Radio Frequency Vacuum Drying of *Eucalyptus nitens* Juvenile Wood

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Wood drying is an important process for adding value and manufacturing innovative products. *Eucalyptus nitens* wood is inherently difficult to dry because of its natural propensity for checking as well as collapse and shrinkage. Lumber recovery after industrial drying of eucalypts is also very low. This study measured the wood quality of *E. nitens* juvenile wood (13 mm thickness) after radio-frequency vacuum (RFV) drying and wood dried in a conventional kiln dryer (KD). Drying cycles were performed using a radio frequency vacuum dryer with a 3 m^3 of capacity and convective kiln-dryer equipment with a 3.5 m^3 of capacity. The results showed that the drying time using the radio frequency vacuum method was reduced by 47% when compared to conventional kiln drying. The shrinkage was significantly lower in the RFV than in the conventional KD. The volumetric collapse decreased by approximately 60% in the RFV drying. RFV drying of *E. nitens* juvenile wood improves the wood quality for solid wood products because the intensity of surface checking and collapse are reduced.

Keywords: Collapse; Drying costs; Drying defects; Drying time; Shrinkage; Wood drying

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INTRODUCTION

Plantations of *Eucalyptus nitens* in Chile cover an approximate area of 270,000 hectares, which correspond to 11.8% of the total plantation surface. In 2018, the industrial consumption of solid wood products from these plantations was 4,820.9 thousand m^3, including wood chips (51%), panels and veneers (4%), and sawn wood, which corresponds to only 0.1% of the harvested wood (Gysling *et al*. 2019). There is high interest in Chile in increasing the amount of *E. nitens* wood processed into sawn wood.

Unfortunately, *E. nitens* wood is inherently difficult to dry because of the natural wood variability and the propensity to surface checking, internal intra-ring checking, and collapse. As a result, the lumber recovery after conventional kiln drying (KD) of *E. nitens* is generally very low. In hardwoods and other lumber types have a propensity for collapse, the conventional KD is a process that consumes high amounts of energy and time (Yang and Liu 2018). Furthermore, the development of high internal stresses due to moisture gradients that develop in KD could lead to considerable degradation and poor quality of the final product (Pérez *et al.* 2018).

The estimated collapse of *E. nitens* by conventional KD is from 1.9% to 2.4% in the radial direction and 2.6% to 4.9% in the tangential direction. Young wood in *E. nitens* is not more susceptible to collapse than the more mature parts of the tree (Ananías *et al.* 2009, 2014). On the other hand, it has been found that the diffusion coefficient in the radial direction is approximately 50% higher than in the tangential direction (Sepúlveda *et al.* 2016). This has been observed even though the strain-stress is developed approximately at the same time in both directions. Mechano-sorptive strain has a high contribution to the total deformation; it is near 59% (Pérez *et al.* 2016). However, the perpendicular compressive strength in *E. nitens* may not be sufficient to resist the high drying stresses that induce collapse (Pérez *et al.* 2020).

In some studies, radio frequency vacuum (RFV) drying in large, thick, or refractory lumber pieces was found to be more appropriate and effective (Harris 1988; Avramidis and Zwick 1996; Jung *et al.* 2004; Fu *et al.* 2018). According to Hansmann *et al.* (2008), RFV drying has been a successful alternative method for wood drying because it allows for a low working temperature and improves the relationship between quality, time, and drying costs. Some authors confirm that RFV drying is associated with a lower occurrence of surface and internal checking, collapse (Espinoza and Bond 2016; Liu *et al.* 2019), and a reduction of shrinkage (Lee and Jung 2000). At the same time, it also reduces the drying time and could lead to higher economic returns (Avramidis and Liu 1994; Elustondo *et al.* 2005; Rabidin *et al.* 2017). During RFV drying, wood is exposed to low pressure conditions and heated with electromagnetic waves. Thermal energy is generated when these electromagnetic waves penetrate green wood. RF heating is produced by dissipation of the energy absorbed, which is transferred to the water within the wood and distributed as volumetric heat transfer (Resch 2006). On the other hand, the vacuum condition reduces the boiling point of water, which makes the water in the wood able to be rapidly vaporized at temperatures below 100 °C. In this condition, temperature and pressure gradients can be developed that can increase the drying rate at the different drying stages (Avramidis *et al.* 1994; Resch 2009; Liu *et al*. 2014; Espinoza and Bond 2016). In conventional KD processes, heat transfer is given by the circulation of hot air to the surface of each wood piece and the subsequent heat transfer from surface to the center (Avramidis and Liu 1994). Furthermore, higher internal stresses are developed due to thermal and moisture gradients (Sepúlveda *et al.* 2016; Pérez *et al.* 2018).

It was hypothesized that the drying problems of *Eucalyptus nitens* juvenile wood can be reduced by using the radio frequency and vacuum (RFV) drying technique, since such processing allows working at relatively low temperatures and heating uniformity. This favors the relationship between quality, time, and drying costs. Thus, the objective of this work was to evaluate the drying time, shrinkage, drying defects, and costs of *Eucalyptus nitens* juvenile wood dried using RFV compared to conventional KD.

EXPERIMENTAL

Materials

The experiments were carried out using fresh green sawn wood of 15-year-old *Eucalyptus nitens* Deane & Maiden trees from a plantation in Yungay, Ñuble Region, Chile. The lumber was sawed to 13 mm (thickness), 160 mm (width), and 2440 mm (length). Twenty boards were used as control samples for each drying method. The average initial MC was 110% with a standard deviation of 18, and the basic density was 490 kg /m^3 with a standard deviation of 72.

Methods

Drying procedures

RFV drying was conducted in an RFV dryer machine of 3 m^3 capacity (Saga HF-VD30SA, Shijiazhuang, Hebei, China). The RF generator oscillated at a fixed frequency of 6.78 MHz and delivered a power output of up to 30 kW (Fig. 1a). The RFV schedule is shown in Table 1. The sawn wood was stacked as solid piles of 800 mm (width), 800 mm (height), and 2400 mm (length), which were adjusted using a plate height of 200 mm. The wood temperature, pressure, and wood mass were measured every 6 min during the drying process. The wood mass was measured continuously by a load cells systems (Fig 1a-11) and controlled by PLC device (Fig 1a-3). The wood temperature was measured continuously by a fiber optic sensor (Fig 1a-3) and controlled by PLC device (Fig 1a-3).

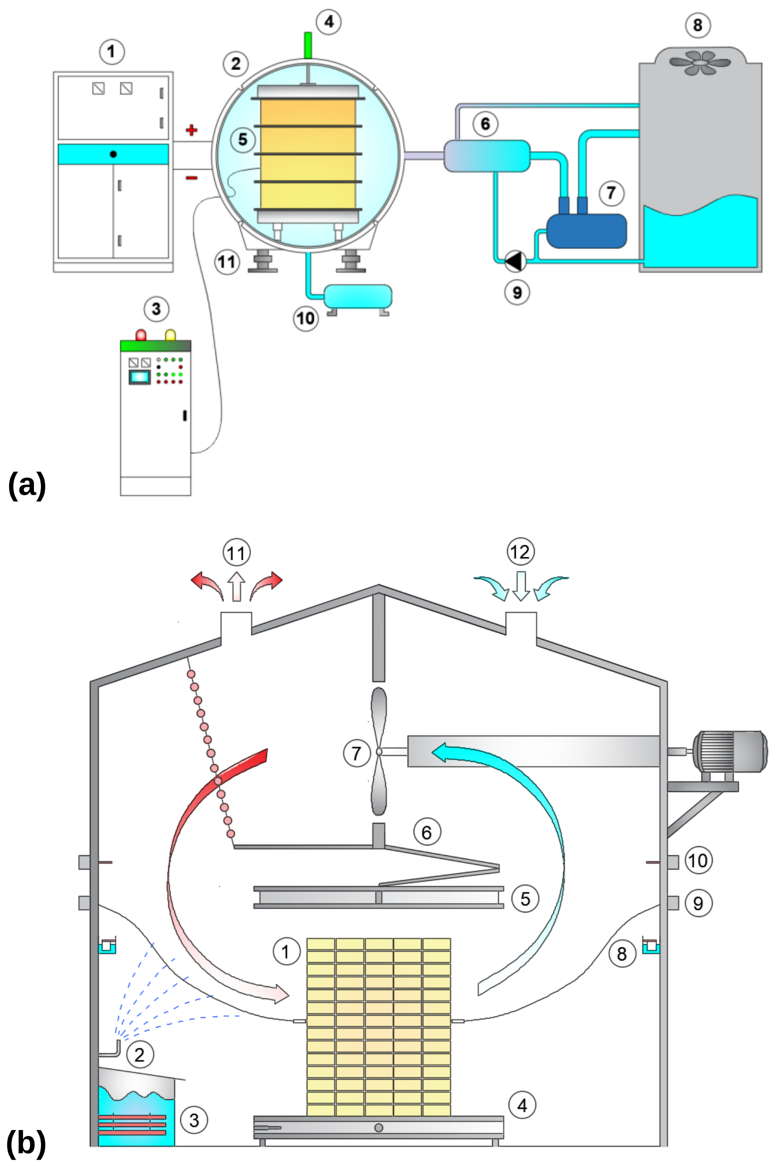

Fig. 1. (a) RFV dryer: 1) RF generator, 2) autoclave, 3) PLC and fiber optic sensor, 4) hydraulic press, 5) wood, 6) cooling tank, 7) vacuum pump, 8) cooling tower, 9) water pump, 10) condensate tank, 11) load cells. (b) KD dryer: 1) wood, 2) sprinkler, 3) evaporation tub, 4) balance, 5) counterbalance, 6) baffle, 7) fan, 8) wet-bulb temperature sensor, 9) wood temperature sensor, 10) dry-bulb temperature sensor, 11) and 12) are vents.

Table 1. RFV Schedule of *Eucalyptus nitens* Wood

T_{wood} (°C)	P (kPa)	T_{boil} (°C)	T_{wood}/T_{boil} (°C/°C)	Pd (kW/m^3)
45.0	9.0	43.8	1.03	1.6

T_{wood} is the wood temperature, P is the chamber pressure, T_{boil} is the boiling point of water, T_{wood}/T_{boil} is the ratio of wood temperature to the boiling point of water, and Pd is the power density (energy per unit volume of wood)

Convective KD with a 3.5 m^3 capacity (Neumann 3,5Lab, Concepción, Chile) was used for conventional drying runs with a temperature of 35 °C to 70 °C and a flow air velocity of 1.5 m/s (Fig. 1b). In this case, a low air flow velocity was used to reduce surface controls, according to a previous work on the conventional drying of *E. nitens* wood (Sepúlveda *et al.* 2016).

The conventional KD schedule is shown in Table 2. The lumber was stacked on 25 mm by 25 mm stickers. The dry and wet bulb temperatures were monitored as well as the temperature and moisture content (MC) of wood according to the setup and kiln schedule.

Table 2. Conventional KD Schedule of *Eucalyptus nitens* Wood

	Time (h)	Temperature (°C)		Relative humidity (%)	MC (%)
		Dry Bulb	Wet Bulb		
Steam heating	1	32	28	74	110
Heating	25	44	38	69	91
Drying > FSP	40	53	43	56	43
Drying < FSP	42	53	43	56	25
Final Drying	34	70	56	50	10
Reconditioning	7	85	84	96	12

The reconditioning was used for collapse recovery in both KD and RFV process. Figure 2 shows some pictures of the wood specimens before and after KD and RFV process.

Determination of drying defects

The total shrinkage of boards (in width and thickness) from green to final MC was determined considering the average of dimension measures in three measuring points located along the specimen (center and both ends), before and after drying. Collapse was calculated based on the difference between shrinkage before reconditioning and shrinkage after reconditioning. Wood warping (cup, bow, crook, and twist of the board) was measured before and after drying by measuring the point of greatest deflection from a straight line between the two ends of the board. Surface checks were visually evaluated to determine the percentage of checked area. A quality index of wood drying defects based to evaluation guidelines for drying quality (Infor 2004) was calculated by comparing both technologies. Additionally, an estimation of production cost was determined after considering the fixed and variables costs (Brenes-Angulo *et al.* 2017).

Data analysis

The results obtained in the study were analyzed using Statistica software (Statsoft Inc., v10.0, Tulsa, OK, USA). Analysis of variance (ANOVA) and Tukey tests were performed on the data set to examine the significance of the differences at a 95% confidence level.

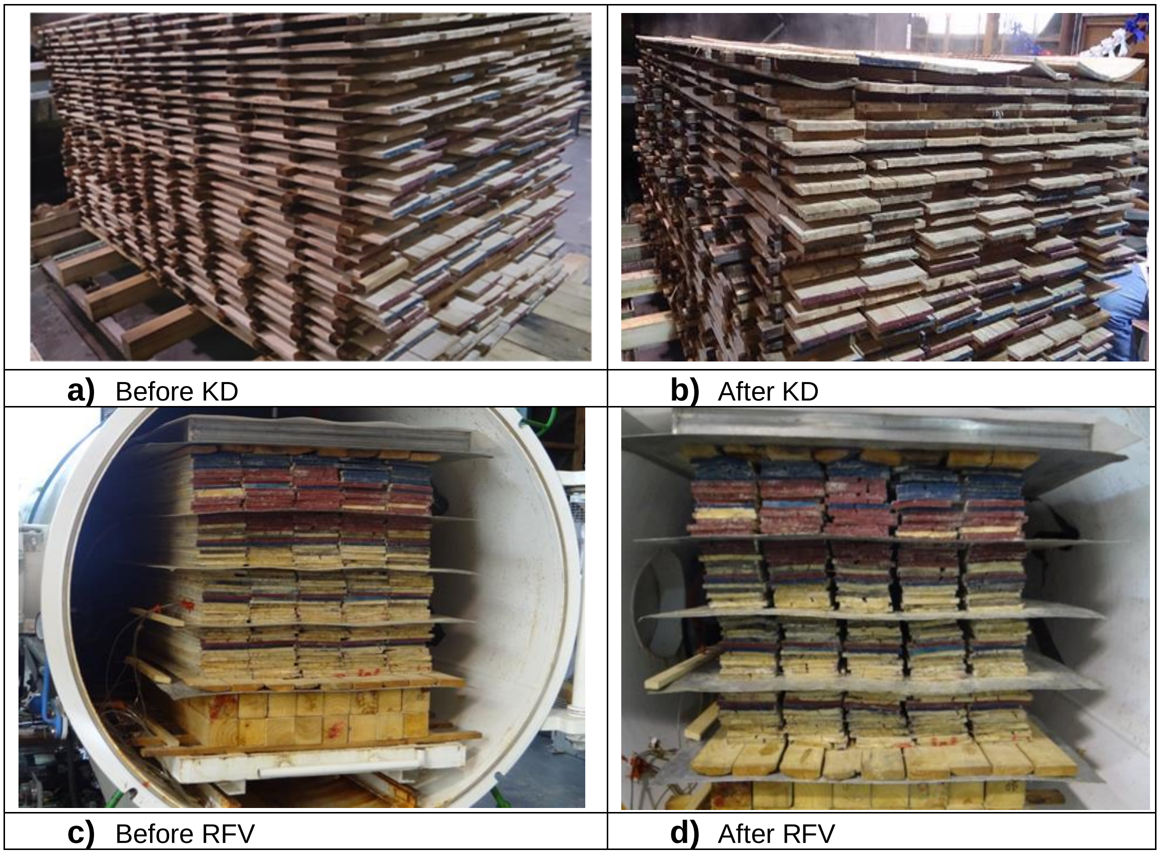

Fig. 2. Wood specimens during the drying process

RESULTS AND DISCUSSION

Drying Time

The drying curves of RFV and conventional KD are shown in Fig. 3. It can be observed that the RFV drying time was about half of the KD time. The total time for the RFV was 84 h with a final MC of 12.4% with a standard deviation of 0.77, while during KD the total time was 149 h with a final MC of 11.7% with a standard deviation of 0.87. These results coincide with those of Avramidis *et al*. (1994), who reported that the RFV drying rates for red cedar were 77% less than KD. Liu *et al*. (1994) and Lee and Jung (2000) also found that the drying time with RFV decreased about 70% to 87% when compared to conventional drying. Recently, Rabidin *et al*. (2017) compared the hardwood drying using the RFV and KD systems and concluded that drying time using RFV was reduced by 50%. According to Liu *et al.* (1994), RFV drying is faster than conventional KD drying due to the higher velocity of free water flow from the inside to the surface.

The average drying rate was 0.65% per h in the conventional KD and 1.14% per h in the RFV. These results imply that the moisture loss per hour in the RFV was approximately two times as fast as that in the conventional KD. Similarly, Rabidin *et al.* (2017) reported a drying rate of 0.07% per h for KD and 0.13% per h for the RFV in 30 mm thick kekatong wood. This difference in moisture loss was also reported by Lee and Jung´s research (2000). They studied the drying behavior of 66 mm thick Korean ash squares. Drying rates of 0.1% per h in RFV and 0.05% per h in KD were obtained in that study (Lee and Jung 2000). The drying rate above the fiber saturation point (FSP) was 2.22% per hour for RFV and 0.37% per hour for KD. Below the FSP, the drying rate was 1.05% per hour and 0.26% per hour for RFV and KD, respectively. The higher drying rate in the RFV can be explained by the reduction of the pressure inside the chamber. This low-pressure condition reduces the boiling point of water, which results in a rapid water evaporation, and as a result, the drying rate is increased. Moreover, the steep pressure gradients caused by the fast generation of vapor accelerate the process. These gradients also increase the rate of diffusion of bound water below the FSP (Avramidis *et al.* 1994). This process implies shorter drying times than those that can be reached at atmospheric pressure (Resch 2006; Espinoza and Bond 2016). Also, the higher penetrability of electromagnetic waves favors rapid heating producing an increase of internal temperature of wood, which increases the moisture transfer from the central part to the surface.

The final MC was between 10.6 and 13.8% in the RFV, while the final MC ranged between 10.1 and 14.0% in KD. For both RFV and KD, 100% of boards were between 10 and 14% MC.

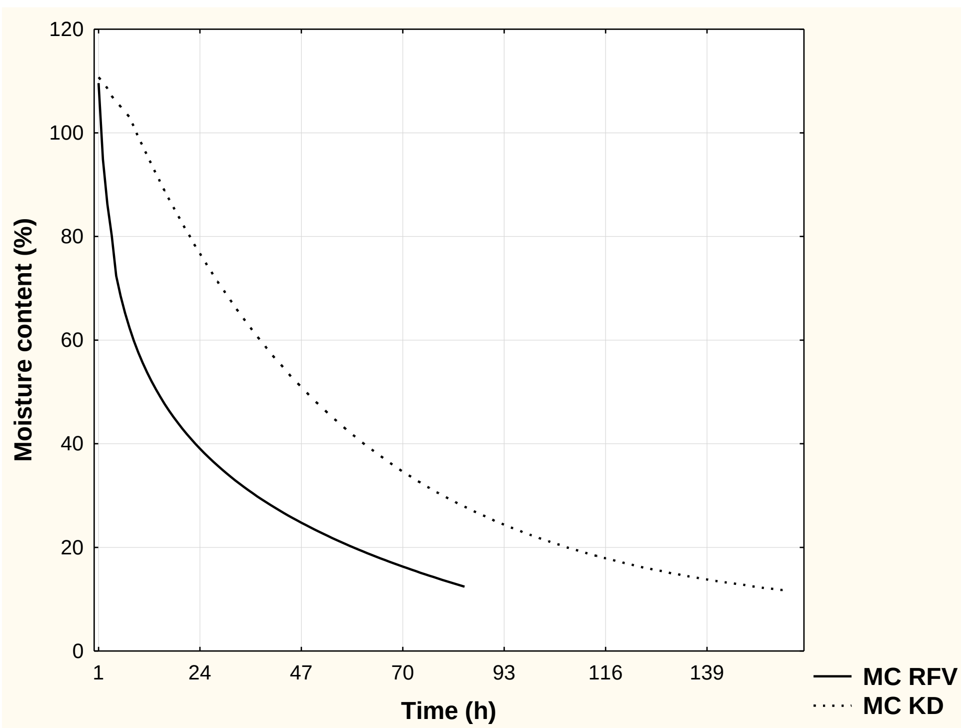

Fig. 3. Drying curves of 13 mm thick *Eucalyptus nitens* juvenile wood

Shrinkage and Collapse

According to F-test results of ANOVA, the drying method had a significant effect on the shrinkage value (Table 3). The shrinkage was significantly lower in the RFV than in the conventional KD. Figure 4 shows the total shrinkage of the RFV and the conventional KD of *E. nitens* at 13 mm thickness. The shrinkage in width and thickness were much lower for the RFV, with values of 2.9% and 2.4%, respectively. For KD, width shrinkage reached 6.7% and thickness shrinkage was 8.2%. Total volumetric shrinkage was 5.3% in the RFV and 15% in KD, which represents a reduction of approximately 65%. These results coincide with those reported in previous studies (Harris and Taras 1984; Lee and Jung 2000). According to the Tukey comparison test, the difference of shrinkage values (width, thickness, and volumetric) between RFV and KD drying was statistically significant at the 0.05 level. The T/R ratio was 0.8 in RFV drying, while the T/R ratio was 1.21 in conventional KD, which represents a reduction of 34%. This decrease of the T/R ratio in the RFV drying is similar to the results of other studies (Lee and Jung 2000; Rabidin *et al.* 2017).

Table 3. ANOVA Results of Drying Method on Shrinkage Values

	F – test of shrinkage		
Source	Width	Thickness	Volumetric
Drying method	20.43 *	49.55 *	72.93 *
*significant at p ≤ 0.001			

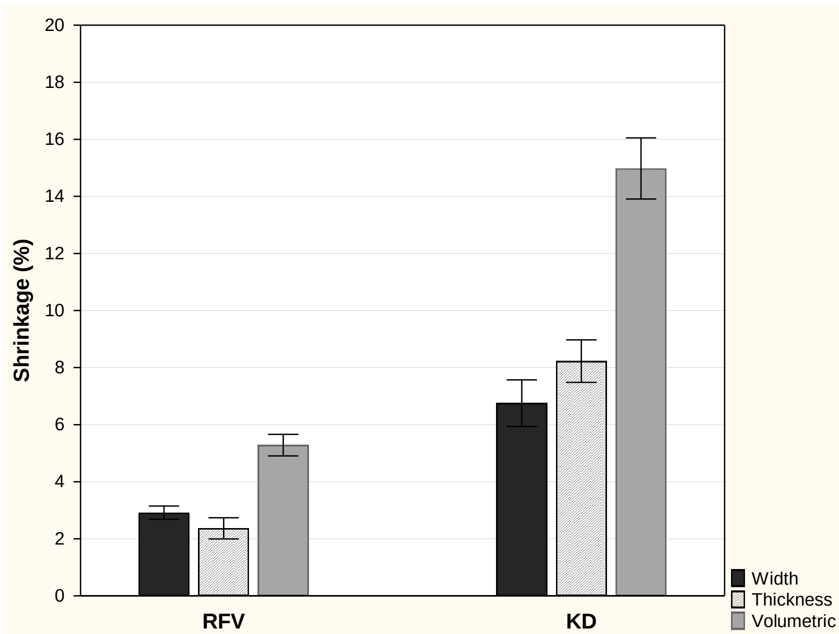

Fig. 4. Total shrinkage in *Eucalyptus nitens*

The collapse in the RFV was lower than in the KD. In the RFV, the collapse values were 1.8% in width and 1.9% in thickness, while in KD the values were 4.3% and 5% in width and thickness, respectively (Table 4). These results imply a considerable reduction of volumetric collapse in the RFV process. In the RFV, the volumetric collapse decreased approximately 60% when compared to the KD. This decrease is much greater than that reported by Lee and Jung (2000), who found that the collapse in the RFV drying of Korean ash squares decreased 20% when compared to KD. Additionally, the estimated collapse of *E. nitens* by conventional KD was higher than pre-drying (Ananías *et al.* 2014).

The shrinkage was excessively higher during drying of *E. nitens* because of the wood collapse prone. Therefore, it was necessary to recovered collapse by reconditioning, which also allowed that internal intra-ring checks were closed. Shrinkage and collapse are lower during RFV process because of drying temperature and drying stresses are lower than in KD. Moreover, during RFV drying the expansion trend effect is low due to a smaller heat expansion of wood.

Table 4. Collapse Values for the RFV and Conventional KD

Drying Technology	Width (%)	Thickness (%)
RFV	1.8 (0.1)	1.9 (0.2)
KD	4.3 (0.4)	5.0 (0.5)
Numbers in parentheses are standard deviations		

Drying Defects

The drying defects are summarized in Table 5. There was no cupping detected in both drying methods. The bow of the boards was 2.3 mm in the RFV and 3 mm in the KD, but this difference was not statistically significant. The boards dried by the conventional KD had the highest crook and twist with values of 10.4 and 2.9 mm, respectively. These values were significantly different from the boards dried by the RFV. Additionally, the checks percentage in RFV drying was reduced to 22% and their lengths were less when compared with KD. The lower percentage of checks in the RFV could be explained by the lower drying stresses developed, which is due to the differential MC in the core and outer surface. Otherwise, the highest percentage and longest checks in conventional KD could be due to the presence of very high drying stresses during this process (Pérez *et al.* 2018).

Following the approaches for evaluation of drying quality described in Infor (2004), the quality index in RFV drying was determined to be 0.4. This result corresponds to an excellent drying quality. The conventional KD quality index was 0.54, which allowed for very good drying quality. In this study and according to the quality index, the RFV and KD drying conditions were adequate for drying the 13 mm thick *Eucalyptus nitens* juvenile wood.

Table 5. Summary of Drying Defects in *Eucalyptus nitens* Dried by RFV and KD

Drying Defects			RFV	KD
Cup	No. boards		0	0
Bow	No. boards		19	20
	Average value (mm)		2.3 (2.0)	3.0 (2.2)
Crook	No. boards		19	20
	Average value (mm)		3.5 (2.2) *	10.4 (7.9) *
Twist	No. boards		5	8
	Average value (mm)		0 (1.8) *	2.9 (3.7) *
Checks	No. boards		12	17
	% surface with checks		60	82.5
	Length of checks (mm)	Extreme 1	107.9 (144.4)	156 (107.2)
		Extreme 2	75.2 (73.0) *	180.8 (123.2) *
Quality-Index			0.40	0.54
Numbers in parentheses are standard deviations *Significant difference between RFV and KD (α = 0.05)				

Drying Cost

The drying cost of 1000 (m^3/year) of *Eucalyptus nitens* was estimated. The results of fixed and variable costs involved in RFV and conventional KD are presented in Table 6. These results show that RFV drying costs are about 15% less than KD, with a value of 67 ($U.S./m^3) compared to 79 ($U.S./m^3), respectively. This decrease in drying costs was similar to the report by Avramidis and Zwick (1997), who found a cost comparison between RFV and conventional KD drying of 101 mm thick western red cedar wood. The study concluded that in RFV drying, the costs were 14% less than KD.

According to Resch (2009), the magnitude of the drying cost is conditioned for the differences in the equipment cost. In this case, the cost of the RFV equipment is nearly 59% lower than KD equipment. The cost involved in KD showed higher depreciation and sticker cost, because at the moment it is required to have a higher inversion in KD equipment, and because of during stack RFV drying it is not necessary the use of sticker. But the RFV showed a higher energy electricity cost. The cost of electric energy in RFV drying was three times higher than KD. It was observed during RFV process that the vacuum pump presented the highest consumption of electrical power. And the power factor was maintained at 0.96 value, which was used as an indicator of low energy losses. Also, the higher efficiency of RFV technologies implies a reduction in losses by drying defects. The difference between drying costs due to drying losses is associated with higher dimensional loss due to higher shrinkage. The wood losses due to superficial and length checks are equivalent to 5% and 21% in RFV and conventional drying, respectively.

Table 6. Drying Cost Values for the RFV and Conventional KD

Costs	RFV	Conventional KD
Fixed costs		
Shed (450 m^2)	$18,634	
Storage yard (5,000 m^2)	$51,475	$51,475
Forklift	$20,326	$20,326
Drying equipment	$66,000	$162,609
Depreciation	$10,564	$17,004
Labor (kiln and handling operators)	$40,994	$40,994
Stickers *	$0	$4,000
Variable costs		
Losses by drying defects	$3,000	$12,600
Electrical energy *	$12,000	$4,000
Total ($U.S./year)	$66,558	$78,598
Total ($U.S./m^3)	$67	$79
*Source: Neumann 2015		

CONCLUSIONS

1. The drying time for *Eucalyptus nitens* juvenile wood using the RFV method was reduced by 47% when compared to conventional KD.
2. The shrinkage was significantly lower in the RFV than in conventional KD. The volumetric collapse decreased about 60% in RFV drying.
3. *Eucalyptus nitens* juvenile wood after RFV drying exhibited better wood quality than KD, due to lower drying defects and surface checks. In RFV drying, the number of crooks and twists were very low and significantly different than boards dried by conventional KD.
4. RFV drying of *Eucalyptus nitens* juvenile wood improved the wood quality for solid wood products.

5. In general terms and when considering the estimated costs for both processes, the RFV drying is more attractive for 13 mm thick *Eucalyptus nitens* than conventional KD. The cost reduction is equivalent to approximately 15%.

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