical uniformity index in pine woods ($250\times300\times60$ mm^3) with three moisture levels when subjected to RF heating (electrode gap = 120 mm)

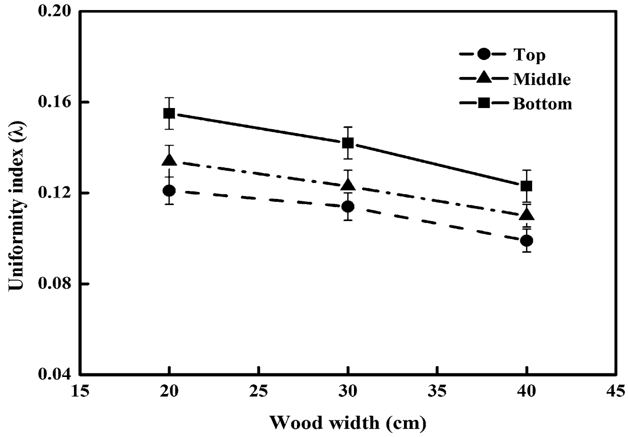

Fig. 9 Typical uniformity index in pine wood samples (moisture content with 13.3% d.b.) with three widths when subjected to RF heating (electrode gap = 120 mm)

distribution was relatively uniform with 25 ± 0.1 °C under preconditioning prior to treatment. After RF treatments, the relatively higher average temperature of samples was observed in the middle and bottom layers, followed by the top layer. The lowest surface average temperatures of wood samples were observed in the top layer, which was probably caused by heat loss to ambient air during and after RF treatments. The standard deviation of the sample temperature was reduced by adding forced hot air, movement of conveyor belt and hot air holding. Adding hot air could help to raise the average temperature of samples, especially the surface temperature of the samples in top layer, because raising the air temperature of the RF cavity reduced heat loss from the top layer. In general, movement, hot air and holding all improved the RF heating uniformity in wood samples

Fig. 10 Comparisons of heating uniformity index (mean ± SD over three replicates) of the wood samples (250 × 400 × 60 mm^3 and moisture content with 13.3% d.b.) after RF heating under different conditions

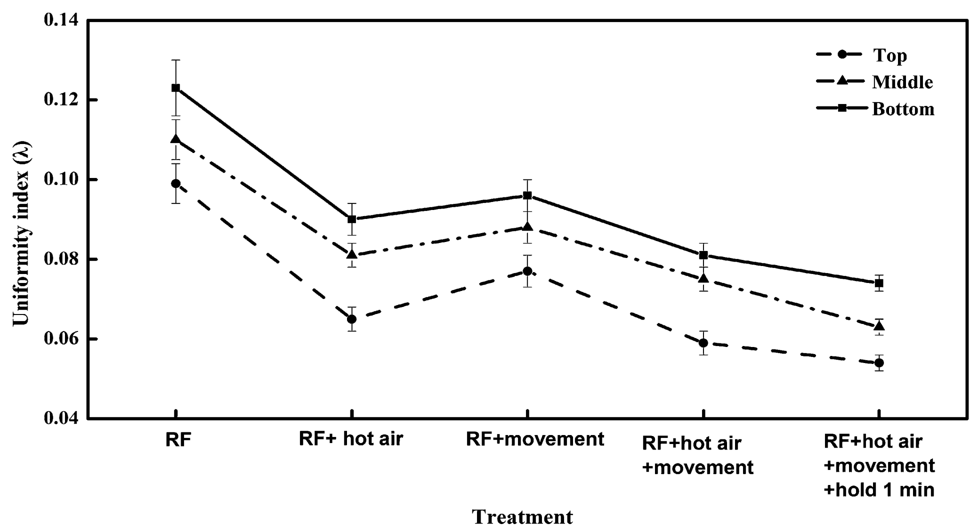

Table 1 Comparison of the temperature and heating uniformity index (mean ± SD over three replicates) of the 400 mm wide wood samples (13.27% d.b.) after RF heating under different conditions

Layers	RF	RF + hot air	RF + movement	RF + hot air + movement	RF + hot air + movement + holding 1 min
Temperature (°C)					
Top	57.22 ± 3.21bB*	58.95 ± 2.18bA	56.03 ± 2.55bB	58.61 ± 2.04bA	58.91 ± 1.83bA
Middle	59.72 ± 3.76aA	60.90 ± 2.91aA	59.01 ± 3.16aA	60.91 ± 2.71aA	60.30 ± 2.24aA
Bottom	60.24 ± 4.24aA	61.65 ± 3.31aA	60.65 ± 3.59aA	61.17 ± 2.94aA	60.84 ± 2.67aA
Heating uniformity (λ)					
Top	0.099 ± 0.005bA	0.065 ± 0.003cC	0.077 ± 0.003aB	0.059 ± 0.003cD	0.054 ± 0.002cD
Middle	0.110 ± 0.005aA	0.081 ± 0.003bB	0.088 ± 0.004aB	0.075 ± 0.003aB	0.063 ± 0.002bC
Bottom	0.123 ± 0.007aA	0.090 ± 0.004aB	0.096 ± 0.004aB	0.081 ± 0.005aB	0.074 ± 0.002aC

*Means followed by different lower case and upper case letters are significantly different at $P = 0.05$ among treatments and layers

Table 2 Quality parameters (mean ± SD over three replicates) of wood samples before and after radio frequency (RF) treatment

Quality parameters	Treatment	Layer		
		Top	Middle	Bottom
MC	Control	0.133 ± 0.004aA*	0.133 ± 0.004aA	0.133 ± 0.004aA
	RF	0.126 ± 0.003aA	0.123 ± 0.005aA	0.124 ± 0.002bA
Modulus of elasticity (MPa)	Control	51.849 ± 9.019aA	51.849 ± 9.019aA	51.849 ± 9.019aA
	RF	52.027 ± 8.844aA	54.767 ± 7.264aA	53.412 ± 9.054aA
Modulus of rupture (GPa)	Control	8.398 ± 1.748aA	8.398 ± 1.748aA	8.398 ± 1.748aA
	RF	8.893 ± 1.641aA	8.023 ± 1.985aA	8.356 ± 0.997aA
Increased checking	Control	0	1	0
	RF	0	1	0

*Different lower and upper case letters indicate that means are significantly different at $P = 0.05$ among treatments and layers

as shown by gradual reductions in the uniformity index value (Table 1). Thus, the optimal heating uniformity was obtained for RF treatment, hot air, movement and holding, which were used for the final treatment protocol (Fig. 10). The uniformity index values in this study were similar to those found for milled rice (Zhou et al. 2015) and almond (Gao et al. 2010), but slightly larger than those found for chestnuts (Hou et al. 2014) and coffee beans (Pan et al. 2012), and smaller than those obtained for walnuts (Wang et al. 2007).

3.5 Wood quality with RF treatment protocol

Table 2 shows moisture content, surface color and checking in the wood samples before and after RF treatment. The moisture content changed mostly between 12.5 and 13.5% d.b. both for control and RF treated wood samples. The moisture was slightly reduced after RF heating, but there were no significant differences between control and RF treated samples ($P > 0.05$) before and after RF treatments in the three layers. The MOR and MOE of wood samples were not significantly different between control and RF treatment ($P > 0.05$). It was observed that no significant difference in the checking of wood samples was found before and after RF treatment. The original number of checking was not changed after RF treatments, resulting in zero increase of checking. The results showed that short treatment times, lower treatment temperature and lower moisture content could be used to reduce RF energy consumption and costs (Stahl and Bentz 2004). Similar results were reported by Biziks et al. (2013) that the morphological structure of wood samples was not significantly changed before and after thermal treatments and by Hansmann et al. (2008) that using high-frequency energy-assisted vacuum drying of fresh wood had low checking.

4 Conclusion

The optimal gap of electrode (120 mm) was determined to develop the RF treatment protocol based on suitable heating rate of 5.17 °C/min. Compared with conventional hot air heating, the RF treatment clearly increased heating rate and had the advantage of volumetric heating through bulk wood samples. The best RF heating uniformity occurred when the lower wood moisture content and width similar to the RF electrode one were applied. The RF heating uniformity was improved by forced hot air surface heating, conveyor movement and holding of the samples due to the reduced heating uniformity index. Based on temperature and time requirements of insect control, a RF treatment protocol was developed with hot air assisted RF heating to 60 °C, conveyer belt movement at 7.4 m/h, and holding at 60 °C hot air for 1 min. Wood quality was not affected significantly by the RF treatments because quality parameters (moisture content, bending properties, and checking) of treated wood samples were similar to those of controls. Therefore, RF treatment provides a practical, effective and environmentally friendly method for disinfesting pine wood. Further research is needed to conduct efficacy tests using infested wood samples based on the developed RF treatment protocol and finally scale up the treatment protocol for industrial applications.

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