Vacuum–Steam Phytosanitation of Hardwood Pallets and Pallet Stringers

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Abstract

The vacuum–steam treatment of pallets and pallet parts for compliance with the International Standards for Phytosanitary Measures No. 15 regulation was evaluated. Vacuum–steam treatment consists of four steps: (1) vacuum, (2) heating, (3) holding at an increased temperature for a period of time, and (4) cooling. The system produces steam and maintains the saturation or superheated state in a flexible container. Hardwood dry and green pallets (122 by 101.6 cm) and notched stringers (122 cm long) were treated. After the vacuum was drawn, steam was injected into the container to heat the pallets through condensation. The steam was turned off when the center of the pallets or stringers reached 56°C. The stringer parts were treated in three stacking patterns: deadpacked piles of 12, 2, and 5 layers in a stack. Vacuum–steam treatment is significantly faster than conventional convective hot air treatment. The pallets were treated in less than 65 minutes, which included a vacuum time of 5 minutes and a holding time of 30 minutes. The average treatment times of dry pallets were 7.1 and 10.4 percent faster than green pallets at 400 and 665 mbar, respectively. Wood species affected the treatment time. The average treatment time of dry yellow-poplar pallets was 15.9 percent faster than that of dry red oak pallets at 400 mbar. Pressure also affected the treatment duration. The stringers could be successfully treated even when they were arranged in various stacking patterns. The moisture content increased after the treatment, but the change was less than 3 percent for both green and dry pallets.

Wood packaging material has been a vector for the intercontinental movement of pests that threaten forest resources. Over 400 insects that feed on trees and shrubs have been introduced into the United States in the last 200 years primarily through the use of cargo containers in world trade (Haack 2006). Reducing the spread of forest pests is a national and international priority, and the United States along with 133 other countries has been implementing the International Standards for Phytosanitary Measures (ISPM) No. 15 to stop or significantly reduce the spread of wood pests around the globe via solid wood packaging material. ISPM 15 requires solid wood packaging materials including wood pallets and containers used for exporting products to be treated (Food and Agriculture Organization of the United Nations 2002, revised 2009). Approved treatment methods include methyl bromide gas fumigant application and heat treatment in which wood is continuously heated for 30 minutes to achieve a minimum temperature of 56°C throughout the profile of the wood. Vacuum–steam treatment of pallets and other raw wood packaging material is more efficient than the current hot air heat treatment (Chen and White 2012). The mechanism of sanitation is the same as convective hot air heat treatment and thus complies with ISPM 15. Previous research indicates that the higher efficiency of vacuum–steam treatment compared with convection systems is associated with the higher heat capacity of saturated steam Using saturated steam under vacuum, treatment temperatures are well below 100°C, which reduces the potential effect of high temperatures on the structure of treated wood commodities (Chen and White 2012).

Literature Review

Chen et al. (2006) has demonstrated the efficacy of vacuum alone to kill wood-boring beetles (*Hylotrupes bajulus* and *Monochamus* spp., Coleoptera: Cerambycidae) with a 24-hour treatment at 20 mm Hg in wood at a moisture content (MC) less than 24 percent. However, treatment

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cycles depended on the MC of wood. The higher the wood MC, the longer the treatment cycle, and larvae died due to desiccation rather than suffocation. The lethal percentage of total body weight loss for Asian longhorned beetle (*Anoplophora glabripennis*) and emerald ash borer (*Agrilus planipennis*) was approximately 30 to 40 percent. The desiccation rate for both types of larvae under vacuum in inoculated wood was constant until death. Different larvae exhibit different desiccation rates, and the desiccation rate is positively correlated with temperature. At higher temperatures, larvae lose weight faster than at lower temperatures (Chen et al. 2008). Chen et al. (2007) has concluded that low pressure also kills pine wood nematodes in naturally infested pine wood.

This previous vacuum research led us to consider combined vacuum and steam treatment for wood packaging materials for compliance with the heat treatment criteria in ISPM 15. Vacuum can be used to lower pressure inside the wood. When steam is added, the steam pressure is higher than the pressure inside the wood. According to Darcy's law, vapor is rapidly transferred due to a total pressure difference and the amount of moisture transferred is directly proportional to the permeability. Water vapor condenses and changes into liquid water during the vacuum–steam treatment. Large amounts of heat are released to the wood and this rapidly increases the temperature of the wood. Vacuum–steam treatment is fundamentally different from the conventional heat kiln treatment. In vacuum–steam treatment, water vapor is used as the medium to exchange the heat rather than air, which is used in the conventional kiln. This has many advantages. First, water vapor allows both more heat and faster heat transfer by means of condensation, which is exothermic. Second, using water vapor rather than air results in less energy loss because treatment time is short and less energy is lost through conduction. Third, the use of hot air causes evaporation, which is endothermic and requires additional energy to compensate for the associated cooling. With the use of steam, no evaporation occurs. Also, in the conventional heat kiln, the air must be heated to a temperature above 56°C and discharged into the atmosphere. Saturated steam can be used at lower temperatures and still increase temperatures to the required level inside the wood. Fourth, treatment quality is good, and wood has a brighter color after treatment due to less oxygen being present inside the container (Simpson 1991). Also in a conventional hot air treating system, green pallets may develop splits during the initial phase of treatment because the relative humidity inside the chamber is low and lumber loses moisture rapidly at the end grain, leading to stresses that split wood.

Preliminary studies indicated the steam–vacuum treatment cycle times are less than half those of current ISPM 15 HT (heat treatment) hot air treatment methods and energy consumption is 25 percent less (Chen and White 2012). The process can be easily tailored to different treatment capacities. A system can be designed to be easily portable, and the technology can be adapted to a rigid or flexible chamber system.

Objectives

The primary goals of this project were to evaluate a flexible vacuum chamber and to determine whether the vacuum–steam phytosanitation treatment process was a faster and more flexible alternative to convective heat treatment systems. Specifically, we aimed to determine (1) the ISPM 15–compliant, vacuum–steam treatment time for wood pallets and stringer parts, and (2) the effect of vacuum levels and other factors on steam–vacuum treatment time.

Testing Equipment

The system consisted of a vacuum source (vacuum pump), flexible vacuum chamber, steam generator, and steam controller (Fig. 1). Monitoring devices were used to record temperatures within the flexible container and the treated materials. The steam boiler supplied the steam to the container. A flexible vacuum container made of high tenacity woven fabrics, coated and impregnated with polyvinyl chloride compounds, was used as the test chamber. The rectangular, pillow-shaped, flexible chamber measured 11 by 10 feet (Fig. 2). The flexible chamber was able to treat 20 pallets or parts to assemble 100 pallets.

A 45-kW steam boiler (CAM Industries Inc., model 12S) was used to supply the steam. The steam boiler was controlled to maintain the desired temperature. An R5 single-stage, oil-sealed, rotary vane, air-cooled direct drive vacuum pump (Busch Inc.) was used to remove air from the flexible container. The pump displacement capacity was 0.57 m^3/min (20 ft^3/min). As treatment continued, vapor was compressed and discharged into the exhaust box.

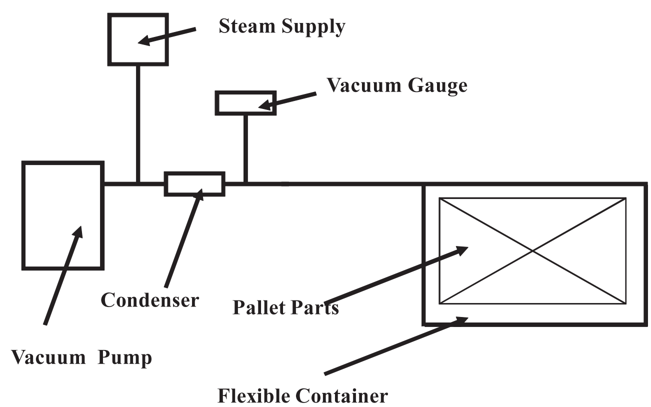

Figure 1.—Schematic diagram of the vacuum–steam treating system.

Figure 2.—Collapsed flexible container after vacuum was applied to the system.

Vapors then passed through several stages of internal oil and mist eliminators to remove 99.9 percent of lubricating oil from the exhaust. Separated oil was returned to the oil reservoir. A built-in gas ballast permitted pumping with high water vapor loads and provided oil drying for maximum performance. An HPM-760 Plus Controller vacuum gauge (Teledyne and Hastings Co.) was used to monitor the vacuum within the flexible container. An air-cooled CC-65 condenser (Neslab Corp.), a mechanical refrigeration system using a single stage with one compressor, was used. Its operating temperature range was –20°C to –55°C, and it had the capacity to remove 120 W of heat at –20°C. Power consumption was approximately 440 W. The cold trap was used to condense and collect the water vapor from the wood.

Testing Materials

Dry and green pallets

Both dry red oak and yellow-poplar 122 by 101.6-cm (48 by 40-in.) pallets were used in this study. The MCs of the wood in the dry pallet varied from 6 to 15 percent. Green mixed hardwood 122 by 101.6-cm (48 by 40-in.) pallets made of hickory, hackberry, and gum were also treated in this study (Table 1). These pallets were manufactured at Pallet One Inc. (Mocksville, North Carolina).

Green pallet stringers

Green yellow-poplar stringers were obtained from Turman Lumber Co. (Christiansburg, Virginia), a regional pallet manufacturer. The sizes of stringers were 8.57 cm (3.375 in.) by 3.49 cm (1.375 in.) by 121.92 cm (48 in.).

Experimental procedure

The MCs of green pallets and stringer parts were measured using the ovendry method covered in ASTM D4442 (ASTM International 2007), and the MCs of the dry pallets were measured using electric moisture meters. After the MCs of samples were measured, holes 50.8 mm deep and 3.6 mm in diameter were drilled into the stringer ''foot'' in order to measure the center temperatures during the tests.

The pallets or stringers were loaded into the flexible container (Fig. 2) and thermocouples (OMEGA, TT-K-24-SLE, diameter 0.51 mm) were inserted into the holes (50.8 mm deep), which were then sealed with plumber putty to prevent the steam from reaching the thermocouple through the holes. The flexible container was zipped closed and vacuum was applied to the test pressure inside the container. After the test pressure was reached, the vacuum pump was stopped and steam was injected into the container. After the temperature inside the chamber reached 80°C, steam injection was slowed to maintain 80°C. When the core temperature of the pallet stringers or stringer parts reached 56°C, steam injection was stopped. The container stayed closed and the internal temperatures of pallets and parts were held at or above 56°C for at least 30 minutes, at which time the treatment cycle was considered complete. The MC of pallets and parts was measured after treatment. During the test, the temperatures inside the flexible chamber, at the pallet or part center and at the pallet or part surface, were recorded every second.

Eleven pallets were treated at a pressure of 500 mm Hg (667 mbar) and 250 mm Hg (333 mbar) each. The test was repeated 10 times for both dry and green pallets. The same treatment temperatures were used for both pressures.

Eleven pallets were loaded into the flexible container and treated at one time. They were treated at a pressure of 300 mm Hg (400 mbar) and a temperature of 80°C. Figure 2 shows the vacuum chamber with pallets under the vacuum.

The stacked stringers were treated at a pressure of 250 mm Hg (333 mbar) and temperature of 80°C. Table 2 indicates the stack pattern and number of replicated tests. There were three stacking patterns: (1) 12 layers deadpacked, (2) every two layers deadpacked, and (3) every five layers deadpacked (Fig. 3). Deadpacked means no spacers or stickers separated the lumber. These are typical commercial stringer-stacking patterns. The temperatures were measured at three locations: inside center, inside edge, and at the surface of the stack. The tests were repeated for each stacking pattern (Table 2). The MCs of stringers were measured before and after treatment.

Table 1.—Specification of the green and dry hardwood test pallets consisting of stringers and deckboard.

Part	No.	Size (in.)	Notch
Stringer	3	1.375 × 3.375 × 48	Standard
Top deck	2	0.625 × 5.875 × 40	
	5	0.625 × 3.500 × 40	
Bottom deck	2	0.625 × 5.875 × 40	
	3	0.625 × 3.500 × 40	

Results and Discussion

The experimental results are summarized in Table 3. Figure 4 represents a typical temperature profile from the vacuum–steam treatment of dry yellow-poplar pallets at a pressure of 300 mm Hg. All pallets exhibited a similar profile. Total treatment time included vacuum, steam, and

Table 2.—The stack pattern and number of repeated tests.

	No. of stacks in the container	No. of layers in a stack	No. of stringers in a layer	No. of tests repeated
Deadpacked pile	1	12	12	5
Two-layer	5	2	12	7
Five-layer	3	5	12	6

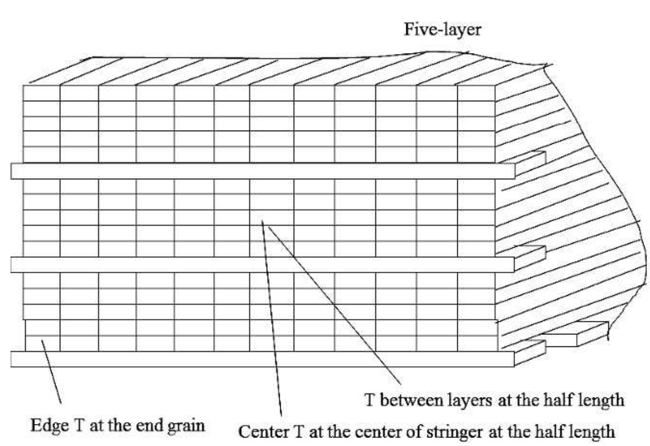

Figure 3.—Five layers and 12 pieces in a layer stacking pattern for treating pallet stringer.

Table 3.—Results of vacuum–steam treatment of pallets and stringer parts to 56°C/30 minutes ISPM 15 criteria.[a]

	MC of wood	Pressure (mm Hg)	Treating temp. (°C)	Avg. vacuum time (min)	Avg. steam time (min)	Avg. wood initial temp. (°C)	Avg. initial temp. inside container (°C)	Avg. total treatment time (min)	SD of total treatment time	Avg. temp. increase rate (°C/min)
Red oak pallets	Dry	300	80	7.0	22.8	14.7	16.6	59.8	1.80	1.8
Yellow-poplar pallets	Dry	300	80	5.6	14.7	16.3	22.4	50.3	3.82	2.7
Red oak pallets	Dry	500	80	3.4	16.9	14.4	19.3	50.3	1.85	2.5
Yellow-poplar pallets	Dry	500	80	3.7	13.6	21.8	25.2	47.4	0.72	2.5
Mixed hardwood pallets	Green	300	80	5.9	22.9	8.7	21.6	58.8	4.96	2.1
Mixed hardwood pallets	Green	500	80	3.8	21.1	7.0	22.8	54.9	1.73	2.3
Yellow-poplar stringers										
12 layers/stack	Green	250	85	9.3	173.6	17.0	12.4	212.3	130	0.4
2 layers/stack	Green	250	85	10.4	91.6	16.8	13.0	132.1	43	0.5
5 layers/stack	Green	250	85	15.4	155.9	28.0	15.5	201.3	73	0.2

[a] ISPM 15 = International Standards for Phytosanitary Measures No. 15; MC = moisture content.

hold time. In the test, it usually took about 5 minutes to draw the vacuum to 300 mm Hg (Fig. 4). This corresponds to about 621 mbar (9 psi) of applied stress to the contents of the flexible container. The 56°C at the center of the stringer was reached in about 10 minutes after the chamber reached treating temperature as shown in Figure 4. All pallets were treated between 46.7 and 63.1 minutes. This can be compared with the 2- to 4-hour treatment cycle of pallets in a regular heat kiln (Denig and Bond 2003).

The data in Table 3 indicates that the treating time for pallets is a function of the initial temperature of wood (0°C to 18°C), the wood species, the MC of wood, and the vacuum level.

The dry pallet treatment was faster than the green pallet treatment. The average treatment times for dry pallets were 7.1 and 10.4 percent faster than those for green pallets at 300 and 500 mm Hg, respectively (t test: $P = 0.030$). The average MC of green pallets was 100 percent. The dry pallet was lighter in weight and required less energy to heat.

Wood species affected the treatment time. The average treatment time of dry yellow-poplar pallets was 15.9 percent faster than that of dry red oak pallets of similar design at 300 mm Hg (t test: $P < 0.0001$). Treatment pressure seemed to affect the treatment duration. The results indicate that treatment time was less with 500 mm Hg vacuum than with 300 mm Hg vacuum. Additional testing should further explore this relationship between pressure and treatment time.

The MC of the wood increased slightly during treatment. After treatment, there was an average increase of 2.4 and 2.8 percent for green and dry pallets, respectively. This increase was from steam condensation on the wood surface and some condensation inside the wood.

The treated dry pallets exhibited brighter and cleaner wood surfaces after treatment. The process changed the appearance of the dried pallets' surfaces. The mechanism causing this color change is unclear. This may have positive implications when treating dry used pallets. A more uniform appearance may add value to used or repaired pallets. Little change in appearance occurred when treating green pallets.

The stringers could be treated in various deadpacked stacking patterns. The average MC of the green stringers

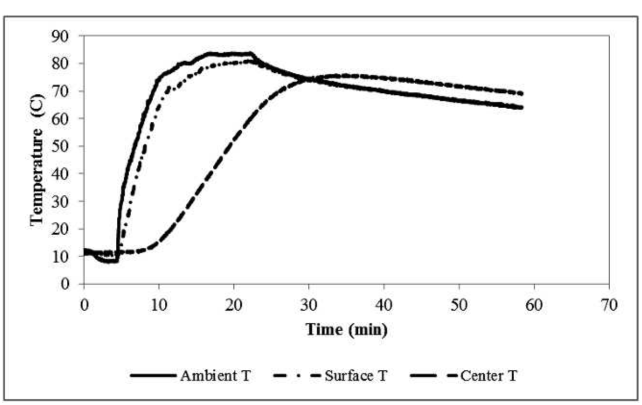

Figure 4.—Typical temperature profile during the vacuum–steam treatment of dry yellow-poplar pallets at the pressure of 300 mm Hg. Ambient T = temperature inside the chamber; surface T = wood stringer surface temperature; center T = wood stringer center temperature.

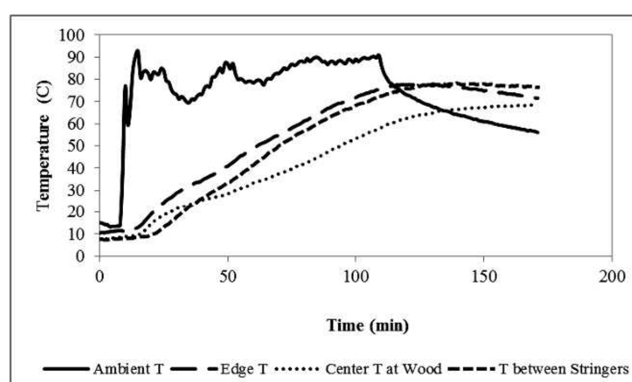

Figure 5.—Typical temperature profile during the vacuum–steam treatment of the deadpacked stringers of two layers of green yellow-poplar pallet parts at 250 mm Hg. Ambient T = temperature inside the chamber; edge T = center temperature of wood stringer located at the edge of stack; center T = center temperature of the wood stringer located at the center of stack; T between stringers = temperature between two stringers at the middle of the stack (see Fig. 4).

was 101 percent. Figure 5 shows a typical temperature profile from the vacuum–steam treatment of the deadpacked stringers of two layers of green yellow-poplar pallet parts at 250 mm Hg. After the chamber reached treatment temperature, it took about 100 minutes to reach 56°C at the center stringer in the stack. As expected, this took longer than when treating pallets. The treatment time depended on the stacking methods and varied from 90 minutes for double-layer stringers and as long as 409 minutes for the 12-layer stringers. The treatment time for the green stringers varied considerably. One reason could be that there were different initial ambient and stringer temperatures during each test. In the first treatment of each stacking pattern, all stringers started at the same relatively cool temperature. However, only the probed stringers were replaced for the subsequent tests, and the stringers already inside the flexible container from the previous tests were relatively warm.

Conclusions

1. Dry pallets were vacuum–steam treated in less than 65 minutes, which included a vacuum time of 5 minutes and a holding time of 30 minutes.
2. Dry pallet treatment was faster than green pallet treatment. The average treatment times for dry pallets were 7.1 and 10.4 percent faster than those for green pallets at 300 and 500 mm Hg, respectively.
3. Wood species affected the treatment time. The average treatment time of dry yellow-poplar pallets was 15.9 percent faster than that of dry red oak pallets at 300 mm Hg.
4. Treatment pressure affected the treatment duration.
5. Stringers could be successfully treated even when they were stacked in various patterns. The treatment time depended on the stacking pattern and varied from 90 to 409 minutes.
6. The MC of pallets increased after the treatment. The average MC change was less than 3 percent for both green and dry pallets.

Literature Cited

ASTM International. 2007. Standard test methods for direct moisture content measurement of wood and wood-base materials. Standard D4442. ASTM International, West Conshohocken, Pennsylvania.

Chen, Z. and M. S. White. 2012. Development of a highly efficient steam and vacuum phytosanitation treatment for solid wood packaging materials. Report submitted to Wood Education and Resource Center, US Forest Service, Princeton, West Virginia. 53 pp.

Chen, Z., M. S. White, J. Eisenback, and T. M. Poland. 2007. Evaluation of the efficacy of vacuum treatment for the control of emerald ash borer and pinewood nematode in naturally infested wood. Report submitted to Wood Education and Resource Center, US Forest Service, Princeton, West Virginia. 21 pp.

Chen, Z., M. S. White, M. A. Keena, T. M. Poland, and E. L. Clark. 2008. Evaluation of vacuum technology to kill larvae of the Asian longhorned beetle, *Anoplophora glabripennis* (Coleoptera: Cerambycidae), and the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae), in wood. *Forest Prod. J.* 58(11):87–93.

Chen, Z., M. S. White, and W. H. Robinson. 2006. Preliminary evaluation of vacuum to control wood-boring insects in raw wood packaging materials. *Forest Prod. J.* 56(7/8):21–25.

Denig, J. and B. Bond. 2003. Heat sterilization of hardwood pallets and pallet material. Pallet Phytosanitary Project Technical Report No. TP-1. The Limestone Bluffs Resources Conservation and Development Area and the Wood Education and Resources Center, Raleigh, North Carolina. 8 pp.

Food and Agriculture Organization of the United Nations (FAO). 2009. Regulation of wood packaging material in international trade. Revision of International Standards for Phytosanitary Measures (ISPM) 15. International Plant Protection Convention, FAO, Rome.

Haack, R. A. 2006. Exotic bark- and wood-boring Coleoptera in the United States: Recent establishments and interceptions. *Can. J. Forest Res*. 36:269–288.

Simpson, W. T. 1991. Dry kiln operator's manual. Agriculture Handbook 188. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 274 pp.