# DURANGO RED OAK DRYING AT LOW TEMPERATURE

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## ABSTRACT

In the West Sierra Madre region of Durango red oak is a species that has traditionally been considered useless due to difficulties in the drying and sawing processes. This work presents the evaluation of a heat pump dryer as an alternative to the commonly used high temperature kiln.

An existing refrigeration system was adapted to investigate red oak drying at laboratory scale. The system accommodates 90 wood pieces (1 ¼" thick x 2 ¼" wide x 24" long) in an arrangement which simulates the flow through one of the typical flow passages of a conventional wood pack prepared for conventional drying. The investigated variable was the drying chamber air inlet temperature at two levels of air superficial velocity through the samples.

Results evaluation showed that the use of air inlet temperatures above 40-45 °C tend to produce wood of bad quality, while temperatures below 30 °C lead to excessive drying times. A preliminary design of a medium sized drying system and a comparison of its performance with that of a conventional system resulted in a competitive product price.

## INTRODUCTION

The properties of Durango red oak, especially its high density and hardness, have induced the producers to regard this species as useless because of difficulties in the drying and sawing processes. Local industry interest on red oak exploitation has been rising, which caused two projects to be developed. The first one was dedicated to measure the mechanical properties of red oak and the second one was started to investigate possible drying time reductions.

Evaluation of alternatives to the most common drying technique, at relatively high temperature and humidity in a wood kiln, produced information regarding the use of a heat pump dryer. This process, in which low temperature and humidity are used for drying, is applied successfully in European countries to dry hard woods and quoted to produce wood of better quality in shorter drying times, Moncayo, 1994.

In order to test such a system a drying chamber was designed, built and adapted to work with an existing refrigeration system to investigate red oak drying at laboratory scale. The system accommodates 90 wood pieces 1 ¼" thick x 2 ¼" wide x 24" long in an arrangement which simulates the flow through one of the typical flow passages of a conventional wood pack prepared for conventional drying.

Drying tests were performed on partially air-dried red oak samples, which were rehydrated by immersion in water and also with recently sawed samples. The investigated variable was the drying chamber air inlet temperature at two levels of air superficial velocity through the samples. Results evaluation showed that there is an optimal value of temperature above which the wood quality is greatly diminished and below which drying times becomes excessive.

With the measured drying curves as a basis, a medium sized drying system was designed and its performance compared with a conventional drying system from the economic viewpoint. It was found that, although the cost of the energy supply for the heat pump system is much greater than that of the conventional system, the large time reductions obtained with the former produce the product price to be competitive.

## APPARATUS AND EXPERIMENTAL PROCEDURES

### Apparatus

Figure 1 is a schematic diagram of the system. As seen there, cold, humid air from the drying chamber is directed towards the heat pump cycle evaporator, where it is cooled and dried as its water is condensed. It flows then towards the heat pump condenser, where it is reheated. If required, an auxiliary heater is used for further heating before the air enters the drying chamber at relatively high temperature and low humidity.

In the chamber, the air provides the energy required for evaporation, causing its dry bulb temperature to fall. As it mixes with the vapor its energy content rises and the overall process is adiabatic.

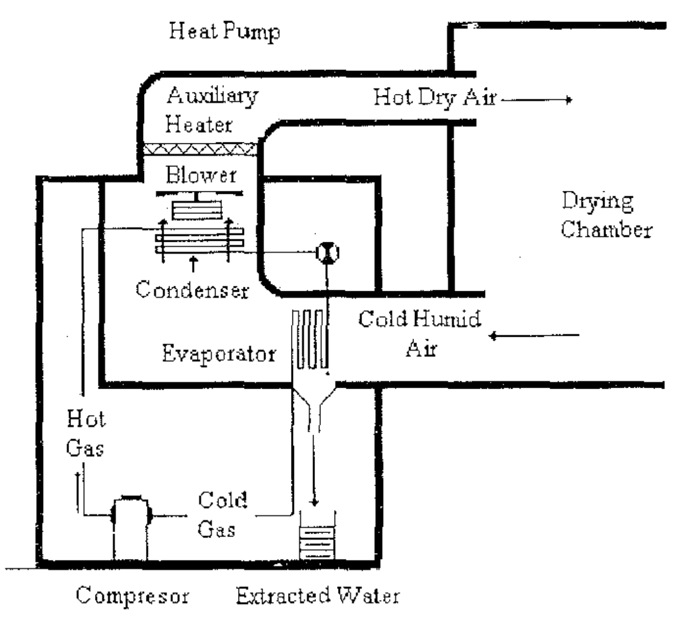


Figure 1-Schematic diagram of the system

### Experimental Procedures

Samples were obtained from the regular production of a typical sawing mill. In some instances the wood pieces had been waiting to be dried in the drier inlet yard for a few days and had to be rewet.

This process was accomplished by submersion of the samples in a water bath at ambient temperature for 24-72 hours. Since wood size was one of the standard mill products no other treatment was required.

The 90 wood samples that is possible to fit in the drying chamber were then set in place in three bundles of three rows each as shown in Figure 2. The chamber air inlet is located at the extreme right and bottom

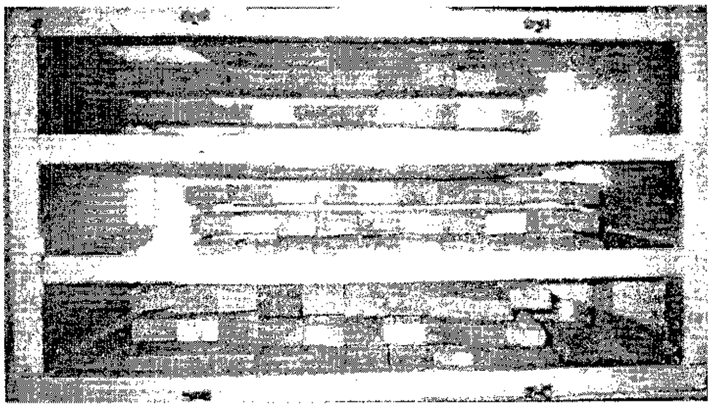


Figure 2-Drying Chamber

of Figure 2, while the exit is at the left and top of the chamber. Wood pieces were placed with their length perpendicular to the flow.

One of the wood pieces of each row was used to track humidity changes. Measurement of their initial humidity content was made on a small sample cut from the edge of each piece and following Standard ASTM D-4442-92.

With the wood pieces in place, the drying chamber was closed and the refrigeration system started. It should be noted that, since the condensation section of the refrigeration system is at a remote location, all heating was effected by the auxiliary system and set at the desired dry bulb temperatures by manual control of the number of auxiliary heating resistances. Wet bulb temperatures were those that could be obtained, without external disturbances, by the evaporator coil capacity.

Measured variables were the wet and dry bulb temperatures at the drying chamber inlet and exit and at the evaporator exit, and the weigh of the nine humidity samples as a function of time. Tests were finished when the average humidity content was below 12% (from the humidity content of the nine samples), or the slope of the H-t curve was too low or an arbitrarily set time limit of seven days was attained.

Two procedures were followed to evaluate wood damage. The first one was a visual inspection of the dried wood, which was classified as follows: 1) Large deformations and surface or end checks, 2) Diamond deformations of wood and 3) No visible damage. Wood that presented damages of type 1 was classified as rejected. The second one was the three prongs test as described by Simpson, 1991.

# RESULTS

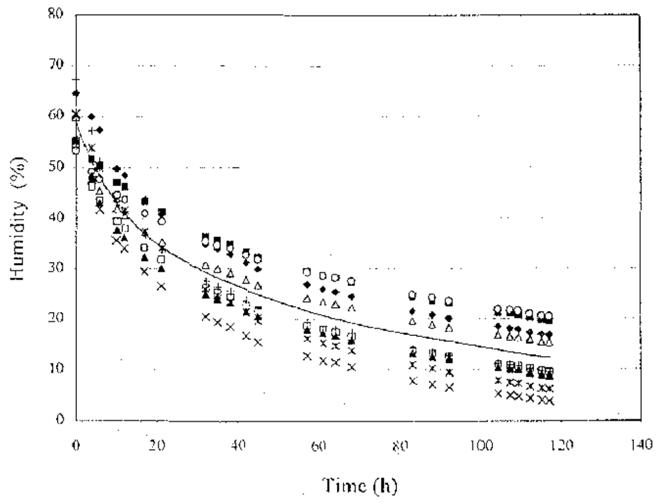


Figure 3. Typical experimental measurements

Experimental measurements

Figure 3 shows humidity as a function of time for the nine selected samples of a typical experiment. Each marker pertains to one of the samples, while the dotted line shows the average.

As seen there, there is a rather large variation in the sample's humidity content, which may be explained by the selection process where the charge was obtained from the piles of mill production. This fact does not affect the desired results since it would be the natural way in which a dryer load would be selected in normal operations.

A total of 12 experiments were made to investigate the effects of air temperature and velocity on the drying rate. Results on the use of temperatures of around 40 °C are

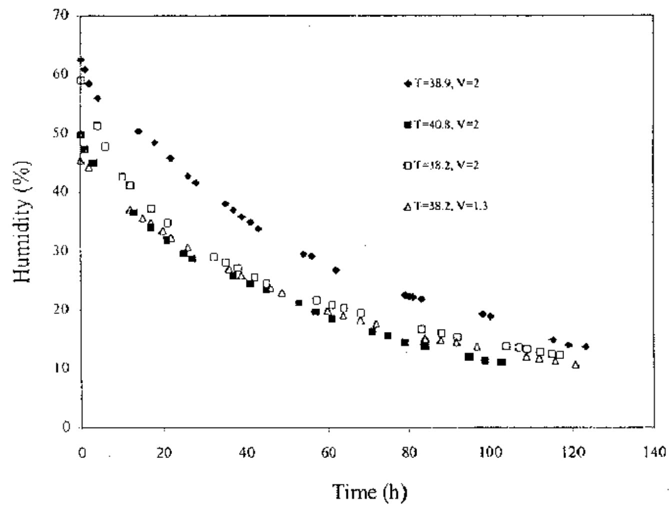


Figure 4. Experimental results at medium temperatures

shown in Figure 4, where the average wood humidity is shown as a function of time for two velocities. An overall evaluation of the curves shows that humidity values of around 12% are reached in around 120 hours for all cases. Although for the lower velocity the initial humidity is also lower, the addition of a few hours is not very important.

Figure 5 presents the experimental drying curves for all the range of investigated temperatures. A comparison among the curves shows that the use of higher temperatures leads to greater drying slopes and, therefore, shorter drying times. This is proved by the greater slope of the curve at 57 °C and its corresponding shorter time to reach 12% humidity although the initial humidity of this experiment was higher than that of either the 38 or 47 °C curves. The use of temperatures of 38 or 47 °C seems to have little effect on the drying time, although it should be noted that no conclusion may be made since the experiment at 47 °C was performed at a lower air velocity. This fact was not very important, and no further experiments were performed, in view of the rejection rates and other experimental results, which will now be presented.

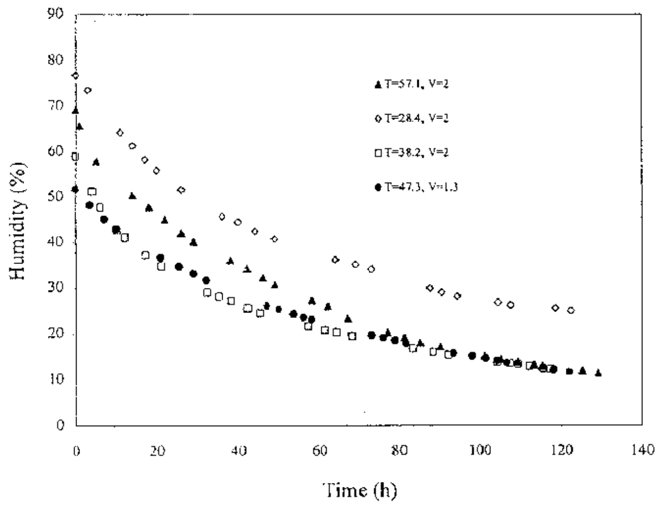


Figure 5. Drying curves for all the investigated range

The whole set of experimental conditions investigated in this work is shown in Table 1. Eleven tests were made with the drying chamber air inlet conditions (main investigated variable) represented in Table 1 by the dry and wet bulb temperatures and the air superficial velocity in columns marked $T_{db}$, $T_{wb}$ and V.

Analysis of temperatures, with the aid of the psychrometric equations of ASHRAE, 1981, show that the average air water humidity content was 0.0158 ± 0.0075 and the corresponding air relative humidity 26.5 ± 4.4. These variations are small if account is made of the fact that the air water content was uncontrolled and dependent only upon the evaporator coil capacity and the drying process itself.

The wood initial conditions (intrinsic to the wood selection and handling processes) and the sampling and measurement times of the year are shown in columns marked G, IC and $H_i$. The first five experiments were performed from January to May and are identified by a one in column G, while two mark experiments from August to November. A "G", for green wood, in column IC notes the way in which wood obtained its initial humidity and an "R" indicates rewet wood.

Average initial humidity content is shown in column headed $H_i$ and varied from 21 to 77 %. It should be noted that the results of experiments No. 4 and 5 were rejected since the tables were too dried before being rewet and did not absorb water even after 72 hours of immersion.

Table 1. Experimental conditions and results

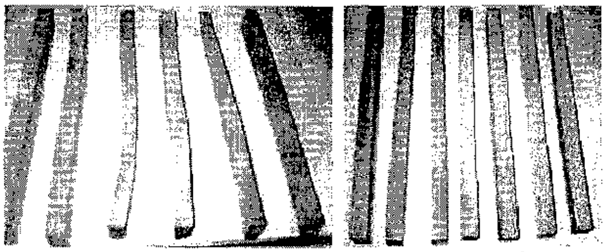
| No | $T_{db}$ | $T_{wb}$ | V | G | IC | $H_i$ | $H_f$ | t (h) | R |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 38.9 | 21.3 | 2.08 | 1 | R | 63 | 13 | 123 | 31 |
| 2 | 40.8 | 24.3 | 2.08 | 1 | R | 47 | 11 | 103 | 35 |
| 3 | 57.1 | 33.3 | 2.08 | 1 | R | 69 | 11 | 125 | 81 |
| 4 | 45.0 | 27.7 | 2.08 | 1 | R | 21 | 10 | 71 | 64 |
| 5 | 44.7 | 29.1 | 2.08 | 1 | R | 36 | 7 | 50 | 77 |
| 6 | 28.4 | 15.2 | 2.08 | 2 | G | 77 | 25 | 122 | 7 |
| 7 | 38.2 | 20.6 | 2.08 | 2 | G | 45 | 12 | 117 | 11 |
| 8 | 38.2 | 23.1 | 1.30 | 2 | G | 58 | 11 | 121 | 27 |
| 9 | 23.8 | 12.7 | 1.30 | 2 | G | 48 | 15 | 146 | 13 |
| 10 | 27.8 | 14.4 | 1.30 | 2 | G | 42 | 11 | 163 | 33 |
| 11 | 47.3 | 24.8 | 1.30 | 2 | G | 52 | 12 | 122 | 60 |
| 12 | Air-dried | | | 2 | G | 58 | 7 | --- | 48 |

Experimental results include final humidity, drying time and the percent of the load that was rejected. These are shown in columns $H_f$, t and R, respectively.

As mentioned before, an average load humidity content of 12% was set as criteria to end an experiment. A sufficiently close value was obtained in all experiments except No. 6, which ended at a value of 25% because it was the first performed by a new assistant who misinterpreted the experimental procedure. It was impossible to finish it but unnecessary, since examination of the slope of the drying curve showed that the time required to reach 12% would have been too much.

All experiments were directed to obtain a total drying time of about 120 hours and, as shown in column t, the use of temperatures below 30 °C fails to satisfy this constraint and this fact leads to conclude that temperatures must be higher. Although with slightly higher rejection rates the use of temperatures below 40 °C meets the time constraint. In fact, the last row of Table 1 shows that the rejection rates are of the same order of magnitude as those of the air-dried wood. Temperatures above 40 °C must be rejected in view of the unacceptable rejection rates.

It seems that the use of different flow velocities, at temperatures of around 39 °C, does not affect either the overall drying time or the rejection rate and, therefore, the lower velocity should be preferred since it would lead to lower power requirements. However, the initial lower humidity content in the lower velocity experiment would add about ten hours of drying time and the savings in power consumption should be weighed against the extra costs for the longer time.



Dried at 57 °C Dried at 39 °C

Figure 6. Comparison of wood quality

The left side photo in Figure 6 shows wood deformations at 57 °C, while that on the right corresponds to 39 °C. It is clear why the reported rejection values are so high for the former. Deformations as large as those of the left side photo were found for temperatures above 40 °C and were similar to those of the right side for temperatures below 30 °C. Besides deformations as those of the photos, side and end checks were found to be a lot more frequent for the higher temperatures.

Transversal cuts Longitudinal cuts

Figure 7. Three prongs test results for wood dried at 39 °C

Figure 7 shows the residual stresses test performed as described in the Kiln's Operator Handbook (Simpson, 1991). The photos show cuts made in one of the samples dried at 39 °C. Since no deformations were in evidence (even after months of test), it may be concluded that the drying process is very mild at these temperature and velocity conditions.

Because of the large deformations found for higher temperatures the three prongs test was not performed on wood dried at those temperatures.

Preliminary design

System heat duty

Taking the above observations into account the economical analysis of the process was based on the air conditions of experiment No.7. The evaluation was based on a medium size drying chamber with a capacity of 20000 ft-bd filled with wood stacks of the regional standard size of 2.4 m long x 1.2 m high x 1.1 m wide. A chamber of this size accommodates 36 stacks of wood and, with 1" thick of a typical red oak green wood humidity of 60% (Pérez, 1999), the load consists of about 95000 kg of dry wood and 57000 kg of water.

The greatest energy demand occurs at the beginning of the drying process, when the evaporation load is at a maximum as it follows the slope of the drying curve. If the system was designed for this condition, the heat pump capacity, and required investment, would be large and the system would work at partial load most of the process time. Therefore the system must be designed for a lower drying capacity with the penalty of employing longer drying times.

For the selected drying curve, the drying rate for the first period of measurement (4 hours) is 1.93 %/h. This is equivalent to evaporate 0.509 kg/s of water with a required energy of $1.212 \times 10^6$ J/s or 345 tons of refrigeration. On the other hand, the use of the process average drying rate (0.4 %/h) requires only 0.1055 kg/s of evaporation, $2.512 \times 10^5$ J/s or 72 tons of refrigeration.

If this capacity were selected, the process would be restricted up to the point where the average drying rate occurs in the drying curve (27 hours and 31.5 % humidity) but it would take 71.25 hours to reach the same humidity with the constant lower drying rate of 0.4 %/h. Therefore, the process would require 71.25 – 27 = 44.25 extra hours, extending the total drying time to 161 hours. This is quite reasonable in view of the large potential savings by the use of smaller equipment.

Since load heating time measurements were not made, the required energy for this part of the process is implicit in the drying curve. However, the dryer structure heating and the dryer wall heat losses have to be accounted for. Estimates of these loads resulted in 3450 J/s for structure heating in five hours and 870 J/s for heat losses. These values are negligible, respect to the evaporation load, because the structure construction was based on polyurethane panels, which have very low heat capacity and thermal conductivity.

System power requirements

Volumetric flow estimates, based on the superficial velocity of the experimental tests of 2 m/s, resulted in 21.83 $m^3/s$ (19.64 kg/s) with a system pressure drop of 2000 Pa and power requirements of about 60 HP for the air handling system.

To obtain the heat pump cycle compressor capacity the operating temperatures must be defined. These depend on the drying air cycle conditions, which will now be analyzed. The drying chamber air inlet conditions are those of experiment No. 7, $T_{db} = 38$ °C, $T_{wb} = 21$ °C, and at the local barometric pressure of 81571 Pa the water content is 0.01247 kg/kg dry air. These conditions are the required air exit conditions from the heat pump cycle condenser and, with the aid of the condenser terminal temperature difference, they fix the high temperature of the heat pump refrigerant. For the purpose of cost estimation, this temperature was set at 43 °C with a reasonable terminal temperature difference of 5 °C.

To obtain the drying chamber air exit conditions, the average drying rate is used to calculate the humidity addition of 0.1055/19.64 = 0.00537 kg/kg, therefore, the air exit humidity is 0.01784 kg/kg. The dry bulb temperature is obtained from the evaporation load, which must be supplied from the air sensible heat. This balance yields an exit dry bulb temperature of 25.2 °C. Since the drying process is adiabatic, these conditions have a wet bulb temperature of 21 °C and are the inlet conditions for the evaporator of the heat pump cycle.

At the evaporator exit the humidity and temperature are obtained as follows. The humidity must be the desired value at the drying chamber inlet (0.01247 kg/kg), since the condenser duty is to heat the air only.

Although the temperature is fixed by the evaporator coil design, its lowest value must be that of the dew point temperature at the air humidity content which is, for the conditions under consideration, 13.8 °C.

Using again a 5 °C terminal temperature difference fixes the refrigerant low temperature for the heat pump cycle in 8.8 °C.

Based on the refrigerant temperatures and the system heat duty, a required compressor power of 60 HP was calculated with the methodology of Bagnoli et al., 1973.

Economic analysis

The heat pump system components' costs were obtained from local companies and resulted in an investment of $1,140,900, while the conventional plant investment costs of $557600 were obtained from a local saw mill (Andrade, 2000). Information about the conventional drier included electrical power, fuel and manpower requirements since additional costs considered were maintenance (5% of investment per year), electrical power ($1.656/kW-h), fuel ($9.6/m$^3$) and direct labor ($200/day).

Costs calculations were based on 9 days of operation for each heat pump drier load (7 days of drying plus two days for loading and unloading operations) and 40 days for the conventional drier, which with an 80% facility use factor result in 36 and 7 loads per year respectively.

Results of the cost estimates are shown in Table 2 for the two different systems under consideration and for all costs considered. All amounts were calculated per drier load except for the unit cost, which is based on 1000 ft-bd. Investment costs were based on a useful time of 20 years for all equipment.

Table 2. Cost comparison

| Concept | Heat pump | Conventional |
|---|---|---|
| Investment | 1584.58 | 3982.86 |
| Maintenance | 1584.58 | 3982.86 |
| Labor | 5000.00 | 24800.00 |
| Electrical energy | 24048.43 | 71253.04 |
| Fuel | ---- | 5168.19 |
| Total | 32217.59 | 109186.95 |
| Unit cost | 1.61 | 5.46 |

Examination of the costs shows that the conventional drier is a lot more expensive than the heat pump drier, this fact results from the length of the drying period.

Although the investment cost is lower for the conventional drier, when divided by the number of loads per year the resulting value is larger. This is also true for maintenance and electrical energy requirements. Labor costs are directly proportional to drying time as there is always an operator tending the drier. Fuel costs are non existent for the heat pump drier.

These results have to be regarded with caution since they were based on experimental results obtained in a small-scale laboratory drier but given the great reduction in costs, further research is fully justified.

## CONCLUSIONS

An alternative to the conventional process for drying Durango red oak, which presents difficulties, was investigated. This process is based on the use of drier air inlet conditions of low temperature and humidity, which are accomplished by means of a heat pump cycle. The air dry bulb temperature was investigated at four levels and the superficial velocity at two levels. Results showed that the best temperature is around 40 °C with an air velocity of 2 m/s.

With a measured drying curve as a basis a preliminary system design was made and the resulting operation conditions were used for a cost comparison between the conventional and proposed dryers. It was found that the cost of drying might be greatly reduced by the use of the heat pump dryer, although further research is needed to support findings at a laboratory scale.

## NOMENCLATURE

| | |
|---|---|
| G | Sample group |
| $H_i$ | Initial wood humidity, % |
| $H_f$ | Final wood humidity, % |
| IC | Initial wood condition |
| R | Percent wood rejection, % |

| | |
|---|---|
| t | Time, hours |
| T | Temperature, °C |
| $T_{db}$ | Dry bulb temperature, °C |
| $T_{wb}$ | Wet bulb temperature, °C |
| V | Velocity, m/s |

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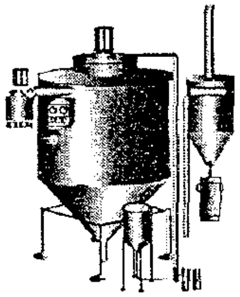

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