

DRYING YELLOW-POPLAR IN A SOLAR-DEHUMIDIFIER KILN WITH HEAT STORAGE AND HEAT RECOVERY SYSTEMS

Peter Y. S. Chen
North Central Forest Experiment Station
Carbondale, Illinois

and

Wayne A. Helmer
Southern Illinois University
Carbondale, Illinois

INTRODUCTION

Using the sun's energy is one way to dry lumber without resorting to costly, limited supplies of natural gas and oil. However, solar lumber drying by itself is time-consuming, especially when trying to dry below 15 percent moisture content, and drying times vary with weather variations.

Dehumidification lumber drying is another drying technique that can reduce fossil fuel energy consumption. Recent technological advances have made dehumidification kilns very reliable and competitive with conventional steam-heated lumber driers for some applications. The use of different refrigerants and centrifugal compressors as well as other innovations has enabled dehumidifier kilns to operate at temperatures in the normal kiln drying range--up to 180°F (1). Dehumidification wood drying systems have lower capital costs but can dry wood as quickly as conventional steam-heated systems. However, dehumidifier kilns are entirely powered by expensive electrical energy.

Research at the North Central Forest Experiment Station, Carbondale, Illinois, has suggested that dehumidification and solar drying can be combined into one system that incorporates the advantages of both methods. The dehumidification unit and energy storage system can provide heat when solar radiation is not available. The solar drying system can provide heat when insulation is available so that less electrical energy is used to drive the dehumidifier.

This paper describes the design and construction of a solar-dehumidifier kiln equipped with a heat storage unit and a heat recovery system, and presents the preliminary results of a test on drying rates, power consumption, energy efficiency, and wood quality with 4/4 yellow-poplar (Liriodendron tulipifera) lumber.

DESIGN AND CONSTRUCTION

KILN, COLLECTORS AND DEHUMIDIFIER

An energy storage unit and a heat recovery system were added to the existing solar-dehumidifier kiln (2)(Fig. 1). Double-glazed air solar collectors (244 ft²) heated the kiln air or the rock storage system. A 1-hp motor drove the fan that continuously

circulated the air in the kiln. The high temperature dehumidification system used R-114, which allows the higher temperature operation, as a refrigerant. A 2-hp motor drove the open compressor that circulated the refrigerant through the thermostatic expansion valve, the condenser, and the evaporator.

HEAT STORAGE SYSTEM

The heat storage system for the kiln was a rock storage unit with enough rock volume (128 ft^3) to heat the kiln for one day without solar radiation (Fig. 2). A volume thermal capacity of $24.3 \text{ Btu/ft}^3/\text{°F}$ was used in the design (assumed a 30 percent void fraction). This would supply the kiln with 124,000 Btu of heat, if the heat storage was discharged from an initial temperature of 140°F to a final temperature of 100°F . The rock-bed was 4 feet deep in the direction of flow and had a flow cross sectional area of 4 feet by 8 feet. The design pressure drop across the bed at $1,000 \text{ ft}^3/\text{min}$ was 0.16 inch of water. The walls were made of 2x10 studs on 16-inch centers with 3/4-inch plywood used as the inside wall. Steel tie bolts were used to help reduce deflection of the four side walls. Polyethylene sheets provided a vapor barrier on the rock side of the plywood. Nine inches of fiberglass insulation and 1/2 inch of rigid polyurethane board gave the wall and top of the rock bin an R value of about 34. Aluminum siding covered the outside of the storage bin.

The weight of the rocks was supported by bond beam blocks covered with a layer of expanded metal lath. The floor of the storage unit was covered with 3 inches of rigid insulation under 3/4-inch-thick plywood. A vapor barrier was also used above the plywood base. The complete storage bin was located on a 6-inch concrete slab. Rocks for the storage unit, obtained from washed river gravel, ranged from 1 to 3 inches in diameter. All air ducts were constructed from 8-inch diameter sheet metal and insulated with 1-1/2 inches of polyurethane foam. Two 8-inch by 48-inch inlet ducts were located at the bottom side of each end of the storage bin. Two 18-inch by 18-inch ducts on the top of the storage unit were attached to two centrifugal blowers (Fig. 1) driven by variable speed 1-hp motors. The blowers were placed on the downstream side of the collectors to reduce infiltration losses into the collectors. Six sets of motorized dampers at the inlet and outlet of the rock storage unit controlled the air flow from the kiln, collector, and the heat storage unit (Fig. 1). Copper-constantan thermocouples were installed in the rock-bed to measure and control the charging/discharging temperature of the storage unit.

HEAT RECOVERY SYSTEM

A finned heat-pipe heat exchanger was placed in inlet and outlet air flow paths to the dehumidifier to precool the kiln air going into the evaporator so that the humid air was closer to the saturation point, allowing a greater amount of moisture

to be removed. The energy extracted from the kiln air in inlet section (dry-bulb temperature dropped from A to B, Fig. 3) was added back in outlet section to the cool, dry air leaving the evaporator (dry-bulb temperature rose from E to F, Fig. 3). The heat-pipe heat exchanger was 6 inches by 9 inches by 24 inches, using heat pipes for the tubes. The heat pipe tubes were 5/8 inch in diameter; the aluminum fins were spaced at 0.07 inch.

A heat pipe consists of three basic elements: the sealed pipe, the wick, and the working fluid (3). The wick is placed adjacent to and around the interior wall of the pipe. When heat is applied to one part of the heat pipe, the working fluid boils. The vapor travels down the center of the pipe and condenses on the cooler portion of the wick and pipe wall. The vapor surrenders its latent heat to the pipe wall and the surroundings. Thus, heat is transported from the boiler section (the inlet section) to the condenser section (the outlet section) with little temperature drop. Then the wick transports the liquid back to the boiler section by capillary action.

CONTROL

The heating and cooling components in the complete wood drying system were controlled by two separate systems: one for the dehumidifier and one for the kiln/collectors/storage system. The heat pump control was activated by a humidistat positioned in the kiln. When the kiln air relative humidity rose above a set value (see Table 1), the dehumidifier was turned on; when the relative humidity fell below that value, the dehumidifier was turned off.

The kiln/collectors/storage system was controlled by a differential temperature controller. The controller continuously monitored and compared the kiln dry-bulb temperature, the solar collector outlet temperature, and the top rock-bed storage temperature. It then activated blowers and dampers based upon the differences in those three temperatures. The control strategy was as follows:

1. Heat was supplied to the kiln whenever the kiln dry-bulb temperature was below the set temperature.
 - a. Heat to the kiln was first supplied by the solar collectors.
 - b. If the solar collectors were not hot enough, then heat was supplied by the storage unit.
2. If the kiln dry-bulb temperature was above the set temperature and the solar collectors were hotter than the storage temperature, then the solar collectors were activated to heat the storage.

MATERIALS AND METHODS

Two 500 BF charges of green 4/4 yellow-poplar lumber were dried in the summer and fall of 1983. The boards were 8 feet long, 4 to 6 inches wide, and 1-1/16 inches thick.

Kiln air velocity was set at 400 ft/min and 250 ft/min at the exit side of the wood stack for summer and fall runs, respectively. The solar collector air velocity was set at 4 ft³/ft² of the collector area for both runs. This relatively lower air velocity was used to reduce electrical energy consumption, compared to our previous use of 9 ft³/ft² of collector area, and to increase the outlet temperature of the collector. Six boards in each run were chosen for moisture samples. The humidistat was progressively reduced from 80 to 25 percent relative humidity as the moisture content decreased (Table 1).

Test runs were terminated when the average moisture content of the high three sample boards reached 8 percent moisture content. The lumber was conditioned approximately 6 to 8 hours with steam from a 7.5 kW, 25-lb-of-steam/hr electric steam boiler outside the kiln, to relieve the drying stresses in the wood before discharge from the kiln.

Boards were weighed before and after drying to calculate the total weight of water removed. Twenty percent of the 150 boards were measured for thickness and width at three different points before and after drying to calculate shrinkage. After kiln drying, these randomly selected boards were measured for twist, bow, and crook. All boards were inspected for surface checking, end checking, and collapse. All boards were also graded before and after drying to estimate the degrade loss due to drying. Two stress specimens were cut from each of the six moisture content sample boards and from each of three randomly selected boards to detect any drying stresses remaining.

Electric energy consumed by the compressor motor, the condenser, and the evaporator blowers was recorded by watt-hour meters. The power consumption rates of the collector blowers storage blowers, and the main fan were measured by an ammeter. The hours of operation of the fan and blowers were automatically recorded, and power consumption was then calculated from these data.

The ambient and kiln temperatures (both dry- and wet-bulb); inlet and outlet temperatures of the solar collector; and the top, center, and bottom temperatures of the rock-bed heat storage unit were recorded at 10-minute intervals. Also, solar radiation was measured and recorded throughout each run by a pyranometer and a strip-chart recorder.

RESULTS AND DISCUSSION

The solar-dehumidifier kiln equipped with a rock-bed heat storage bin and a heat-pipe heat recovery system dried and conditioned 4/4 yellow-poplar lumber from green (98 percent) to 8 percent moisture content in 7 to 10 days during summer and fall (Fig. 4). These drying times were nearly identical to the 6- to 9-day drying times of the same kiln without the heat storage and heat recovery systems (Table 2) and to the 6- to

10-day drying times of the conventional steam-heated kiln (4). Apparently, the heat storage unit did not shorten the drying time during warmer seasons of the year; however, the energy consumption was reduced.

The electrical energy required to dry a charge (approximately 500 BF) of 4/4 yellow-poplar lumber varied less between summer and fall in the new kiln equipped with a heat storage bin than in the same kiln without the heat storage bin (Table 2). The kiln was more energy efficient with recovery and storage systems than without in both summer and fall runs in terms of power (kWh) required to remove a pound of water from the wood (Table 2).

The heat storage bin supplied 187,000 and 146,000 Btu of solar heat to the kiln in summer and fall runs, respectively. The heat storage unit worked mainly to raise the initial kiln temperature to the operational temperature of the heat pump and supplied additional heat to the kiln during the first or second night of the run because the storage temperature never exceeded the kiln temperature from then on.

The quality of dried lumber was excellent and the light color of the lumber was very attractive. No collapse, surface checking, or end checking were noted at the end of drying. There was a \$2.00/MBF degrade loss due to drying, even though only one board out of 150 dropped one grade in the summer run. There was no degrade loss in the fall run (Table 3). The degrade loss apparently was not related to the volumetric shrinkage, but was related to the degree of warpage (Table 3). There was no difference in twist between the summer and fall runs. However, bow and crook warpage showed a highly significant difference between the summer and fall runs (Table 3). The reason was not known.

The total degrade loss of yellow-poplar lumber dried in 1983 was identical to that of lumber dried in 1980. Again, the degrade loss appeared to be related to the degree of warpage, but not related to the volumetric shrinkage (Table 4).

FUTURE PLANS

We plan to test one run per season for one year to determine the effect of season on the drying time, wood quality of 4/4 yellow-poplar and red oak, and the energy efficiency of the drying system equipped with a heat storage and a heat recovery system.

LITERATURE CITED

1. Chen, P. Y. S. and W. A. Helmer. 1982. Principles of lumber drying. For. Prod. J. 32(5):24-28.
2. Chen, P. Y. S., W. A. Helmer, H. N. Rosen, and D. J. Barton. 1982. Experimental solar-dehumidification kiln for lumber drying. For. Prod. J. 32(9):35-41.
3. Kent, A. C., H. N. Rosen, and D. A. Crotty. 1981. Energy conservation in wood dryers using vent air energy recovery devices. For. Prod. J. 31(2):43-49.
4. Rasmussen, E. F. 1961. Dry kiln operator's manual. U. S. Dept. Agric. For. Serv. Agr. Hanb. 188, p. 144. Forest Products Laboratory, Forest Service, U. S. Department of Agriculture, Madison, Wisconsin.

Table 1.--Assumed average board moisture content and kiln humidity control setting

Assumed average board moisture content	Humidistat setting (RH)
(%)	(%)
> 50	80
40-50	75
35-40	65
30-35	50
25-30	35
< 25	25

Table 2.-- Comparison of drying time, power consumption, and energy efficiency of drying 4/4 yellow-poplar from green to 8 percent moisture content in a solar-dehumidifier kiln with and without heat storage¹

	<u>Kiln type</u>	<u>Summer</u>	<u>Fall</u>
Green MC (%)	With storage	102	93
	Without storage	94	99
Final MC (%)	With storage	7.7	8.4
	Without storage	7.2	7.7
Drying time (days)	With storage	7	10
	Without storage	6	9
Water removed (lbs)	With storage	1,278	1,292
	Without storage	969	1,150
Power consumption (kWh)	With storage	372	411
	Without storage	323	501
Energy efficiency [kWh (Btu)/lb. of water removed]	With storage	0.29(990)	0.32(1,093)
	Without storage	0.33(1,127)	0.44(1,503)

¹Data from Chen et al. (2).

Table 3.--Drying data for 4/4 yellow-poplar lumber

<u>Runs</u>	<u>Summer</u>	<u>Fall</u>
Dates (1983)	July 5-12	September 26- October 6
MC (%)		
Green	102	93
Dry	7.7	8.4
Drying time (days)	7	10
Volumetric shrinkage (%)	11.0	11.5
Warpage (in.):		
Twist	0.20 NS	0.15
Bow	0.31 **	0.13
Crook	0.38 **	0.13
Degrade loss (\$/MBF)	2.08	0.00
Water removed (lb.)	1,278	1,292
Power consumption (kWh):		
Dehumidifier	183	272
Kiln fan	142	88
Collector blowers	38	40
Storage blowers	9	11
Total	372	411

NS - Nonsignificant

** - Significant at 1% level

Table 4.-- Comparison of wood quality of 4/4 yellow-poplar
dried in a solar-dehumidifier kiln with and without heat storage¹

	<u>Kiln type</u>	<u>Summer</u>	<u>Fall</u>
Warpage (in.)			
Twist	With storage	0.20	0.15
	Without storage	0.17	0.08
Bow	With storage	0.31	0.13
	Without storage	0.09	0.10
Crook	With storage	0.38	0.13
	Without storage	0.25	0.22
Volumetric shrinkage	With storage	11.0	11.5
(%)	Without storage	10.9	10.6
Degrade loss	With storage	2.08	0.00
(\$/MBF)	Without storage	1.46	0.62

¹Data from Chen et al. (2).

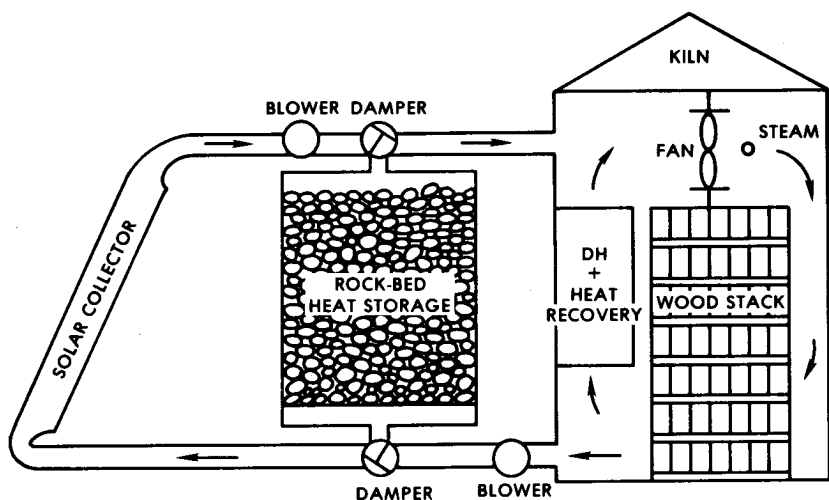


Figure 1.--Solar-dehumidifier kiln with heat storage and heat recovery systems

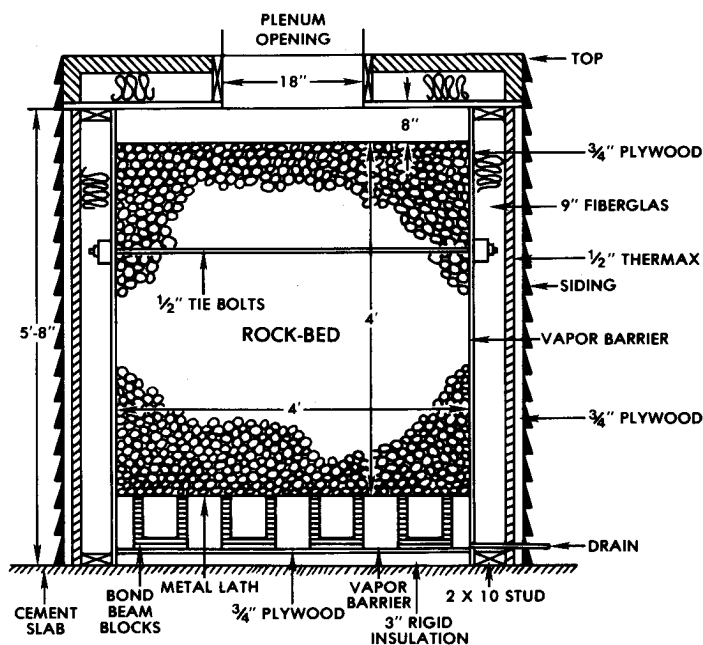


Figure 2.--Rock-bed energy storage system--side view

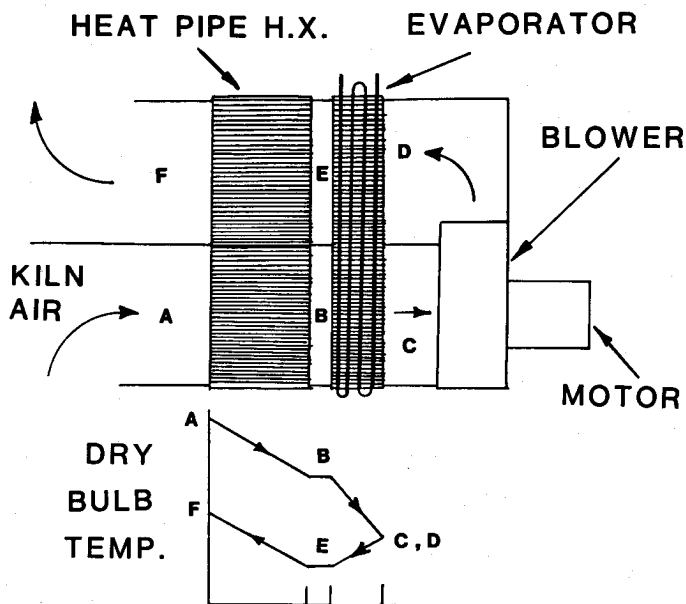


Figure 3.--Dehumidifier heat recovery system

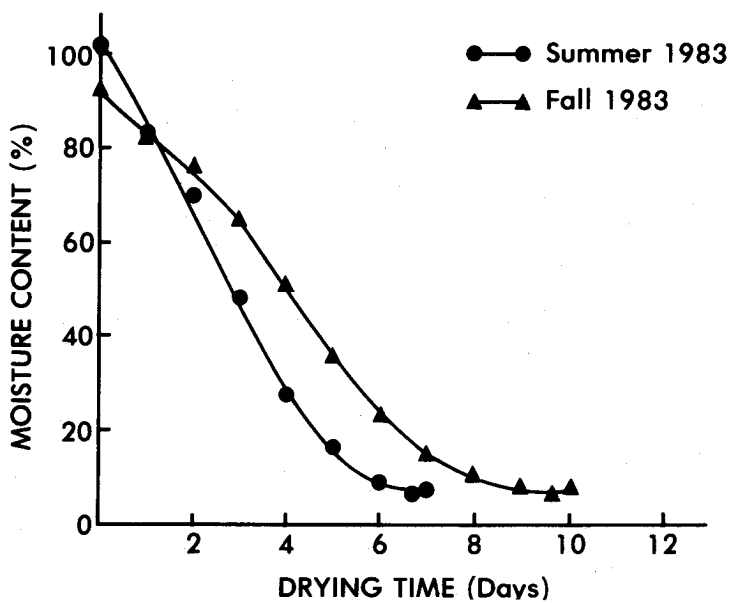


Figure 4.--Drying curves for summer and fall runs