Investigation of Vacuum and Steam Treatments to Heat Treat and Sanitize Firewood-Grade Ash Logs and Ash Firewood

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Abstract

The goal of this project was to investigate the efficacy of vacuum–steam technology to sanitize low-quality ash logs and ash firewood. It is difficult to heat treat logs and firewood because of the relatively large cross-sectional dimension. Compared with hot air, steam has a greater heat capacity, and the condensation, without reducing the moisture content of wood, results in more efficient heat transfer. Also, the pressure gradient created by the vacuum accelerates heat transfer through the wood cross section. The vacuum–steam system consists of a vacuum source, a controlling device, a flexible container, and a steam generator. The white ash logs and firewood were harvested in Montgomery, Virginia. Ash log diameters ranged from 16.5 to 27.9 cm on the small end. The logs were cut into lengths of 1.82 m. After the vacuum was drawn to 300 or 500 mm Hg inside the container, steam was injected into the container. The steaming continued until 56°C was reached at the center of the lengths. The treatment time for all the logs varied from 5.5 to 14.5 hours, including a vacuum and a holding time of 30 minutes. The 1.82-m logs were cut into 40.6-cm-long bolts and then split into firewood, rarely larger than 15.2 cm on the wider side. The treatment time for firewood varied from 80 to 137 minutes, including a vacuum and a holding time at 56°C for 30 minutes at the core. There is no effect on quality, and the process can be tailored to different treatment capacities and is easily portable.

Foreign invasive forest pests have damaged forest ecosystems and affected forest utilization. Fungi, nematodes, or insects introduced through the importation of logs, lumber, and solid wood packaging have infested forests in North America (Fleming et al. 2005). The resulting loss of forest seriously impacts water quality, habitat, and food supply for wildlife, recreation, and other commercial activities (Fleming et al. 2005). More recently, these infestations include the Asian longhorned beetle (ALB; *Anoplophora glabripennis*) and the Emerald ash borer (EAB; *Agrilus planipennis*), which will eventually deplete the indigenous ash tree population in North America. After introduction into the United States, one common way these pests migrate from region to region is in firewood and firewood-grade logs. Pretreatment before these products are transported can slow the spread of these forest pests.

Literature Review

Firewood is any wooden material used for fuel. Currently, split firewood provides only about 1.5 percent of domestic household heating. As energy costs rise, firewood used for home heating will grow. Harvesting firewood logs and processing them into firewood varies considerably. Some regions have specific areas for firewood collection. In heavily wooded areas, it is common to harvest firewood as a by-product of commercial logging. Harvesting timber for firewood is normally carried out manually with chainsaws. Commercial producers cut raw wood automatically using conveyors and power splitters. Wood is typically cut in the

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winter when trees have less sap so that it will season more quickly.

The EAB arrived in the United States on solid wood packaging material carried in cargo ships from Asia in the summer of 2002 (Haack et al. 2002). The beetles were found in Ohio in 2003 and since then have spread from the Midwest to the Southeast. The EAB has killed more than 100 million ash trees (*Fraxinus* spp.) in the United States (Emerald Ash Borer Information Network 2016).

Unfortunately, ash is a popular firewood species. EAB moves around the country in firewood carried by campers, hunters, and commercial firewood producers. These users are frequently not aware that they are moving the eggs or larvae of these pests, which may be hidden under the bark. Once transported to new locations, eggs may hatch, or larvae may mature and emerge as adults and spread throughout the local forest. These new infestations are hard to detect until numerous trees have died, by which time the infestation has become very difficult to control.

The ALB, which has infested many native hardwood trees in the United States, was first introduced in solid wood packaging and pallets of cargo from Asia (Animal and Plant Health Inspection Service [APHIS] 2011). The ALB has also spread in firewood and logs because they are raw wood products that are minimally processed. They have been cut to usable length with bark in place, are possibly split, and are often obtained from recently killed or stressed trees. Surveys of firewood have found that 20 percent were infested with insect or pathogen forest pests (APHIS 2010).

Oak wilt and the Sirex wood wasp and other insects can also be spread through the transport of firewood. Nonnative insects have few predators, and native trees have little natural resistance to these insects.

In order to reduce the spread of forest pests in firewood, firewood can be sanitized using heat treatment. The combination of vacuum and steam is more effective for heat treating large wood cross sections than is hot air. Vacuum lowers the pressure inside in 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 as a result of the pressure gradient produced. Water vapor condenses and changes into liquid water during the vacuum–steam treatment. A large amount of heat is released and rapidly increases the temperature of the wood. Using vacuum–steam treatment, water vapor is used as the medium to exchange the heat rather than hot air, as used in conventional kilns. This has many advantages. Water vapor carries more heat, and heat transfer is faster because condensation is exothermic. Traditional hot-air heating is less efficient because the associated evaporation is endothermic. Additional energy is required to compensate for the endothermic cooling. By using steam, no evaporation occurs. Saturated steam can be used at lower temperatures than hot air and meet the required heat treatment schedules.

Preliminary studies of wood pallets indicated that steam–vacuum heat treatment cycle times are less than half those of current hot-air treatment methods and that the energy consumption is 25 percent less (Chen and White 2012). This research also found that the wood picks up very little moisture and can therefore be easily removed using a short final vacuum cycle. The process can be tailored to the different treatment capacities. The system can also be designed to be easily portable. The technology can be adapted to a rigid or flexible container system because the products can withstand the pressure resulting from the vacuum.

Objectives

The overall goal of this research was to investigate the feasibility of using vacuum and steam to heat treat ash logs and split firewood. The specific objectives were the following: (1) measure the temperature gradients from the surface to the center during steam–vacuum treatment of ash logs and firewood, (2) determine the treatment times required to achieve 56°C for 30 minutes at the geometric center of ash logs and firewood (International Standard for Phytosanitary Measure [ISPM] 2002), (3) determine the effect of the steam–vacuum treatment on the quality of ash logs and firewood, and (4) determine the effect of vacuum level on the treatment time.

Equipment

The system, shown schematically in Figure 1, consists of a vacuum pump (Model R5, Busch Inc.), a flexible vacuum container, a steam generator (45KW, Model 12S, CAM Industries Inc.), and a steam controller (HPM-760 Plus, Teledyne and Hastings Co.). Thermocouples were used to record the temperature within the flexible container and within the treated ash logs and split firewood. The steam boiler supplied saturated steam to the container. The 335 by 305-cm (11 by 10-ft) rectangular flexible vacuum container made of high-tenacity woven fabrics, coated and impregnated with polyvinyl chloride compounds, was used as the test container. An airtight and watertight zipper was installed on the flexible container to seal the opening through which the materials to be treated were loaded and unloaded (Fig. 2).

Vacuum–Steam Treatment of Firewood-Grade Ash Logs: Test Procedure

The white ash logs were acquired from a local lumber company located in Christiansburg, Virginia. Those logs were cut from local ash trees. The logs were transported to the Brooks Forest Products Center at Virginia Tech University, Blacksburg, where the vacuum–steam tests were

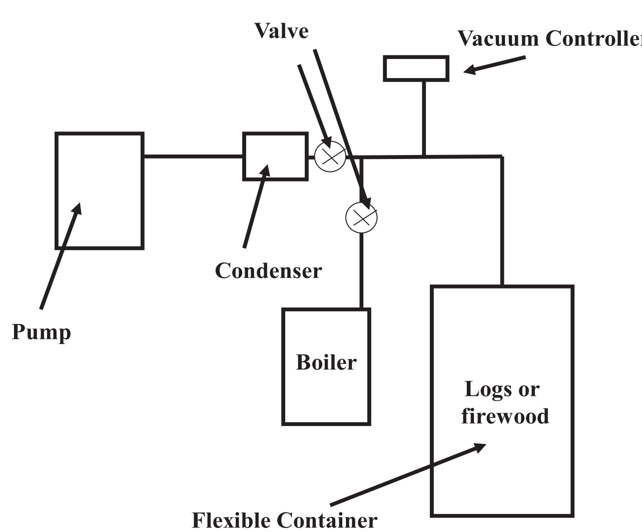

Figure 1.—Schematic diagram of the vacuum–steam treatment system.

Figure 2.—Airtight and watertight zipper used to seal the opening for loading and unloading in the flexible vacuum container.

conducted. The inside-bark log diameters were measured and are shown in Table 1. If the log was not perfectly round, then two measurements were taken at 90° from each other, and the average was used.

Seven ash logs were bundled on a 122 by 183-cm (4 by 6-ft)-long wood pallet for forklift movement (Fig. 2). The largest log in each test bundle was selected for measuring the temperature profile inside the log.

Six-millimeter-diameter holes were drilled into logs in the locations shown in Figure 3 for measuring temperature. The locations included the surface, the depths of one-third and two-thirds of the radius from the log's geometric center, and two locations along the length of the log. The surrounding temperature inside the container was also measured. The thermocouples were inserted into the holes, and the holes were plugged with plumber's putty to prevent steam from entering the hole. Thermocouples were connected to a six-channel data acquisition system.

The pallet with the logs was loaded into the flexible container. The opening of the flexible container was closed. The air was then removed until the preset pressure was reached. Two vacuum levels were used in the experiments: 250 and 500 mm Hg. After the required pressure was reached, saturated steam at 107°C was injected into the container.

The log surface temperature was maintained at 90°C for all the tests. When the center of wood reached 56°C, steaming was stopped. After 30 additional minutes, the test

Table 1.—Treatment time and energy consumption during ash log treatment at 90°C.

Test no.	Treatment pressure (mm Hg)	Environmental temp. (°C)	Log length (cm)	Log diam. (cm) Large end	Log diam. (cm) Small end	Treatment time (h)	Energy used (kWh/kg of log)
1	250	12	190.5	26.7	25.4	14.5	0.573
2		20	188.0	33.0	27.9	12.0	0.630
3		16	185.4	20.3	16.5	9.5	0.681
4		19	182.9	26.7	22.9	8.3	0.632
5		20	193.0	25.4	21.6	7.6	0.522
6		20	193.0	25.4	20.3	9.5	0.531
7		20	182.9	25.4	22.9	7.4	0.447
8		20	188.0	22.9	17.8	5.5	0.544
9		15	185.4	20.3	19.1	6.8	0.339
10		16	185.4	20.3	17.8	5.8	0.555
Avg.			187.5	24.6	21.2	8.7	0.545
11	500	17	198.1	27.9	22.9	7.7	0.423
12		17	177.8	25.4	16.5	5.5	0.467
13		21	185.4	20.3	20.3	6.5	0.579
14		22	182.9	25.4	22.9	7.5	0.559
15		20	182.9	25.4	25.4	9.8	0.650
Avg.			185.4	24.9	21.6	7.4	0.536

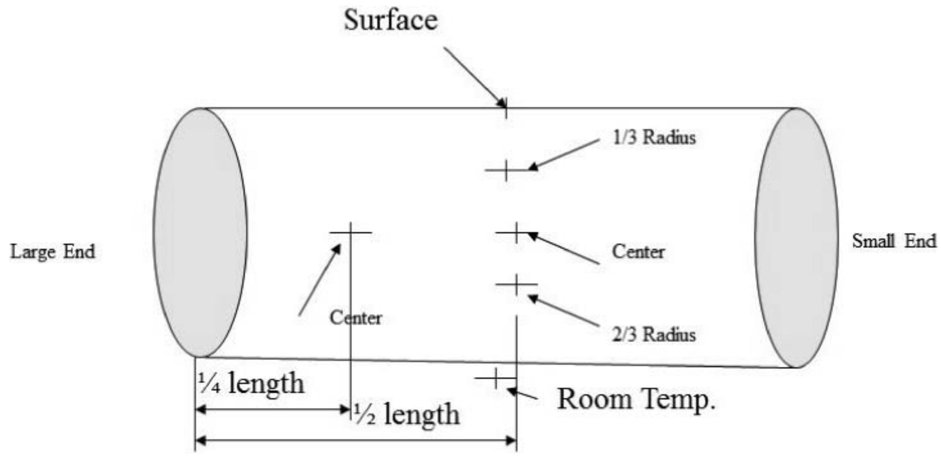

Figure 3.—Schematic diagram showing the locations of the thermocouples in the firewood log.

was stopped. The temperatures were recorded every minute. The volume of steam used for each test was measured using a steam flow meter. Before and after treatment, the logs were visually inspected to observe any quality changes.

Results

Figures 4 and 5 show typical temperature profiles of ash logs at pressures of 500 and 250 mm Hg, respectively. The temperature profiles from other log tests were similar. The temperature inside the flexible container increased rapidly. This was followed by a rapid increase of log surface temperature and internal log temperatures. Because of the manual steam control, the container temperature fluctuated ±10°C.

Treatment time

The treatment duration and energy consumption results are summarized in Table 1, which includes the initial vacuum time and 30-minute temperature hold time. The treatment time for logs varied from 5.5 to 14.5 hours at an initial temperature of 20°C. There was no significant difference between the treatment duration at 250 and 500

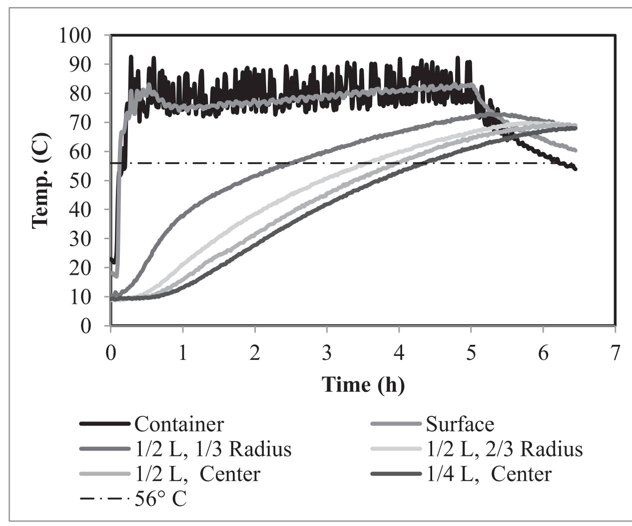

Figure 4.—Typical temperature profile during vacuum–steam treatment of ash logs at a pressure of 500 mm Hg (Test 12).

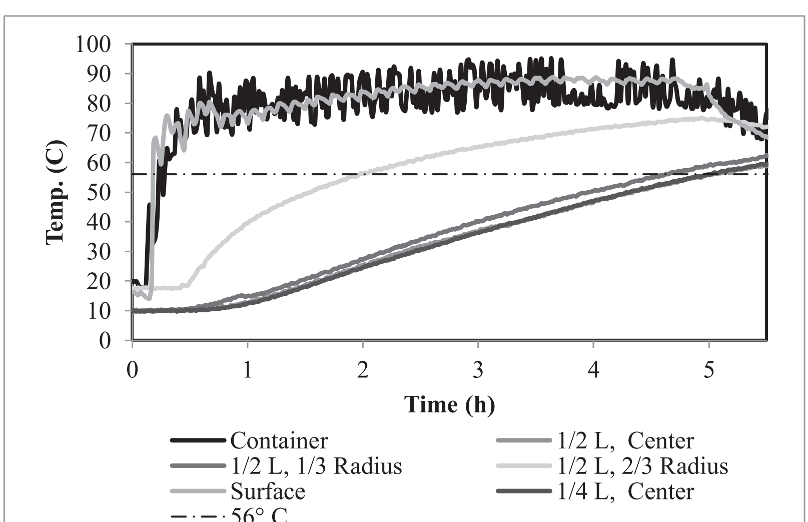

Figure 5.—Typical temperature profile during vacuum–steam treatment of ash logs at a pressure of 250 mm Hg (Test 8).

mm Hg initial pressures (P value = 0.35). The correlation between log diameter and treatment duration is shown in Figure 6. Regression analysis indicated a linear relationship between the log diameter and treatment time with treatment time increasing with increasing diameter. Some small-end splits increased in width during treatment. The growth in end splits, however, was not large enough to affect the quality and yield of firewood. Qualitatively, the wood darkened as a result of the treatment.

Vacuum–steam treatment of split firewood

The local ash logs were cut by a chainsaw into bolts 40.6 ± 5.1 cm (16 ± 2 in.) long. The bolts were split with a Huskee log splitter. The maximum thickness was about 15.2 cm (6 in.) on the wider side of split firewood. A hole was drilled to the geometric center of the largest piece in the bundle. Another hole was about 2 inches deep into the end grain of the firewood. Before treatment, the moisture content (MC) of the firewood was measured by removing samples and using the ovendry method. The weight of one bundle of firewood was measured before and after treatment in order to calculate the moisture gain during the treatment. The firewood bundles were stacked on a pallet, three layers high and three layers wide (Fig. 7). Thermocouples were attached to or embedded in the edge bundle of the firewood at the bottom layer. This region of the chamber was the coolest. The holes with the embedded thermocouples were tightly plugged with plumber's putty. One temperature probe was attached to the surface of the bundle (Fig. 8). The

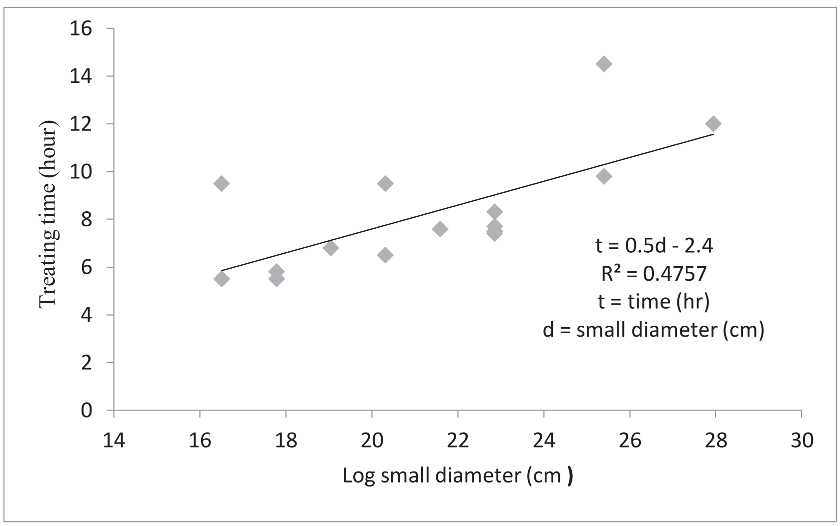

Figure 6.—Relationship between the ash log diameter and the treatment duration.

Figure 7.—Firewood bundles were loaded into the container for treatment.

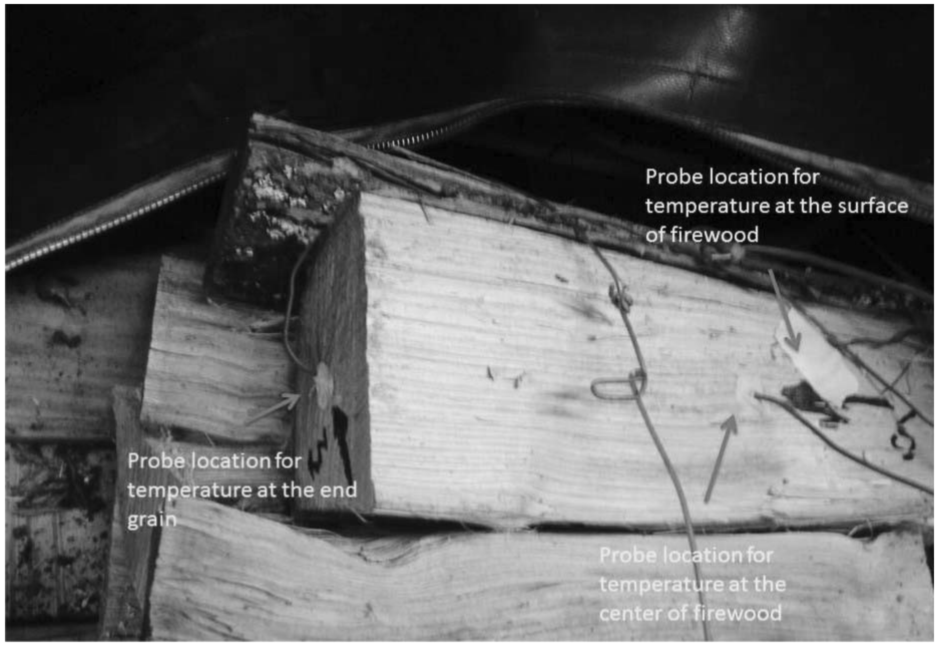

Figure 8.—Temperature probes were embedded in the firewood for temperature measurements.

split firewood was associated with the log from which it was cut through the use of identification number. Before the treatment, selected firewood samples were removed and oven-dried to determine the initial MC. The entire firewood bundle was weighed before and after treatment and MC change estimated based on the MC of the samples.

After the flexible container was loaded with the bundled firewood, it was closed. Two vacuum levels were used in the experiments: 300 and 500 mm Hg. It generally took about 5 to 10 minutes to reach the required vacuum level. After the required vacuum pressure was reached, steam was injected into the container.

Results

Temperature profiles were obtained from the probed firewood bundles after each test. Figures 9 and 10 are typical time–temperature profiles for tests at 300 and 500 mm Hg, respectively. The flexible container temperature increased rapidly. This was followed by the surface temperature and

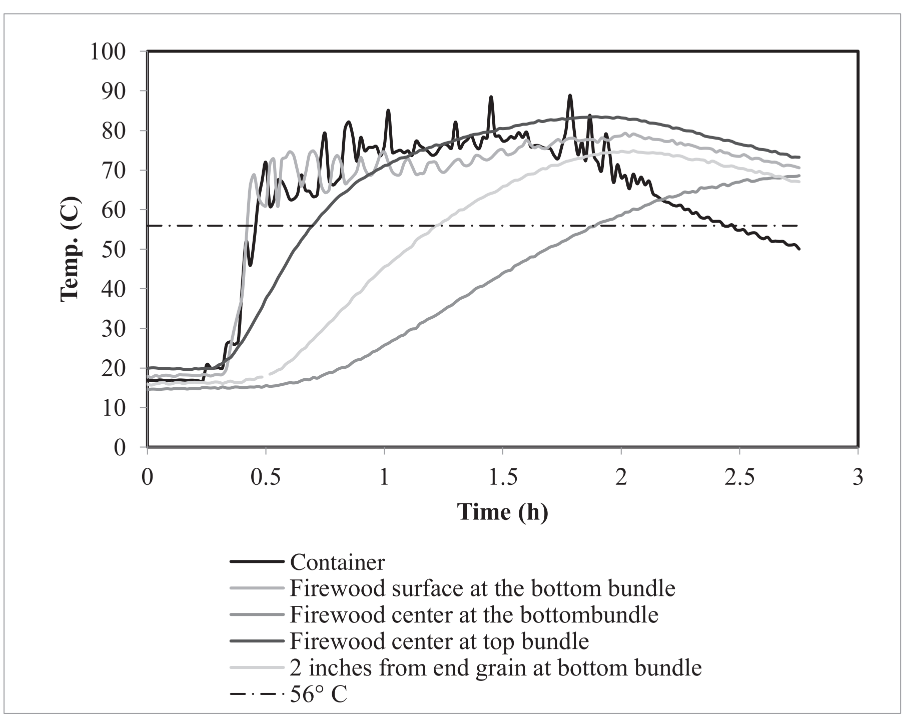

Figure 9.—A typical temperature profile during vacuum–steam treatment of split ash firewood at a pressure of 300 mm Hg.

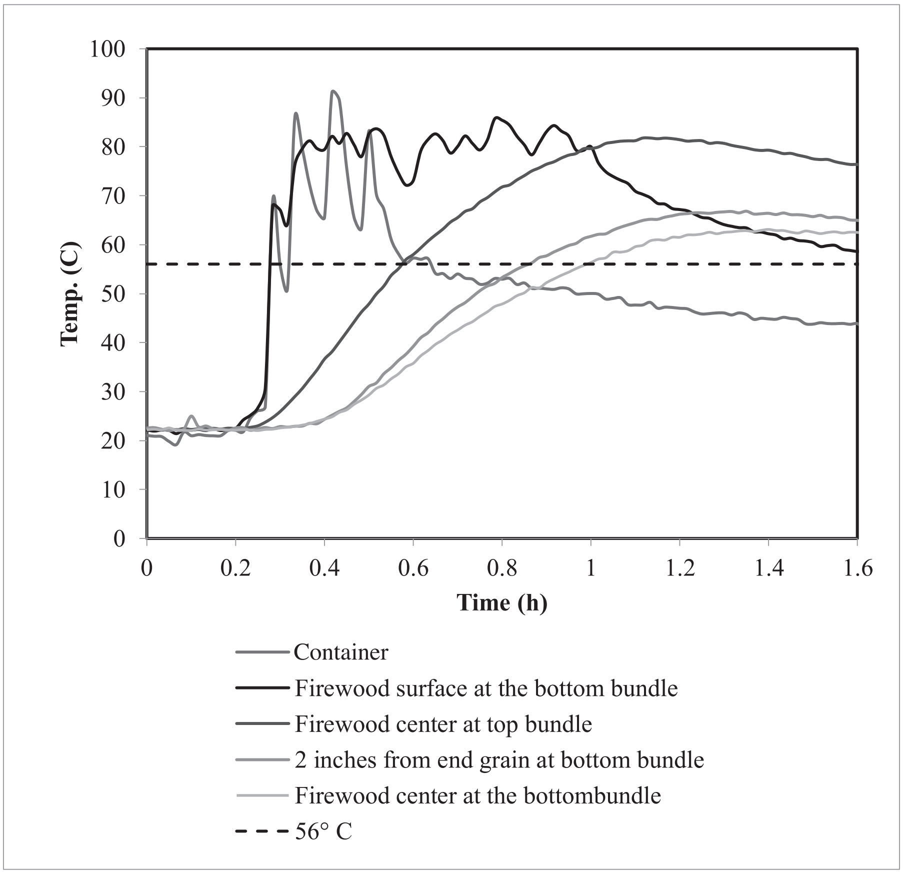

Figure 10.—A typical temperature profile during vacuum–steam treatment of split ash firewood at a treatment pressure of 500 mm Hg.

Table 2.—Treatment time and energy consumption during the ash firewood vacuum–steam treatment.

Test no.	Treatment pressure (mm Hg)	Wood initial temp. (°C)	Firewood weight (kg)	Treatment time (min)	Energy used (kWh/kg of firewood)
1	300	22	59.1	70	0.244
2		24	60.0	92	0.368
3		21	61.2	112	0.392
4		22	61.3	113	0.456
5		22	59.7	70	0.267
6		18	68.6	93	0.370
7		17	59.5	92	0.278
8		17	67.6	140	0.372
9		18	67.7	110	0.441
10		16	69.4	137	0.482
Avg.			63.4	103	0.367
11	500	15	68.5	103	0.430
12		19	67.8	87	0.381
13		20	66.5	107	0.350
14		20	68.3	107	0.374
15		20	67.6	112	0.377
16		20	67.7	86	0.416
17		21	69.6	102	0.482
18		19	68.3	98	0.379
19		18	67.6	104	0.392
20		20	66.6	90	0.313
21		20	67.4	100	0.374
22		18	68.5	80	0.388
Avg.			67.9	98	0.388

Table 3.—Firewood moisture gain during the firewood vacuum–steam treatment.

Test no.	Bundle wt (kg) Before treatment	After treatment	Calculated ovendry wt of bundle (kg)	Calculated MC[a] of the bundle after treatment (%)	MC change (%)
1	13.88	14.01	11.11	26.1	1.2
2	15.88	16.26	12.71	27.9	3.0
3	18.55	18.77	14.85	26.4	1.5
4	18.91	19.11	15.14	26.2	1.3
5	15.37	15.55	12.31	26.4	1.5
6	18.34	18.63	14.68	26.9	2.0
7	14.94	15.15	11.96	26.7	1.8
8	16.14	16.39	12.92	26.8	1.9
9	16.29	16.71	13.04	28.1	3.2
10	19.99	20.36	16.00	27.2	2.3
11	18.06	18.2	14.46	25.9	1.0
12	16.58	16.86	13.27	27.0	2.1
13	13.63	13.88	10.91	27.2	2.3
14	17.7	18.04	14.17	27.3	2.4
15	16.05	16.33	12.85	27.1	2.2
16	16.4	16.75	13.13	27.6	2.7
17	20.61	20.81	16.50	26.1	1.2
18	17.56	18	14.06	28.0	3.1
19	16.2	16.44	12.97	26.8	1.9
20	13.8	14.09	11.05	27.5	2.6
21	15.62	16.12	12.51	28.9	4.0
22	18.1	18.71	14.49	29.1	4.2
Avg.	16.8	17.1	13.4	27.1	2.2

[a] MC = moisture content.

interior temperatures. The firewood test results are summarized in Table 2. The treatment time for firewood varied from 1.2 to 2.3 hours, which included vacuum time and a temperature holding time of 30 minutes. There was no statistical difference between the average cycle times at 300 and 500 mm Hg (P value = 0.53).

As expected, during the steam treatment, firewood absorbed some moisture, as indicated by the increase in bundle weights. Table 3 contains the result of the MC measurement. The average increase in MC was 2.2 percent. This was not considered a large enough gain to result in a noticeable increase in drying time for the firewood.

The treating energy varied from 0.34 to 0.68 kWh/kg of log mass, with an average of 0.541 kWh/kg. However, the energy required to treat the split firewood was 0.24 to 0.48 kWh/kg of firewood, with average of 0.378 kWh/kg. This was significantly less than that consumed when treating the logs. This indicates that it may be more efficient to treat the finished firewood product than to treat the raw log material. Treating ash firewood also required less time than treating the ash logs.

Conclusions

1. Steam and vacuum can quickly and effectively heat treat ash firewood and firewood logs to comply with the ISPM 15 requirement of 56°C for 30 minutes at the core.
2. Treatment times for the 183-cm (6-ft)-long ash logs between 16.5 and 27.9 cm (6.5 and 11 in.) in diameter were 5.5 to 14.5 hours, which included a holding time of 30 minutes.
3. Treatment times for the split ash firewood bundle were 70 to 137 minutes, which included vacuum and a holding time of 30 minutes.
4. The treatment of split firewood consumes 30 percent less energy per kilogram of wood than treating the logs before splitting. Treating the split firewood was more efficient.
5. During treatment of split firewood, the MC of firewood increases an average of 2.2 percent.
6. The average treatment cycle times were not statistically different when treated using an initial pressure of 250 to 300 and 500 mm Hg.
7. There was no effect on quality of the treated ash log and firewood.

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