Improved Radio-Frequency Heating through Application of Wool Insulation during Phytosanitary Treatment of Wood Packaging Material of Low Moisture Content

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Abstract

The International Standard of Phytosanitary Measures No. 15 (ISPM-15) requires signatory countries of the International Plant Protection Convention to use approved treatment methods on wood packaging materials used in international trade to significantly reduce the risk of spreading alien species. One of the approved methods utilizes dielectric heating (DH) to raise the temperature in the wood to 60°C through the profile of the workload for 1 minute to eradicate pests. To improve the uniform distribution of heat within a wood workload using radio frequency, a form of DH, we tested the use of a wool blanket as a thermal insulation material for wood pallet components. Three species commonly used in the pallet industry—yellow poplar (*Liriodendron tulipifera* L.), northern red oak (*Quercus rubra* L.), and eastern white pine (*Pinus strobus* L.)—of low moisture content were used to generate matched sets of stringer samples. Internal wood temperatures were monitored continuously during treatment to comply with the ISPM-15 schedule. Applying a wool (keratin) insulation blanket increased the rate of heating, improved heating uniformity throughout the workload, and reduced moisture loss compared to uninsulated controls for some wood species, but not all. These findings were most significant for pallet materials with higher moisture content and more permeability (white pine and yellow poplar). By reducing treatment time, power consumption costs can be reduced using wool insulation when implementing the ISPM-15 DH treatment schedule.

Introduction

Dielectric heating (DH) methods using electromagnetic field (EMF) energy applied by microwaves or radio frequency (RF) have been approved for several years as more rapid sanitation methods for solid wood packaging in the revised International Standard of Phytosanitary Measures No. 15 (ISPM-15, Annex 1; FAO 2018). ISPM-15 requires signatory countries to treat all solid wood packaging using an approved method to mitigate the spread of infesting pests.

During RF processing, internalized moisture movements can develop very rapidly due to the spontaneous EMF interactions throughout the volumetric wood load, leading to potential reductions in heating uniformity. It is especially problematic for mixtures of wood materials with differential moisture contents or relative permittivity that can adversely prolong the required treatment duration. To address this problem, rigid foams (expanded polystyrene or polyurethane) sheets are often used above and below the RF electrode applicators as thermal insulation barriers. The use of foam is common in DH applications to improve heat retention by controlling conductive heat loss within larger bulk volumes, typically for batch treatments. Avramidis

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(2012) investigated the use of low-dielectric-coefficient polystyrene and polyethylene as heat enclosure sheets to help prevent conductive thermal losses and reduce loss of thermal energy to the surrounding air. However, testing was performed only on a single piece of RF-treated material to optimize RF effectiveness to sterilize green wood sections.

Our study examined the potential of using thermal insulation blanketing as a method to control heat dissipation that can result from the effects of conductive core heat energy transfer with subsequent surface evaporative cooling during RF phytosanitary treatments. More uniform workload heating with better heat retention reduces treatment time to reach the ISPM-15 temperature requirement, which is a critical factor in reducing energy consumption during RF treatment to render this technology economically competitive with conventional heating. A technical review of the available literature revealed that keratin (natural) wool exhibits favorable dielectric permittivity properties during moisture state changes (Algie and Gamble 1972). We hypothesized that a wool blanket could act as a low-cost, durable, and flexible thermal wrap that could be applied to an array of wooden pallet components during phytosanitary DH treatments using continuous equipment conveyance or an indexed-type RF oven system to improve heat retention in the workload. We chose wool for this experiment because it provides a highly effective insulation barrier that retains heat even after the advent of moisture adsorption. The intrinsic qualities of keratin wools are well established and often superior to many synthetic or natural fabrics such as cotton that suffer a significant decline in thermal resistance due to water infiltration (Akcagun et al. 2017). Synthetic polymeric fiber barriers often lack the ability to absorb water vapor compared with the same moisture-wicking capacity of wool fabrics. As an unwanted consequence, water vapor release will condense beneath a nonwicking surface and could result in sufficient liquid accumulation that might increase the risk of an RF electrical arcing problem.

For this study, we tested the use of a wool blanket (90% keratin wool and 10% unknown woven fiber content) as an insulation barrier over a workload of wood pallet (stringer) materials during RF operational treatment in compliance with the ISPM-15 DH schedule of a minimum temperature of 60°C for one continuous minute throughout the entire profile of the wood, including its surface. In comparison to an uninsulated control workload, we hypothesized that wool insulation would (1) improve heating uniformity and reduce treatment time and (2) minimize the percentage of water loss from the treated wood (maintain original green moisture content).

Materials and Methods

Processing of treatment samples

For this study, we tested the benefits of using an insulating blanket during RF treatment using a range of green-moisture-content hardwood and softwood species that are widely used by the pallet industry. We obtained freshly sawn cants of three commonly used pallet species—yellow poplar (*Liriodendron tulipifera* L.), northern red oak (*Quercus rubra* L.), and eastern white pine (*Pinus strobus* L.)—to generate pallet stringer samples for the wool insulation treatments and controls. Each 10.16 by 15.24-cm cant (2.75 m long) was cut into 48.26 by 3.81 by 10.16-cm pallet material stringers. Processing of the cut-to-size samples was carefully conducted by resawing the original cants to recover the straight-grained heartwood pieces and removing large knots. The rough-sawn stringers were planed to obtain uniform thickness to permit a tight array during treatment with minimal interlayer air gaps. We sorted the samples to minimize the content of wood with dielectric dissimilarities by excluding sapwood (higher green moisture) pieces to maximize heartwood with similar chemical extractives (notably the softwood species) that otherwise could cause altered dielectric properties (e.g., ε^1 and ε^2; Torgovnikov 1993). Each cant was utilized to prepare paired control and wool-insulation treatment samples of similar density. We removed pieces with heartwood deterioration caused by fungal wood decay, which can affect RF permittivity heating properties (Hakam et al. 2017).

Specimens were double wrapped in polyethylene bags and stored at –4°C to maintain the original green condition (above the fiber saturation point, i.e., more than 30% wood moisture content). Prior to the trials, specimens were conditioned for a minimum of 48 hours in an environmental chamber at 25°C so that all specimens started at a constant ambient temperature. Thermal ambient conditioning is essential in a well-controlled experimental design due to the temperature dependence of wood dielectric properties (James 1975). Because moisture content was not identical among all paired sets of material (matched sets of control and wool treatments) in the stacked array within a workload, orthogonal dielectric properties within the array were randomized throughout the workload rather than by randomizing the individual pieces. There were nine individual stringer pieces in each RF trial and the experiment was replicated 10 times. We performed 10 control and 10 wool-insulation RF treatment cycles for each of the three wood species, thus there were 60 treatment cycles in total.

Workload preparation

To prepare samples for insertion of fiber optic temperature probes, we drilled specimens to 5.08-cm depths at midlength and 2.54 cm from the top surface for insertion of the fiber-optic probes (Neoptix Model T1S-03-W-PR17 thermal sensors) to continuously monitor the core temperature profile (Fig. 1). Kerf cuts were made to facilitate probe placement throughout the array. The experimental materials were arranged in a three by three workload heating array when placed in the RF oven. Fiber-optic probes were inserted in individual specimens, and wood stacks were loosely covered with a thin (~3-mm) wool fiber blanket for the insulation trials. A secondary electrode with a winged surface plate (attached 1.9-cm diameter rod) was placed over the workload for both insulated and noninsulated (control) trials to minimize edge DH effects. Secondary electrodes provide for modulation of field strength intensity from the active primary oven applicator to aid in heating uniformity within the workload. After all probes recorded the target temperature of 60°C, the specimens were kept inside the oven for 2 minutes to ensure compliance with ISPM-15 (60°C for 1 min).

To compare the efficacy of 100 percent wool to recycled wool blends containing other fiber contents (type of material undisclosed by manufacturer), we conducted preliminary RF tests on a single hardwood species, white ash (*Fraxinus*

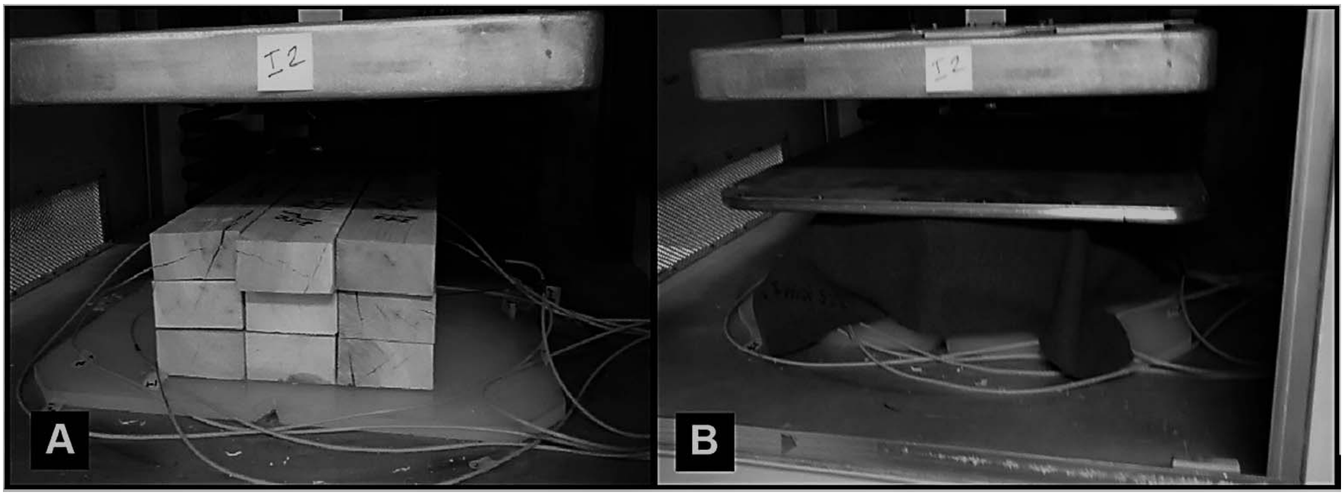

Figure 1.—Photograph of assembled stringer pieces into three-by-three bundles (treated workload array) on the bottom electrode table inside the PSC radio-frequency oven chamber. (A) control, (B) wool insulation. The fiber-optic thermal probes were installed in each stringer connected to a multichannel data acquisition Neoptix Model T1S-02-W15-PR-15 with a personal computer recording system for temperature monitoring.

americana L.), that was processed in the same way as the three species referenced above. This allowed us to observe heating behavior using insulation to select the experimental power density we should use for treatments. Preliminary results showed no overheating of insulation material using 90 to 100 percent wool layering. The wool remained near ambient temperature while the temperature of the underlying wood surfaces adequately increased. Blankets composed of nonwool fiber content greater than 10 percent showed evidence of selective heating; thus, we used a minimum of 90 percent wool for subsequent experiments.

Kerf-cut wood specimens were weighed before treatment to determine mass-to-volume ratio of each workload to allow us to calculate power density (kW/m^3). Individual pieces were reweighed within a few minutes posttreatment to determine water loss and calculate original green wood moisture content using standard ASTM D 4442 procedures (oven-drying method) (ASTM 2010).

Operation of RF unit and monitoring temperatures

For all experiments, we used a custom RF unit (PSC, Inc., Model No. PP15L) with 15 kW maximum power and 19 MHz dielectric oscillator frequency. At 19 MHz, this dielectric oven unit is similar to the 13.56 and 27.12 MHz-frequency commercial RF tunnel-design units used by the industry. This RF functional design restricts power management based on oscillatory equipment technology compared to the more modern 50-Ω amplifier RF heating system (Awuah et al. 2015). This PSC unit has a wood-loading chamber with an adjustable top electrode, which provides impedance calibration for RF field power application. Actual power input was controlled by calibrating the air-gap space of the top electrode over the assembled wood to balance oven voltage with amperage strength of oven impedance with the experimental workload. Impedance calibration was done with the wool draped over the wood array (see Fig. 1B). We recorded the appropriate adjusted air-gap distance to achieve a similar plate amperage strength (RF operator operation tuning), which was 14 cm. This height of opening was close to the target wood array thickness. However, this large air gap can create some incident wave reflection as a power loss factor. The same air-gap height was held constant for all experimental trials.

Temperatures inside the wood were continuously monitored and recorded at fixed intervals using Neoptix fiber-optic sensors with a multichannel data acquisition system (model T1S-02-W15-PR-15). Temperature sensors were factory calibrated and rechecked before experiments using a boiling water bath and a standard laboratory thermometer. Data logging was optimized for the automated multiple-channel Neoptix sensor data collection system using Neo-Link software provided by the sensor manufacturer. The fiber-optic sensors do not interact with electromagnetic fields, have a short response time, and range up to several meters in length without affecting the accuracy of the measurement (Guan et al. 2015).

We heated the wood specimens for a minimum of 15 minutes or until all the probes reached 60°C and continued to monitor temperatures for at least 1 minute to ensure compliance with the ISPM-15 DH schedule. We treated control specimens with similar power settings (Table 1), but without the wool blanket cover. After all the probes recorded the target temperature of 60°C, we kept the specimens inside the treatment chamber for 2 minutes to ensure compliance with ISPM-15 requirements (60°C hold for 1 min).

Data collection and analysis

We weighed the specimens before and after treatment for moisture-loss calculations. Then we cross-cut them near the temperature measurement points using a radial arm saw and processed the samples for moisture content measurements as per ASTM-D4442 (ASTM 2007; Table 2). During treatment, we recorded or calculated several RF heating parameters, including time to achieve 60°C in all the probes of a workload stack (T_{60}), the difference between initial and final temperature (ΔT), and heating rate ($\Delta T/\Delta t$) calculated as ΔT divided by treatment time (Δt) expressed in °C/min. To determine if wood species and/or treatment were

Table 1.—Mean ± SE values for operational power (P) and calculated specific power density (SP) during radio-frequency treatment with or without (control) wool insulation.

Species	Control		Insulation	
	P (kW)	SP (kW/kg)	P (kW)	SP (kW/kg)
Yellow poplar (*Liriodendron tulipifera*)	2.74 ± 0.05	0.27 ± 0.01	2.73 ± 0.08	0.27 ± 0.01
White pine (*Pinus strobus*)	2.36 ± 0.06	0.23 ± 0.01	2.42 ± 0.05	0.23 ± 0.01
Red oak (*Quercus rubra*)	2.25 ± 0.04	0.13 ± 0.00	2.27 ± 0.03	0.13 ± 0.00
Mean for all species	2.45 ± 0.05	0.21 ± 0.01	2.47 ± 0.05	0.21 ± 0.01

predictive of treatment time (T_{60}) we used Cox;s proportional hazards model with wood species and treatment as main effects using JMP v.16.0 (SAS). For determining effects of treatment and wood species on T_{60}, $\Delta T/\Delta t$, and/or percentage moisture loss, we performed full factorial, 2-way analyses of variance (ANOVAs) using log-transformed data due to heteroscedasticity of variances. These analyses were performed in RStudio (version 1.1.463, RStudio, Inc.).

Results and Discussion

RF unit operational power and specific power

RF oven operational power (kW) based on average impedance calibration and specific power density (kW/kg) are shown in Table 1. We monitored voltage and amperage throughout the treatment cycle, and these are reported as the average values of the operational power output for individual wood species. We maintained similar specific power density for the treated mass volume for both control and insulation trials. There were minimal differences in the adjusted power densities (mass to volume) among the experimental trials. Also, power density could not always be managed at a constant value between the control and insulation treatment trials within a wood species due to the disparity in wood permittivity among individual wood specimens. Softwoods, especially white pine species, tend to exhibit greater longitudinal and transverse RF permeability compared to more refractory hardwood species (Hansmann et al. 2002). Further, power density may vary slightly with impedance changes due to alteration of the wood temperature-dependent complex dielectric properties that occur during a DH cycle. Power applied during the experiments varied from 2.25 to 2.74 kW; however, specific power density was consistent for all the species with the standard error up to ±0.01 kW/kg.

Treatment time to achieve 60°C (T_{60})

Monitoring of the fiber-optic probes showed that all wood pieces met the ISPM-15 DH schedule of 60°C maintained for at least one continuous minute through the profile of the workload (T_{60}), at which time the power was shut off. In some instances, maximum wood temperatures were retained longer throughout the stringer array with the wool application after the power cycle terminated. Cox's proportional hazards model showed that both wood species and wool treatment strongly influenced T_{60} (model $\chi^2 = 78.8$, df = 3, $P < 0.0001$; effect likelihood ratio tests: species $\chi^2 = 78.3$, df = 1, $P < 0.0001$, treatment $\chi^2 = 5.12$, df = 1, $P = 0.0237$). Two-way ANOVA results indicated that the T_{60} differed significantly between wood species ($F_{2,54} = 151$, $P < 0.0001$) and between the control and wool insulation treatment ($F_{1,54} = 4.63$, $P = 0.0360$), but there was no interaction ($F_{2,54} = 0.97$, $P = 0.3864$; Table 3). The mean ± standard error for time to achieve 60°C was significantly faster (17%) for yellow poplar with insulation compared to controls (13.3 ± 1.1 and 17.9 ± 1.8 min, respectively), but not for red oak or white pine. While the T_{60} for white pine was 26 percent faster with insulation, this difference was not statistically significant.

Observation of DH treatment effect on wood moisture

Percentage of moisture loss (Fig. 2) was significantly affected by treatment ($F_{2,533} = 19.0$, $P < 0.0001$), wood species ($F_{1,533} = 38.1$, $P < 0.0001$) and their interaction ($F_{2,533} = 3.14$, $P = 0.0440$). Percentage of moisture loss was significantly lower using wool insulation compared with the controls for yellow poplar (39% reduction in moisture loss, $P = 0.0002$) and white pine (63% difference, $P < 0.0001$), but not for red oak (32% difference, $P = 0.6545$). These findings represent improvements in retention of wood moisture content with RF treatment, suggesting better treatment process control using wool insulation for two of the three species tested.

Heating rate (T/t) and heating uniformity

Wool insulation ($F_{1,53} = 42.1$, $P < 0.0001$), species ($F_{2,53} = 216$, $P < 0.0001$) and their interaction ($F_{2,53} = 15.8$, $P < 0.0001$) significantly impacted heating rate (Fig. 3). All three wood species heated at different rates, with and

Table 2.—Posttreatment ASTM D 4442 derived moisture content (MC; mean ± SE following radio-frequency treatment with and without (control) wool insulation.

Species	Control MC (%)	Insulation MC (%)
Yellow poplar (*Liriodendron tulipifera*)	27.0 ± 0.5	25.2 ± 0.5
Red oak (*Quercus rubra*)	36.7 ± 0.7	39.6 ± 0.4
White pine (*Pinus strobus*)	36.6 ± 0.3	35.8 ± 0.8
All species	33.6 ± 0.4	33.9 ± 0.5

Table 3.—Mean ± SE treatment time (T_{60}) for each wood species in minutes during radio-frequency treatment. *P* values are for means comparisons between treatment and control.

	Treatment time		
	Red oak	Yellow poplar	White pine
Control	47.5 ± 1.80	17.9 ± 1.8	24.7 ± 2.96
Wool	47.2 ± 2.62	13.3 ± 1.07	19.4 ± 1.26
P value	0.9311	0.0333*	0.1167

* Significant difference ($P < 0.05$).

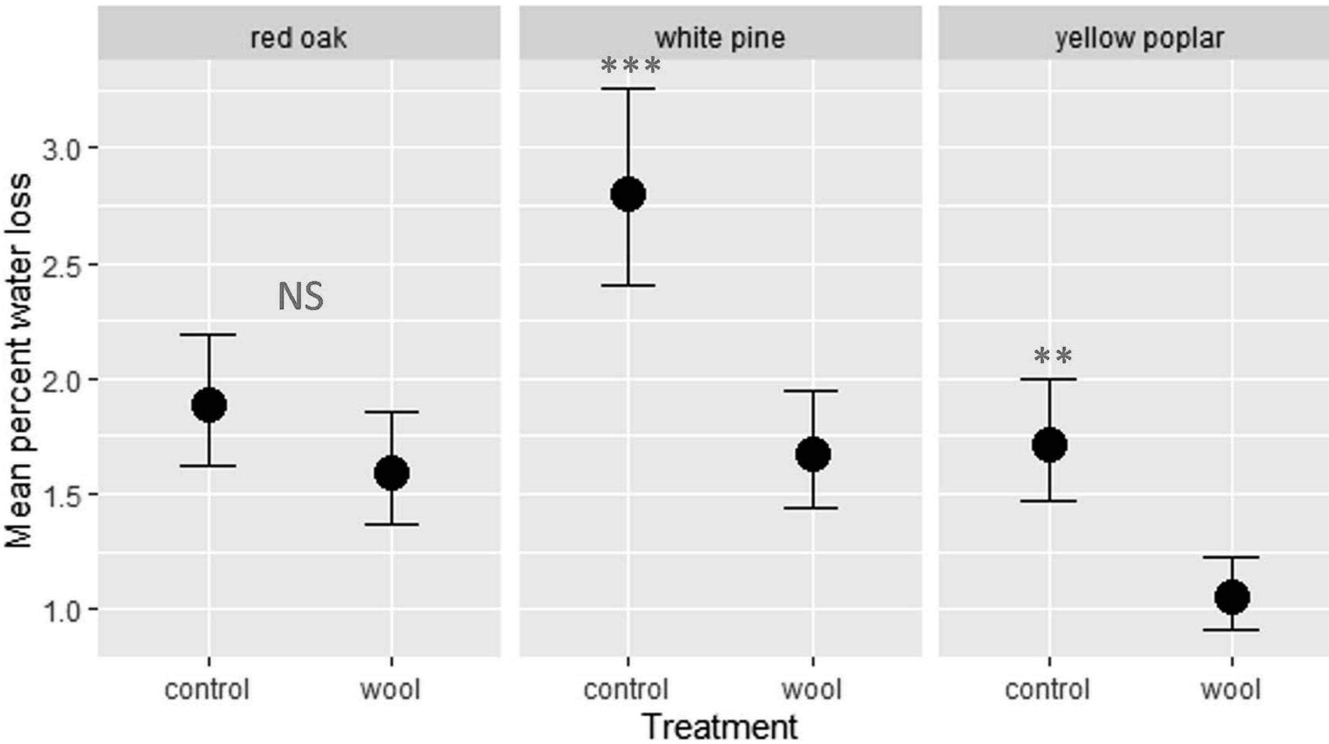

*Figure 2.—Mean percentage moisture loss during radio-frequency treatment with or without wool insulation by wood species. Bars represent standard error of the mean. **= P $<$ 0.001; ***= P $<$ 0.0001; NS = not significant.*

without wool insulation. Insulation of the workload doubled the heating rate for white pine, from 1.54 ± 0.09°C/min to 3.14 ± 0.26°C/min compared with the control (Fig. 3; $P < 0.0001$), but the difference between the treatment and control was not significant for red oak ($P = 0.9842$) or yellow poplar ($P = 0.5389$).

Temperature response in a white pine workload during RF high-power heating using wool insulation compared

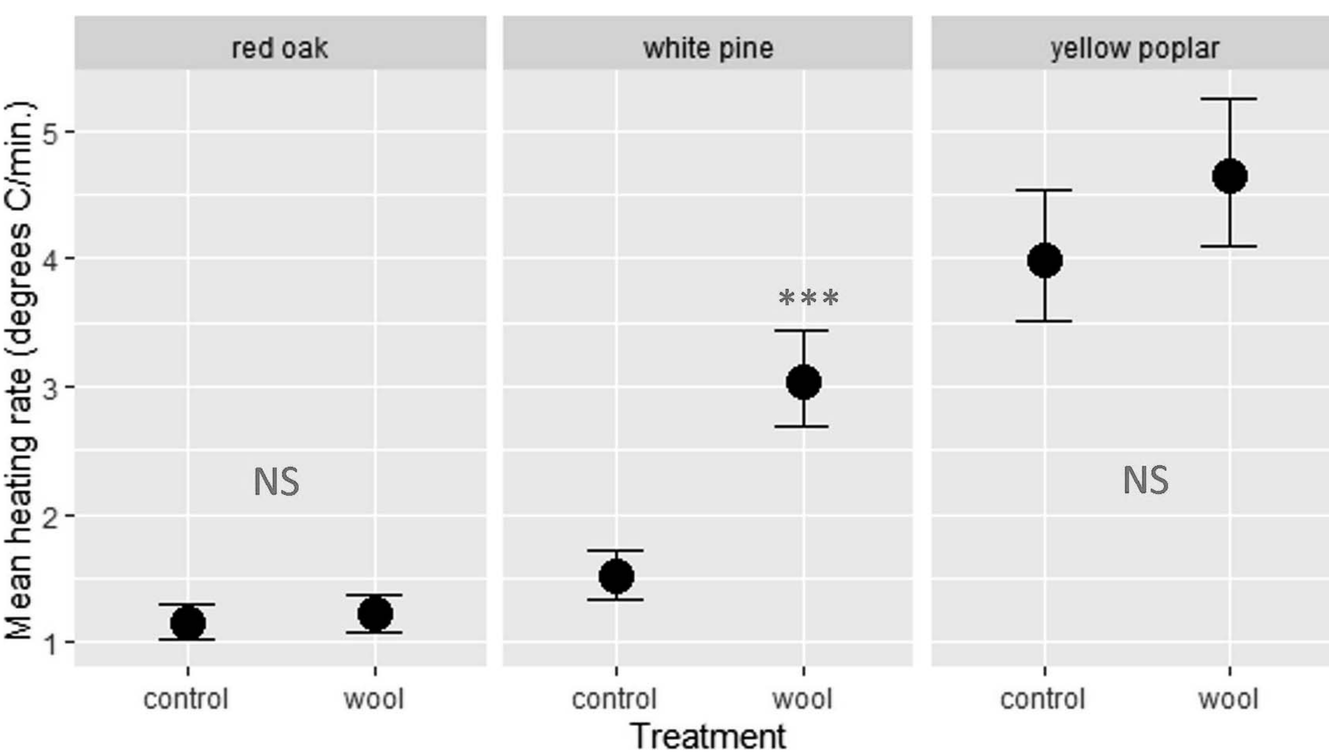

*Figure 3.—Mean heating rate during radio-frequency treatment with or without wool insulation by wood species. Bars represent standard error of the mean. ***= P $<$ 0.0001; NS = not significant.*

with the uninsulated control is highlighted in Figure 4. Note that the wool insulation treatment required less time for the wood temperatures to meet or exceed the requisite 60°C and resulted in greater thermal uniformity, creating a more linear and predictable heating response. Under nearly identical specific power, the wool blanket treatment minimized potential deleterious effects on material strength and stiffness properties due to excess temperature buildup (>100°C) in the workload.

Lower thermal variability between workloads improves the heating quality control process and can increase heating rate and reduce moisture content loss. Also, this simple wool application treatment may help to reduce the number of fiber-optic probes required to adequately monitor temperatures in the workload during an operational treatment cycle.

A limitation of our study was that all wood specimens had moderate to very low initial moisture content, especially yellow poplar at 26 to 27 percent (Table 2). The moisture contents of green heartwood for yellow poplar, white pine, and northern red oak are described in the literature as ~83 percent, ~62 percent, and ~80 percent, respectively (FPL 1987). It is likely that the reduced moisture content resulted from extended log storage at the sawmill. These wood materials may have experienced less heat dissipation during testing, resulting in lower free-moisture movement, which may have impacted our ability to realize the full benefit of the wool application treatment for all metrics for white pine and yellow poplar. Tang et al. (2005) and Marra et al. (2009) point out that water content is a dominant factor affecting moist materials; dielectric properties. Material conductivity exposed to dielectric electromagnetic fields is significantly affected by the concentration of free and bound water contents (Figura and Teixera 2007). Northern red oak generally has lower moisture movement related wood permeability compared to the other wood species used in this study due to lower porosity or liquid to material flow properties.

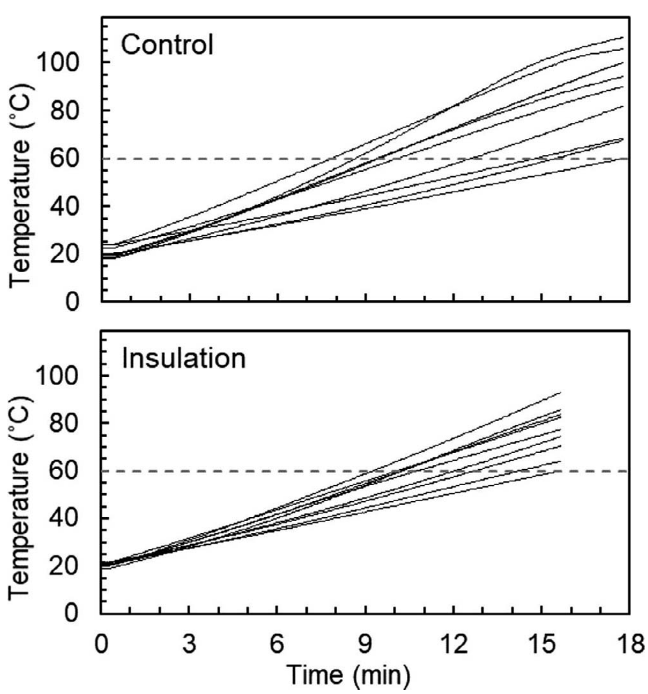

Figure 4.—Temperatures recorded by fiber-optic probes during treatment of white pine using wool insulation over the workload compared with the uninsulated control.

The intrinsic qualities of keratin wool are well established and often superior to many synthetic (polyester) or other natural (cotton) fabrics that suffer a significant decline in thermal resistance to water infiltration (Akcagun et al. 2017). Synthetic polymeric fiber barriers often lack the ability to absorb water vapor compared with the moisture-wicking capacity of wool fabrics. As an unwanted consequence, water vapor released from wood will condense underneath a nonwicking surface and can result in sufficient liquid accumulation to possibly increase the risk of an RF electrical arcing problem. A technical review of available literature reveals that natural keratin wool substances exhibit favorable dielectric permittivity properties with respect to moisture state changes (Algie and Gamble 1972). Alternately, use of synthetics that differ in their electric power storage (ε^1 relative dielectric constant) and thermal energy development (ε^2 relative loss tangent) relative to wood could result in excessive selective heating. This would promote insulation material deterioration, or worse, alter the reflectivity of the RF incident frequency wave that could negatively impact the effective time to reach the end of the treatment cycle. Some synthetic polymerics as a selected insulation material are moderately to completely incompatible with RF exposure and should be strictly avoided for EMF power-density applications (Awuah et al. 2015). Our early work included examining a thin 0.5-mm metalized polyester film as a heat retention barrier, resulting in considerable thermal runaway irrespective of the applied power field intensity. Researchers have noted the issue of selective heating with protective wraps using RF or microwave technology in the food processing industry (Zhao 2006).

In addition to performance, a simple cost analysis highlights a further advantage of selecting wool over synthetic fabric for dielectric insulation. In this study at reduced scale, the wool blanket size (63.5 by 71.1 cm) cost $1.96 USD. When considering that power consumption for yellow poplar was 2.74 and 2.73 kW for control and insulation trials, respectively (Table 1), and factoring in a treatment time reduction of 4.6 minutes along with an average US electricity cost at 7 cents/kWh (EIA 2021), the power savings per treatment cycle equals 1.49 cents (a 25.7% reduction) in processing cost reduction. Over time, using bulk treatment for large-scale industrial applications, this reduction in energy costs would be significant. Wool blanketing is widely available from many supply sources and is generally considered inexpensive relative to synthetic fabrics. Additional considerations for properly evaluating and integrating dielectric insulation for commercial use include specific knowledge of the type of wood species and scaled-up treatment array that would be treated along with more specifics on the industrial RF equipment capacity design, including operational power input density.

Conclusions

Wool or natural keratin-based fibers in the form of a woven fabric blanket provided highly effective insulation in retaining heat in the wood workload for lower-density-permeability wood species, even after the advent of moisture adsorption. In wool insulation tests, the heating rate was doubled for white pine. In comparison, no significant change in treatment time with insulation was observed for red oak or yellow poplar, although moisture loss was significantly reduced for yellow poplar and especially for white pine. While the heating rate ($\Delta T/\Delta t$) was 18 percent faster for yellow poplar, this difference was not statistically significant.

Our results suggest that applying a wool blanket can reduce the total time required to reach the ISPM-15 DH temperature requirement while reducing thermal variability in the workload, especially for higher-moisture and more permeable wood materials. Improvements in DH uniformity were also observed in the reduction in moisture loss levels with insulation, suggesting better control of the treating process. Control over the moisture level in the wood material may be critical if the pallet manufacturer needs to retain original green moisture content to facilitate wooden fastener installation.

Though not investigated here, the beneficial application of wool thermal blankets could be utilized for RF treatment of large bulk volumes to improve ISPM-15 DH processing economics. The improvements in RF efficiency observed here with small stringer arrays may be more significant for large bulk loads with more layers, with the array mass more tightly packed with added air gaps to permit more spontaneous heat exchange for functional thermal energy dissipation.

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