

SIMULATED COMPARATIVE ANALYSIS OF SORTING STRATEGIES FOR RFV DRYING

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(Received March 2002)

ABSTRACT

In this work, a numerical stochastic model is used to compare three possible sorting strategies in radio frequency vacuum (RFV) drying of thick timbers, namely, moisture content based pre-sorting (MCPS), batch dry/sort/redrying (b-DSRD) and continuous or retro-feed dry/sort/redry (c-DSRD). The model parameters were calibrated with experimental data of western hemlock dried in a commercial RFV dryer, and the results of the simulations were compared to a single pass base case (SPBC). The numerical results clearly demonstrated the differences among these strategies. The MCPS showed no significant improvement in final timber quality as defined by average timber moisture content, but there is an evident improvement in both b-DSRD and c-DSRD. The comparison was based on the increment of the percent of the on-grade wood (within moisture content range) and the reduction of overdried and underdried (wets) percentages. Furthermore, it was also shown that the effective drying time is roughly independent of the drying strategy.

Keywords: Timber drying, stochastic model, moisture dispersion, sorting strategies.

INTRODUCTION

Wood drying is a process of stochastic nature. Drying conditions are not always constant and homogeneous throughout the drying timber volume, and the timber population usually exhibits significant differences in individual moisture contents (M) and intrinsic characteristics. As a result, the final moisture content (M_f) is not a precise value, but a frequency distribution within a certain range of dispersion (usually with a logarithmic profile).

According to commercial requirements, only timbers within a narrow range of M_f dispersion can be considered suitable with the rest usually sold at a lesser price, in part because of the unacceptable levels of defects (re-

lated to overdrying) and in part because of its inherent dimensional instability (related to wet timber). A small and precise range of M_f distribution is strongly desired by the industry and users. In recent years, some new drying strategies for western hemlock timbers have been studied (Aune 2000; Avramidis 2001), namely, moisture content presorting (MCPS), in which the initial green timber charge is split into two or more subgroups with smaller ranges of dispersion, and the dry/sort/redry method (DSRD), in which the timbers that remain wet after a first drying pass (where M_f is much higher than normally intended by the industry) are redried in one or more successive passes.

With the development and verification of a new stochastic predictive model (Elustondo et al. 2002; Elustondo and Avramidis 2002a, b),

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it is now possible to explore these drying strategies by using numerical simulation exclusively. In this paper, both MCPS and DSRD were simulated and scrutinized, and a comparative analysis was carried out in regards to a single pass base case (SPBC). Consequent theoretical analysis showed that the DSRD technique clearly increased the within-range percentage of wood and therefore reduced the underdried and overdried portions of the population. The MCPS method also showed some improvement, but small in comparison to the DSRD one.

MODEL ANALYSIS

In a former study (Elustondo et al. 2002; Elustondo and Avramidis 2002a, b), a numerical method was developed to simulate stochastic RFV drying of wood. This was based on well-known deterministic models, but some representative parameters like green or initial moisture content (M_i), timber thermo-physical properties and drying conditions, were assumed as distributed between a certain range of dispersion. The method calculates the fraction of measurements associated with different M_i values and parameter combinations, and several simulations are performed simultaneously in order to calculate the variables that depend on the average conditions. The sources of random dispersion depend on each system, but in the case of RFV timber drying, the proposed stochastic model works with three basic data sets, namely, M_i distribution of the charge, variation of thermo-physical properties and drying conditions, and an additional error that could be introduced during the experimental measurements.

In a common industrial run, M_f is normally obtained with in-line capacitance moisture meters, and discrepancies between the measured and actual M_f values are usually observed as was shown in Avramidis (2001). In order to estimate the random error introduced by the meter, each timber was measured at six different points. The results showed that the M_f dispersion for points obtained within the same

specimen tends to increase with the timber's average moisture content. Therefore, the relation between the simulated moisture content (M_m) and the measured one (M) is calculated from a correction factor (α), and a dimensionless and normally distributed random error ($f(\sigma)$), according to the following empirical relation

$$M = \alpha(1 + f(\sigma))M_m \quad (1)$$

For this study, a correction factor of $\alpha \approx 0.8$ and a $f(\sigma)$'s standard error of approximately 10% were estimated from the experimental data.

In Elustondo et al. (2002), it was concluded that the basic stochastic behavior of an RFV drying curve could be attributed to a minimum of three stochastic parameters and their standard deviations. These are the intrinsic permeability (K) that is related to the initial time delay, the proportional factor (Ψ) that affects the amount of electric energy absorbed by the wood, and the critical moisture content (M_{crit}) at which the drying curve starts to have asymptotic behavior. The simulation model is then calibrated with experimental moisture content histograms. These histograms are usually lognormal (Catalin 2001; Cohen 1951; Cohen et al. 1985; Crow and Shimizu 1988), so they can be represented with three parameters, i.e., the scale (equivalent to the average), the shape (equivalent to the standard deviation), and the threshold that quantifies the fact that the M distribution has a positive lower boundary (θ).

Random dispersion of the stochastic parameters is simulated by transforming the continuous probability density curves into sets of discrete value-probability points. Green timber charges also have their own frequency distribution, so that the M_i distribution is divided into a set of discrete points with associated fractions of the total population. The simulation is repeated for all possible combinations among these discrete curves, and the different M_f values with probabilities given by their corresponding parameters and M_i combination are obtained. Although the accuracy of the meth-

TABLE 1. Experimental drying data and results of the model calibration.

	Charge 1		Charge 2		Charge 3		Average	
Experiment M_f								
M_f [%]	19.07		18.64		15.33			
σ [%]	6.31		5.95		5.56			
θ [%]	9.00		8.33		7.83			
Drying conditions								
PD [W/m ³]	667.5		714.0		630.3			
t [hrs]	100.7		88.3		119.0			
Fitted parameters	Mean	σ	Mean	σ	Mean	σ	Mean	σ
$\log(K)$	-10.89	0.547	-10.70	0.483	-10.75	0.569	-10.78	0.533
Ψ	1.43	0.188	1.43	0.178	1.43	0.194	1.43	0.186
M_{crit} [%]	31.8	1.77	3.22	2.30	28.8	2.21	31.0	2.09

od will increase with the number of simulations, the discrete value-probability points represent complete distribution curves, so that the number of points does not have a determinant effect in the average and range of dispersion of the result. For the purpose of this work, 5, 3 and 3 discrete points were used to represent K , Ψ and M_{crit} probability distributions, and 5 discrete points were used to represent the M_i distribution. The total number of simulation was the result of $5 \times 3 \times 3 \times 5 = 225$ possible combinations.

An iterative optimization subroutine was incorporated in the model in order to fit the experimental histogram's mean, standard deviation, and threshold. Since the positive lower boundary is not totally sharp in the experimental histograms, some range of tolerance (ξ) was accepted for the experimental threshold; thus the following objective function (F_{obj}) constant for any threshold inside the ξ range was implemented in the optimization subroutine:

$$F_{obj} = (M - M_m)^2 + (\sigma - \sigma_m)^2 + \left(|(1 + \xi)\theta - \theta_m| + |(1 - \xi)\theta - \theta_m| \right)^2 \quad (2)$$

where ξ was assumed equal to 10% (consistently with the dimensionless standard error on the experimental M measurement).

Experimental data were collected from western hemlock timbers (*Tsuga heterophylla*

(Raf.) Sarg.) dried in a commercial RFV dryer described by Avramidis (2001). The green timber dimensions were 116 mm by 233 mm by 4 m long, and three drying runs were carried out to explore the relationship between the average M_f and the final data dispersion. A total of 480 green timbers (50.8 m³) freshly cut in a local sawmill with no visual defects were randomly split into three charges of 160 pieces each (see Table 1).

Before each drying, the M_i distribution was measured from a 90-piece sample population by cutting a slab of 25 mm in thickness, one from each timber end. The slabs were oven-dried ($103 \pm 2^\circ\text{C}$) and their M_i was calculated gravimetrically. The results showed that the M_i distribution had a mean of 62.6%, a standard deviation of 18.7%, a minimum of 33%, and a maximum of 111.4%. After drying, the M_f of all 480 pieces was measured with a capacitance moisture meter. Six independent measurements were taken on each timber, three on each of the 233-mm-width faces (in the center and the ends).

RESULTS AND DISCUSSION

The data of the experimental histograms, as well as the model calibration results, are shown in Table 1. These are in good agreement with the ones previously obtained in our laboratory for pure western hemlock, but the wood permeability is quite high ($1.66 \cdot 10^{-11}$ m³/m). in comparison to the $10^{-12} \sim 10^{-13}$ m³/

TABLE 2. Individual pass results for the different drying strategies.

Case	t [hrs]	Mean M_f [%]	σ [%]	Min M_f [%]	Max M_f [%]	Over dried [%]	On grade [%]	Wet [%]
SPBC	97.16	16.09	5.18	7.81	58.22	26.50	53.75	19.76
MCPS								
Lower 50%	71.41	16.09	3.49	8.57	33.86	8.29	33.09	8.62
Higher 50%	121.27	16.09	5.07	7.73	51.79	13.66	26.61	9.73
b-DSRD								
Pass 1	65.69	22.81	8.39	9.35	75.90	5.29	32.81	61.90
Pass 2	42.50	17.82	4.57	9.35	63.28	5.06	38.59	18.25
Pass 3	37.78	16.31	3.12	9.35	52.14	2.01	13.48	2.76
c-DSRD	48.61	21.62	8.31	9.35	81.15	5.76	42.43	51.80

m measured by Koumoustakos et al. (2001). This occurs because the model considers only one-dimensional longitudinal heat and mass transfer; thus the wood permeability contribution within the model increases to compensate the overpredicted longitudinal flow.

The different drying strategies were compared using the same model information, namely, the green M_i distribution measured experimentally in the 90-piece western hemlock sample, the average stochastic parameters calibrated with the three 160-piece experimental histograms, and a constant power density of 800W/m^3 . The range of on-grade M_f is assumed between 13% and 19%, according to commonly accepted values by the timber industry. Since no economical analysis was carried out, both overdried and underdried wood is considered out-of-range.

The results of the simulations are shown in Table 2, namely, drying time, M_f average, standard deviation, minimum and maximum, and percentages of on-grade, overdried and wet timbers. The SPBC is a single-pass run to an average M_f of 16.09% that is the target for

which the model predicts the maximum percentage of on-grade timbers. As can be seen, the drying time is 97.16 h, the percentage of within-range timber is 53.75%, and the percentages of overdried and wet wood are 26.5% and 19.76%, respectively.

For the MCPS strategy, only the simplest case was simulated. The initial green population was split into two subgroups at an intermediate M_i of 60.5% that represents the point for which both subgroups contain 50% of the green population. The results of the simulation are shown in Table 2, where it can be observed that 71.41 h were necessary to dry the lower 50% and 121.27 h to dry the higher 50%. Table 2 also shows that the minimum M_f obtained for the higher 50% is smaller than the minimum M_f obtained for the lower 50% (7.73% and 8.57%, respectively), and even smaller than the one obtained for SPBC (7.81%). This is an indication that the effect of the process's intrinsic dispersion is as important as the effect of the green moisture distribution, so this particular MCPS strategy does not produce considerable improvement with respect to SPBC. The results are shown in Table 3, where the percentage of within-range wood increases by only 11% with respect to SPBC (from 53.75% to 59.70%). In Fig. 1, the simulated histograms for M_f for the sort-out method and the SPBC are compared. It can be seen that in the former, the frequency distribution is a little more symmetrically distributed within the $13\% < M_f < 19\%$ range.

TABLE 3. Combined all passes results for the different drying strategies.

Case	t_{eff} [hrs]	Over-dried [%]	On-grade [%]	Wets [%]
SPBC	97.16	26.50	53.75	19.76
MCPS	96.34	21.96	59.70	18.35
b-DSRD	98.89	12.36	84.88	2.76
c-DSRD	100.85	11.95	88.05	0.00

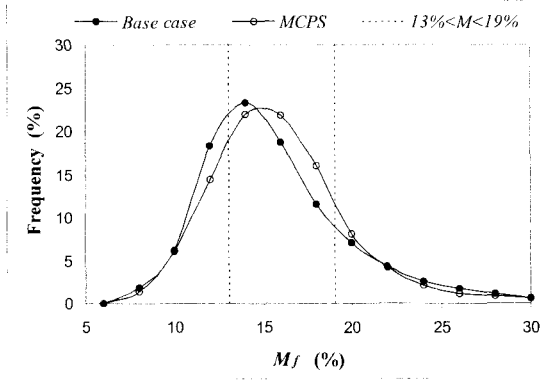


FIG. 1. Histograms comparison between SPBC and MCPS strategies.

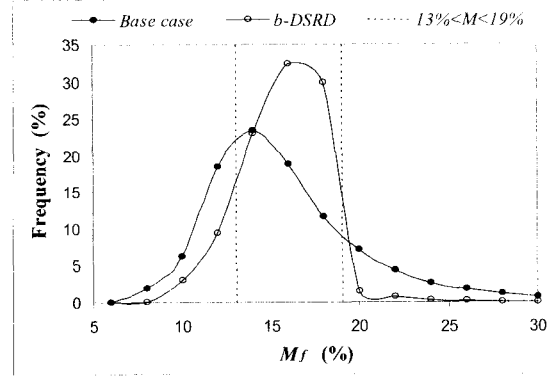


FIG. 2. Histograms comparison between SPBC and b-DSRD strategies.

In order to calculate the drying time, the kiln is assumed completely filled at any step of the process. Despite the fact that the runs use only a fraction of the initial charge, the total amount of initial material will be scaled to fill an integer number of kilns. Under this assumption, an effective time (t_{eff}) is defined as the time needed to dry all the green population, divided by the number of kilns that this green population can fill. For the MCPS strategy, effective drying time is the summation of the number of kilns filled for each subgroup, multiplied by their respective drying time, and divided by the kilns filled for the green charge:

$$t_{eff} = \sum_n x_n t_n \quad (3)$$

where x_n is the fraction of the green charge contained in the subgroup n . Table 3 lists and effective drying time of 96.34 hours.

In the b-DSRD strategy, wood is not completely dried during the first pass, but a second or more passes are performed in order to dry the residual wets. For this study, the number of redry passes was arbitrarily fixed to three and the minimum M_f was set at 9.35%, that is, the point for which the model predicts the maximum percentage of on-grade timbers. Table 2 shows the results for the three single passes. It is interesting to note that contrary to common sense, it is not in pass 1 in which most part of the wood is dried, but in pass 2

(38.1% has been dried in pass 1, counting on-grade and overdried, and 43.65% in pass 2).

In order to calculate the effective drying time for the b-DSRD technique, it is assumed that each pass n will be repeated (and the wets stored apart) until there is enough wet material to completely fill a kiln and continue with pass $n + 1$. Then, the effective drying time is the summation of the number of kilns filled in each pass, multiplied by their respective drying time, and divided by the kilns filled for the green charge:

$$t_{eff} = \sum_n w_{(n-1)} t_n \quad (4)$$

where $w_{(n-1)}$ is the fraction of the green charge that remains wet after the pass $n - 1$ ($w_0 = 1$ for the green charge). Final results of the b-DSRD strategy can be seen in Table 3. The effective drying time is 98.89 h, and there is a notable improvement with respect to SPBC, i.e., on-grade percentage increases from 53.75% to 84.88%, overdried percentage reduces for 26.50% to 12.36%, and the percentage of wets is almost zero. Figure 2 shows the comparison between b-DSRD and the SPBC histograms. It can be observed that, contrary to the trend encountered in the latter, in b-DSRD the highest frequency of measurements is close to the 19% limit. This is an encouraging result because wood degradation increases with the reduction of M_f .

The c-DSRD strategy is also simulated. The

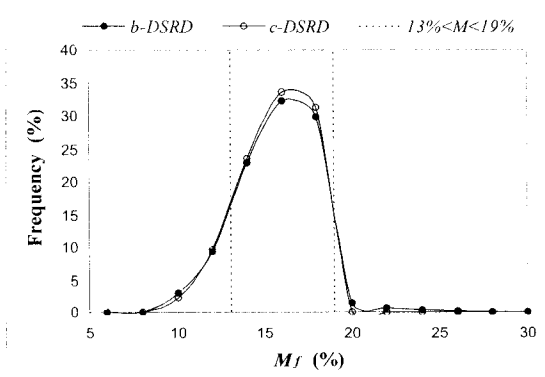


FIG. 3. Histograms comparison between b-DSRD and c-DSRD strategies.

difference between this and the b-DSRD one is that in the former, wets obtained after one drying pass are not stored, but redried in the next pass mixed with more green material (retro-feed strategy). Results for the c-DSRD method are shown in Table 2, where it can be observed that 51.8% of the timbers is continuously retro-fed (together with an extra 48.2% of green material). The comparison between b-DSRD and c-DSRD strategies is shown in Table 3 and Fig. 3, where the absence of wets, a slight increase of the on-range percentage, and a slight reduction of the overdried percentage are observed in the latter.

In order to calculate the effective drying time, it is assumed that the c-DSRD strategy is in a stationary regime, namely, M_i and M_f distributions do not change in successive iterations. While after each pass only the fraction of non-wets is taken out from the process, the effective time is then calculated by the following equation:

$$t_{\text{eff}} = \frac{t}{1 - r} \quad (5)$$

where r is the fraction of recycled timbers. Table 3 shows that for the c-DSRD strategy, the effective drying time was 100.85 h.

CONCLUSIONS

In this work, different drying strategies in order to reduce the range of M_f dispersion in

RFV drying of timbers were studied. The first involved the sorting out of M_i distribution in subgroups with smaller range of dispersion, and the second, the sorting out of M_f distribution and the redrying of the timbers that were still wet. A theoretical analysis was carried out in comparison to SPBC, and in the case of the redrying method, the retro-feeding option was also simulated. Results showed that in the case of the MCPS strategy, there is not enough improvement to justify its implementation, but the improvement obtained with the DSRD strategies is clear. In the DSRD, a very high percentage of on-grade timbers, very low percentage of wets, and a reduction of overdried timbers were obtained with respect to SPBC.

Another interesting conclusion about RFV drying is that the effective drying time of the different methods is almost the same. That is because the RFV technology incorporates the capacity to control the average power density absorbed by the wood at any instant; therefore, at constant power density and charge volume, drying time is basically a function of only the total amount of evaporated water (and therefore of the target). Since losses of energy are directly proportional to the drying time, the fact that the effective drying time does not change with the method means that the percentage of within-range wood can be improved without detriment on the energy efficiency.

The sort-out methods presented in this paper are designed to reduce M_f distribution in industrial drying of timbers, and this is according to the premise "the lower the M_f range of dispersion, the higher the quality of the dried timbers" (Welling 2002). Although this affirmation is usually accepted, the possibility to implement these strategies in industry depends on the fact that revenues from a higher quality of wood could compensate the additional operation costs. Therefore, optimization of the MCPS or DSRD strategies cannot be done only on the base of M_f distribution, but a more complete assessment is required. A previous study (Avramidis 2001) showed that

the DSRD strategy is economically viable at industrial scale (so future trials are projected in order to perform a more accurate evaluation), but two mayor issues must still be addressed in order to optimize these methods: to determine the timber grade of improvement produced by reducing the M_f range of dispersion, and to develop an economic model capable of quantifying revenues and costs in the more complex DSRD strategy.

ACKNOWLEDGMENTS

This project was financially supported by a Technology Partnership Program grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada and by a grant-in-aid from HeatWave Technologies Inc.

NOTATION

- F_{obj} = Objective function for the calibration of the model.
 $f(\sigma)$ = Dimensionless random error introduced by the MC meter.
 K = Wood permeability. [m^3/m]
 M = Moisture content.
 M_{crit} = Critical moisture content.
 PD = Power density. [W/m^3]
 r = Fraction of recycled material.
 t = Drying time. [h]
 t_{eff} = Effective drying time. [h]
 w = Fraction of the green population that remains wet after drying.
 x = Sorted out fraction of the initial green population.
- Greek letters
 α = Relation between real M and the value obtained with the M -meter.
 θ = Threshold of the M distribution.
 σ = Standard deviation.
 ξ = Range of tolerance for the threshold parameter.
 Ψ = Proportional factor affecting the wood dielectric loss factor.

Subscripts

- f = Final.
 i = Initial.
 m = Simulated with the stochastic model.
 n = Number of drying pass.

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