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Effect of stacking position on drying rate during radio-frequency vacuum combined with mechanical press drying of Douglas-fir and Radiata pine

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Abstract

In this study, the effect of stacking position in the dryer on the drying rate during radio-frequency vacuum combined with mechanical press (RF/VP) drying was investigated for Douglas-fir and Radiata pine. Drying test was performed at a temperature of 40 °C using RF/VP dryer with approximately 3 m^3. The results showed that the stacking position has a significant effect on the drying rate, with a more pronounced decrease in drying rate as the stacking position of specimens approaches the ground plate. Previous moisture content was an important factor in determining the drying rate in both species. The MC distribution of specimens in the dryer before drying was very irregular, but over time, specimens stacked on the RF charge plate side in the dryer tended to have lower MC distributions than those stacked on the ground plate side, which was serious at the specimens in contact with the upper ground plate. In addition, as the MC decreases below the fiber saturation point during RF/VP drying, the difference in MC distribution within the dryer according to the stacking position became clearer. These findings provide new insights into the effect of stacking position on drying rate during the RF/VP drying and are expected to improve RF/VP drying technology.

Keywords Drying rate, Permittivity, Radio-frequency drying, Stacking position, Vacuum drying

Introduction

Radio-frequency vacuum (RF/V) drying offers significant advantages for in wood drying. While the drying rate of wood generally depends on capillary and bulk flow (above the fiber saturation point, FSP) and bound water diffusion (below FSP), moisture movement in a vacuum environment is significantly influenced by the pressure gradient between the interior and exterior of wood [1, 2]. Reducing the pressure inside the drying dryer lowers the boiling point of water, improves wood permeability, and increases the rate of moisture movement inside the wood [1, 3, 4]. In addition, the radio-frequency (RF) heating method enables uniform heating without temperature gradient in thickness direction than that of conventional kiln drying, so RF/V drying has become popular [5]. However, there was a need to improve heat transfer during RF/V drying with a fixed frequency, and eventually the radio-frequency vacuum combined with mechanical press (RF/VP) drying was developed [6–8].

The feature of RF/VP drying was that it dries wood in conjunction with a mechanical compression load by a vacuum, which also has the effect of reducing the occurrence of warp during drying [6–8]. During RF/VP drying, exposure to the alternating electromagnetic field results in the heating of water molecules within the wood due

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to the polarization effect [9, 10]. At this time, the heating intensity depends on the moisture content (MC) and the size of the electric field [1]. However, since the dielectric properties and the MC of wood are inversely proportional, the permittivity of wood during drying decreases with the decreasing MC [5, 10]. This property inhibits energy transfer necessary for heating from the RF charge plate to the ground plate as the MC of the wood decreases below the FSP during RF/VP drying [4]. More energy builds up on the RF charge plate side, resulting in higher temperatures than on the ground plate side. This temperature gradient thus formed could affect the MC distribution and the quality of the wood after drying, depending on the stacking position within the dryer [11].

Even though RF/VP drying can improve heat transfer during drying and reduce warping during drying [6–8], to further improve the drying technology, the problem of uneven MC depending on the stacking position in the dryer during RF/VP drying needs to be solved. However, the previous studies have not reported the effects of the stacking position in the dryer on the drying rate during RF/VP drying.

This study was conducted to confirm the effect of stacking position on drying rate during RF/VP drying of Douglas-fir and Radiata pine. For this purpose, 50 pieces each of Radiata pine and Douglas-fir lumber with 30 mm × 100 mm × 2,400 mm were prepared and stacked in 10 layers. The RF/VP dryer with about 3 m^3 was used in the RF/VP drying test and the temperature during drying was controlled at 40 °C. The purpose of this study was to provide new insights into the effect of stacking position within the dryer on drying rate to improve the RF/VP drying technology.

Materials and methods

Preparation of materials

To investigate the effect of stacking position on Drying rate, 50 pieces of Radiata pine (*Pinus radiata*) and Douglas-fir (*Pseudotsuga menziesii*) lumber with 30 mm × 100 mm × 2400 mm were prepared, respectively. The stacking of specimens in the drying dryer was stacked in 10 layers (L), from the radio-frequency (RF) charge plate (L-1) to the ground plate (L-10) (Fig. 1).

Radio-frequency vacuum combined with mechanical press drying test

Radio-frequency vacuum combined with a mechanical press (RF/VP) dryer was used in the drying test [4], which designed as a rectangular shape with approximately 3 m^3 in capacity (Fig. 1). The upper cover was made of a flexible rubber sheet with a thickness of 5 mm. It was designed to transmit a vertical pressure force of up to approximately 10,000 kgf/m^2 to the residual surface of the lumber inside during pressurization. Condensed water was set to be drained every 30 min for a duration of 5 min. The pressure and the RF generator were controlled a vacuum level set at 60–70 torr and an oscillation rate of 90% (9 min ON, 1 min OFF), respectively.

The radio-frequency (RF) oscillator had a maximum output of 25 kW and a fixed frequency of 13.56 MHz. An aluminum plate with a thickness 5 mm, width 1000 mm, and length 2400 mm was used as the ground and RF charge plates. The ground plate was placed at the top and bottom of the stack. The RF charge plate was placed in the middle of the top and bottom of the stack and connected to the RF oscillator. Grounding was connected partially done using aluminum and copper plates.

A temperature sensor (∅ 3.5 mm, Teflon-sheathed platinum, 100 Ω) was used. It was installed at a depth of 50 mm in the center of the thickness of the Radiata pine specimen in contact with the upper ground plate at 300 mm from the cross-section. The temperature during RF/VP drying test was controlled at 40 °C.

Investigation of moisture content (MC), drying curve, drying rate

The weight of all specimens was measured at 24-h intervals during RF/VP drying to investigate the effect of

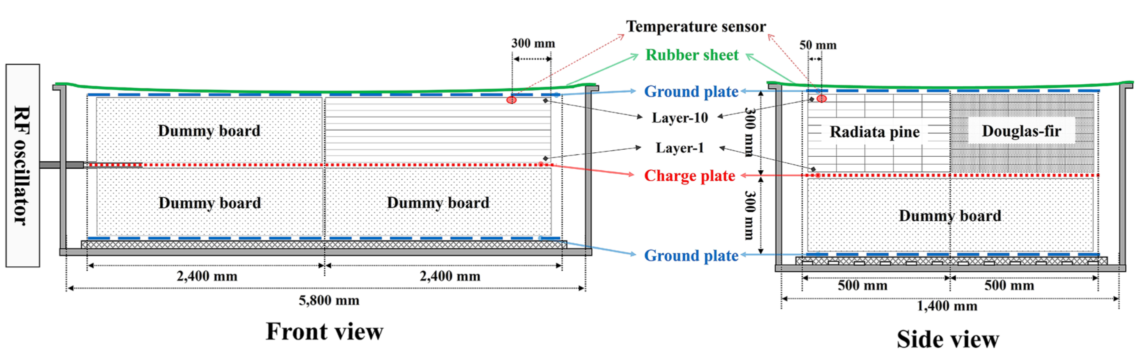

Fig. 1 A schematic diagram of the stacking of specimens in the RF/VP dryer

stacking position in the dryer on the drying rate during RF/VP drying of Douglas-fir and Radiata pine. Based on the measurement results, drying curves and drying rates were calculated.

The final moisture content (MC) was determined for all 100 specimens (50 Douglas-fir and 50 Radiata pine) using the oven-drying method. After RF/VP drying test was completed, two oven-drying samples with a thickness of 20 mm were taken from each oven-drying sample at 300 mm from both cross-sections of the specimen (Fig. 2). The MC for all weight measurements of specimens was calculated from the weight changes before and after drying and the final MC.

Statistical analysis method

Statistical analysis was performed using RStudio. For both Douglas-fir and Radiata pine, a multiple regression analysis was performed to assess the relationship between various factors and the drying rate during the RF/VP drying. The dependent variable is the drying rate, and the independent variables include stacking position (Layer 1–10), species (Douglas-fir and Radiata), previous moisture content (MC on day n-1), and drying time.

For each Douglas-fir and Radiata pine, a multiple regression analysis was performed to assess the relationship between drying rate and various factors, specifically stacking position (Layer 1–10), MC on day n-1, and drying time. The analyses were performed for different MC levels: the Full model (all data), MC > 30, MC ≤ 30, MC ≤ 25, MC ≤ 20, MC ≤ 15, and MC ≤ 10.

Results and discussion

The drying rates of Douglas-fir and Radiata pine were observed over a six-day period according to various factors, specifically stacking position and previous moisture content (MC on day n-1) (Tables 1, 2, 3, 4; Figs. 3 and 4). During RF/VP drying, Douglas-fir showed a constant drying rate, and Radiata pine showed a decreasing drying rate at the end stage of drying (5th and 6th days) (Tables 1, 2; Fig. 4). However, the drying rate between L-1 and L-10 showed a clear difference in both species (Table 2).

The drying rate of Douglas-fir was relatively very low at 0.1% on the first day and 0.3% on the second day, and some of the specimens stacked on L-10 (One day- column 7, 8, and 10, Two day- column 7 and 8) even showed an increased in MC (Fig. 3). In Radiata pine L-4 (column 4), L-5 (column 4), and Douglas-fir L-1 (column 8 and 9), L-2 (column 9), and L-3 (column 9), there were some specimens whose MC decreased to less than 20% on day 2, but it took 3 days to decrease to less than 10%. In the specimen stacked in the Radiata pine L-3 (column 5), the MC decreased by more than 50% on both the 4th and 5th days.

Average drying rate during RF/VP drying according to the previous moisture content and stacking position is showed in Tables 3 and 4. For both species, the drying rate was highest when the previous moisture content (MC on day n-1) was above the fiber saturation point (FSP). However, as the MC on day n-1 decreased to below 10%, the drying rate decreased significantly. Nevertheless, when the MC on day n-1 was above 30%, the

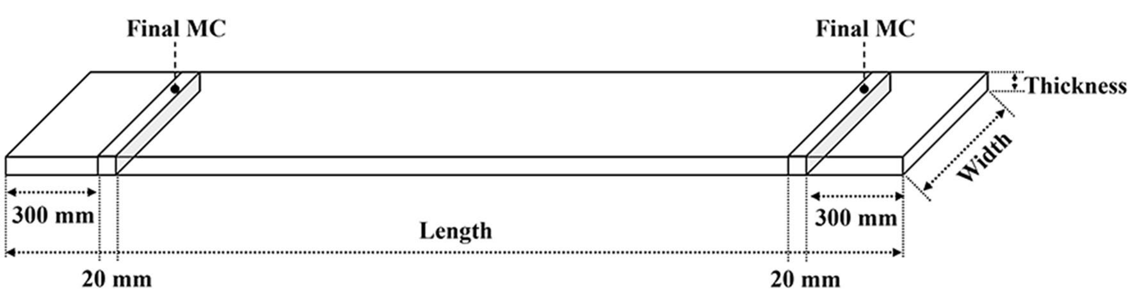

Fig. 2 Schematic diagram of final MC sampling

Table 1 Average daily drying rate of Douglas-fir and Radiata pine during RF/VP drying

Species	Drying rate (%/day)					
	One	Two	Three	Four	Five	Six
Douglas-fir	4.1	5.3	5.2	5.4	5.4	4.6
Radiata pine	17.6	15.5	17.2	17.7	13	6.2

Table 2 Average daily drying rate of Douglas-fir and Radiata pine during RF/VP drying according to the stacking position

Species	Layer	Drying rate (%/day)					
		1 day	2 day	3 day	4 day	5 day	6 day
Radiata pine	Layer-1	13.8	19.1	25.6	27.2	6.9	3.8
	Layer-2	16.3	16.8	18.9	19.6	14.5	4.8
	Layer-3	21.2	18.9	23.6	22.0	15.3	5.4
	Layer-4	23.4	17.2	9.6	8.5	4.9	5.0
	Layer-5	19.1	11.9	12.4	10.7	5.1	5.2
	Layer-6	20.6	21.2	24.3	22.5	17.7	6.5
	Layer-7	15.4	13.0	15.1	20.9	16.1	6.5
	Layer-8	17.2	14.8	18.1	18.2	19.6	9.7
	Layer-9	18.9	14.9	15.3	14.3	10.9	7.2
	Layer-10	9.9	7.6	9.4	12.7	18.6	7.8
Douglas-fir	Layer-1	5.8	7.7	4.8	4.7	4.8	3.6
	Layer-2	5.1	4.7	4.1	4.6	5.2	4.4
	Layer-3	5.4	7.3	6.7	5.9	5.6	5.1
	Layer-4	5.4	5.5	4.5	4.6	5.1	5.0
	Layer-5	3.9	6.9	7.5	7.1	6.2	5.5
	Layer-6	4.0	4.8	4.9	5.0	5.0	4.9
	Layer-7	3.8	6.7	7.7	7.4	5.6	4.9
	Layer-8	4.1	4.8	4.4	4.3	4.8	4.5
	Layer-9	3.2	4.3	5.2	5.8	6.2	4.4
	Layer-10	0.1	0.3	2.2	5.1	6.0	4.1

Table 3 Average drying rate of Douglas-fir RF/VP drying according to the previous moisture content and stacking position

Douglas-fir	Drying rate (%/day)					
	MC > 30%	MC ≤ 30%	MC ≤ 25%	MC ≤ 20%	MC ≤ 15%	MC ≤ 10%
Layer-1	11.2	4.9	5.3	4.3	4.8	1.8
Layer-2	5.9	4.2	4.3	4.3	5.2	2.2
Layer-3	7.7	6.7	5.4	4.9	5.0	2.5
Layer-4	5.4	5.4	4.7	4.7	4.9	1.9
Layer-5	7.1	5.4	6.5	4.9	5.4	0.8
Layer-6	4.3	5.2	5.1	4.9	4.8	–
Layer-7	7.9	5.2	5.4	4.4	4.9	–
Layer-8	4.3	5.2	4.7	3.6	4.5	–
Layer-9	6.1	4.0	3.6	4.3	1.4	–
Layer-10	1.5	4.7	4.9	2.0	–	–
Average	5.5	5.0	5.0	4.2	4.3	1.4

drying rate of L-10 was clearly lower than that of other layers.

In addition, the MC of specimens within the dryer before drying was very irregularly distributed, with an initial MC average of 36.5% (± 10.5%) for Douglas-fir and 86.7% (± 42.4%) for Radiata pine. However, during the RF/VP drying process, as the MC of the specimens decreased below the fiber saturation point (FSP), the moisture content within the dryer tended to distribute higher toward the ground plate than the RF charge plate depending on the stacking position (Fig. 3).

These results suggest that both the moisture content and the stacking position can significantly affect the drying rate of Douglas-fir and Radiata pine during RF/VP drying.

Table 4 Average drying rate of Radiata pine during RF/VP drying according to the previous moisture content and stacking position

Radiata pine	Drying rate (%/day)					
	MC > 30%	MC ≤ 30%	MC ≤ 25%	MC ≤ 20%	MC ≤ 15%	MC ≤ 10%
Layer-1	26.7	5.8	5.5	7.1	6.3	1.9
Layer-2	22.6	13.4	6.2	5.7	5.7	2.4
Layer-3	27.1	8.0	4.0	5.4	6.0	2.1
Layer-4	23.3	9.1	3.4	4.0	4.9	2.1
Layer-5	21.0	6.9	4.4	3.9	5.2	1.3
Layer-6	24.8	11.5	8.3	8.1	5.0	0.8
Layer-7	19.4	3.3	6.8	6.6	5.9	–
Layer-8	22.0	–	5.4	4.8	4.3	–
Layer-9	22.3	10.1	2.9	4.2	2.0	–
Layer-10	16.1	1.9	3.7	4.5	–	–
Average	22.5	7.3	4.7	5.1	4.4	1.5

As a result of statistical analysis, the stacking position had a significant effect on the drying rate during RF/VP drying of Douglas-fir and Radiata pine (Table 5). There were significant differences in drying rate depending on species ($p < 0.01$), MC ($p < 0.01$), drying time ($p < 0.05$), and stacking position ($p < 0.01$) during RF/VP drying. The drying rate tended to decrease as the drying time increased. The drying rate also tended to decrease depending on the stacking position, with a more pronounced decrease in drying rate as the layer increased.

Previous moisture content (MC on day n-1) was an important factor in determining the drying rate for both species (Tables 6, 7) ($p < 0.01$). The drying rate increased as the MC on day n-1 of the specimens increased, which was statistically significant in both models with respect to MC on day n-1 ($p < 0.01$). In the case of Radiata pine, when the MC on day n-1 exceeded 30%, the drying rate of L-7, 8, 9, and 10 was lower than those of L-1 to L-6. On the other hand, Douglas-fir showed a more significant decrease in drying rate with increasing layers in most of MC range on day n-1, with L-10 being the most severe.

The frequency of the high-frequency oscillator used in this study was fixed at 13.56 MHz. A fixed frequency of 13.56 MHz has problems reaching sufficient frequency stability [3]. At a fixed frequency of 13.56 MHz rather than floating frequencies within a specific range, the permittivity of wood has a characteristic that is directly proportional to the change in MC [5, 10]. In general, free water can be removed more easily with less energy than bound water, and below the fiber saturation point, the drying rate decreases because more energy is required as the moisture content decreases [12, 13]. In addition, since the permittivity of wood decreases with decreasing MC below FSP, the energy required for water evaporation from wood increases [4]. Furthermore, frequency stability problems cause temperature gradients with distance from the RF charge plate, and these temperature gradients become more severe over time [4]. As a result, because moisture movement in a vacuum environment is significantly influenced by the pressure gradient between the interior and exterior of wood [1, 2], the temperature gradients according to the stacking position can cause differences in drying rates and non-uniform distribution of MC within the dryer during RF/VP drying.

On the other hand, when the upper cover was opened to measure the weight of specimens during RF/VP drying, a large amount of moisture was condensed between the upper cover and the specimens. During RF/VP drying, the convection also occurs within the dryer. Since the temperature of water vapor released from the wood is relatively higher than the temperature inside the dryer, the water vapor released from the wood will mainly move to the upper part of the dryer. In this process, when the temperature of the water vapor decreases to the dew point, the water vapor is condensed. Therefore, the humidity on the ground plate side of the top of the dryer was inevitably maintained higher than that on the RF charge plate side during RF/VP drying.

In this study, a clear difference in drying rate was observed depending on the stacking position within the dryer during RF/VP drying. The drying rate of wood depends on capillary and bulk flow (above FSP) and bound water diffusion (below FSP), but moisture movement in a vacuum environment is strongly influenced by the pressure gradient between the interior and exterior of the wood [1, 2]. When a fixed frequency is used during RF/VP drying, the permittivity of wood has the characteristic of decreasing proportionally to changes in MC below FSP [5, 10]. The use of fixed frequency in RF/VP drying causes temperature gradients with distance from

Befroe drying

	Column 1	2	3	4	5	6	7	8	9	10	
Ground plate	125.0	34.6	107.9	103.1	30.9	30.7	31.2	36.7	35.8	31.3	→ L10
	129.1	130.9	67.8	96.5	35.5	32.9	45.6	58.1	32.1	31.8	→ L9
	160.3	126.4	113.1	39.5	92.2	33.9	36.6	39.3	37.4	32.4	→ L8
	117.9	47.7	144.7	123.6	38.5	53.2	71.0	33.2	29.0	32.2	→ L7
	130.9	62.9	149.3	158.1	91.1	31.8	35.8	38.6	35.7	34.9	→ L6
	65.9	43.3	147.1	53.3	37.9	61.1	55.0	32.5	31.0	32.6	→ L5
	79.1	58.0	42.5	72.1	113.3	31.6	36.3	37.4	37.0	33.4	→ L4
	67.8	43.7	136.3	138.3	163.4	36.0	64.8	32.1	32.5	32.6	→ L3
	84.6	57.8	44.3	145.2	138.3	28.3	32.1	32.2	32.4	31.7	→ L2
Charge plate	44.4	118.7	37.2	141.5	153.9	36.2	50.1	27.8	27.0	29.0	→ L1
	Radiata pine					Douglas-fir					

below 10 (%)
10 ~ 20 (%)
20 ~ 30 (%)
30 ~ 50 (%)
50 ~ 100 (%)
more then 100 (%)

One day

114.6	27.4	91.1	91.8	27.0	30.1	32.2	38.2	32.5	32.1
109.0	121.7	40.3	70.3	23.9	27.9	40.7	57.3	28.6	30.1
142.5	116.4	87.7	24.4	74.5	29.5	34.3	36.4	29.4	29.4
105.5	41.2	121.0	100.9	27.1	45.6	65.8	32.1	25.9	30.1
101.5	51.8	131.4	135.4	69.3	30.7	31.6	34.9	27.6	32.0
51.5	32.3	116.7	27.4	24.4	56.0	48.5	31.3	25.3	31.4
53.2	38.7	23.9	35.1	96.9	30.5	30.1	31.0	26.6	30.2
50.7	28.2	100.8	112.5	151.2	31.9	55.4	29.3	25.0	29.3
63.2	43.2	31.7	120.9	129.7	26.6	27.2	27.4	22.9	27.4
35.2	101.2	28.3	127.1	134.7	28.3	38.8	25.3	23.2	25.8

Two days

104.2	25.9	77.3	81.3	25.0	30.0	32.6	39.0	31.3	30.9
85.1	107.7	25.6	49.6	22.4	24.3	33.8	52.7	25.2	27.3
123.9	105.0	63.9	22.6	56.1	23.7	30.7	31.7	23.1	25.7
88.5	35.2	102.4	80.9	23.8	36.2	54.5	27.9	21.9	25.4
70.4	40.9	114.5	112.5	45.2	27.8	27.0	28.7	22.0	27.4
37.9	25.4	88.2	19.6	21.6	47.4	36.4	26.7	20.2	27.2
26.2	21.9	21.1	18.9	73.7	27.6	23.9	23.6	20.2	25.3
33.9	20.2	70.1	88.3	136.6	27.0	41.0	23.6	19.4	23.5
41.1	28.2	25.0	93.6	116.7	22.5	22.2	22.6	18.8	22.1
24.9	71.3	22.4	103.9	108.5	20.5	24.4	18.1	19.3	20.6

Three days

90.8	23.7	61.6	67.5	23.2	28.6	30.1	37.1	28.7	28.3
57.9	89.8	20.2	25.4	20.8	21.7	26.2	44.2	21.6	23.8
102.6	87.9	35.7	20.4	34.5	19.8	26.1	26.1	19.2	21.8
65.4	30.0	82.0	56.6	21.2	27.1	39.4	22.0	18.5	20.2
36.2	29.3	91.1	82.3	23.2	23.8	22.0	22.5	18.3	22.2
21.0	19.5	54.2	17.6	18.5	36.0	24.4	21.1	17.0	21.9
17.1	16.5	19.2	16.7	44.3	23.3	19.4	18.7	16.8	19.9
18.4	16.2	33.9	50.3	112.4	21.9	25.6	18.5	16.2	18.6
20.2	18.7	20.4	59.7	91.1	17.9	17.8	18.2	15.9	18.0
18.1	31.1	18.2	66.5	69.1	15.4	16.5	14.7	15.7	16.4

Four days

69.9	21.5	41.9	48.7	21.1	25.3	25.4	28.8	23.2	24.5
23.6	67.1	17.5	16.6	17.8	19.1	20.3	31.4	18.0	19.4
74.0	62.7	18.1	16.6	18.3	16.7	20.4	20.3	16.0	18.2
31.8	23.2	53.5	24.6	17.4	19.1	22.7	16.8	15.2	16.3
15.5	17.8	62.3	39.3	14.9	18.2	17.0	16.6	14.8	16.9
13.6	14.6	17.8	16.1	15.2	22.9	17.1	15.5	13.6	15.9
12.8	12.9	14.7	13.4	17.7	17.4	15.1	14.7	13.4	14.8
12.7	12.7	13.2	15.8	66.5	15.8	15.3	13.8	12.7	13.7
12.4	13.0	14.3	25.1	47.5	13.4	12.9	13.3	12.1	13.2
12.8	11.9	11.8	15.8	14.4	11.0	11.5	10.2	11.3	11.4

Five days

30.6	18.4	19.5	23.1	18.6	20.7	19.8	20.0	17.3	19.4
18.2	26.9	14.2	13.9	14.8	15.7	15.5	17.7	14.0	14.4
22.0	31.3	13.5	12.0	13.1	13.1	14.3	14.1	12.1	13.8
13.7	14.8	16.0	12.4	12.9	13.8	13.6	12.0	11.3	11.7
9.2	11.5	17.4	11.8	11.2	12.8	12.0	11.3	10.6	11.6
8.8	9.7	11.0	10.5	11.9	12.7	11.5	10.4	9.1	10.5
8.3	8.4	9.4	9.4	11.5	11.2	10.2	9.9	8.9	9.8
7.9	8.0	7.2	8.7	12.5	9.5	8.8	8.8	7.9	8.7
6.8	7.3	8.3	7.8	9.4	8.5	7.8	7.7	7.2	7.8
7.5	5.9	5.9	6.4	6.4	6.1	6.4	5.8	6.4	6.5
Radiata pine					Douglas-fir				

Six days

14.2	14.2	13.8	14.3	15.0	17.0	16.2	15.3	13.7	14.8
10.5	10.8	9.8	9.7	11.1	12.6	11.6	11.5	10.2	9.7
8.3	9.4	8.4	7.9	9.4	9.7	9.9	9.0	7.9	8.5
6.5	7.9	7.3	6.8	9.0	9.0	8.0	7.1	6.8	6.8
4.5	5.8	5.6	5.5	7.0	8.1	7.1	6.0	5.8	6.6
4.4	4.8	4.3	4.9	7.7	6.6	5.5	5.2	4.1	5.6
3.9	4.0	4.8	4.0	5.3	6.1	5.0	4.8	4.0	4.9
3.6	3.6	2.9	3.0	4.2	4.2	3.0	3.9	3.1	4.0
2.7	3.1	4.0	2.5	3.4	4.2	3.4	3.2	2.9	3.4
3.4	2.5	2.3	2.4	2.7	2.7	2.7	2.3	2.7	2.8
Radiata pine					Douglas-fir				

Fig. 3 MC distribution according to the stacking position during RF/VP drying

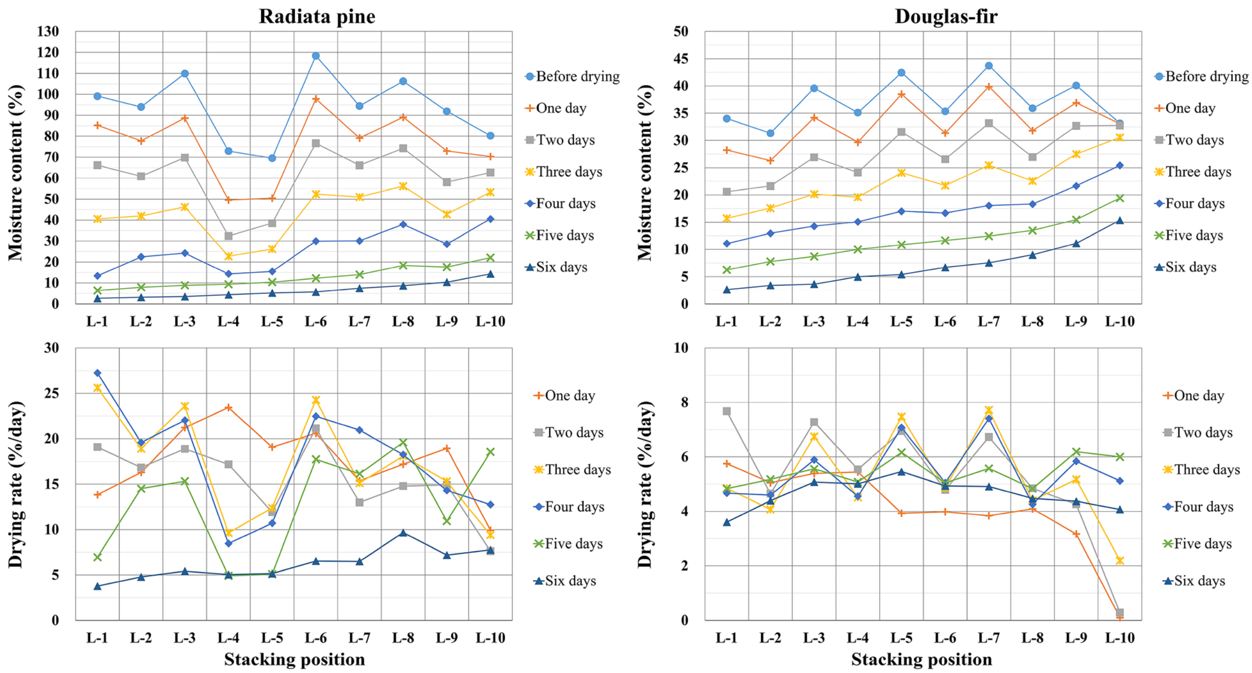

Fig. 4 Drying rate and drying curve according to the stacking position during RF/VP drying

the RF charge plate due to frequency stability problem [3, 4]. These reports suggest that in this study, the difference in drying rate during RF/VP drying may have resulted in different pressures forming within the wood due to the temperature gradient formed depending on the stacking position. In addition, during RF/VP drying test, the phenomenon of moisture condensation was also observed on the ground plate side of the top of the dryer. Therefore, it was considered that the difference in drying rates according to the stacking position during RF/VP drying was caused by (1) permittivity characteristics of wood, (2) use of fixed frequency, and (3) moisture condensation phenomenon at the top of the dryer.

Conclusion

This study showed that the stacking position had a significant effect on the drying rate during RF/VP drying of Douglas-fir and Radiata pine. When the previous moisture content (MC on day n-1) was above 30%, the drying rate of L-10 was clearly lower than that of other layers. As the MC decreases below the fiber saturation point during RF/VP drying, the difference in MC distribution within the dryer according to the stacking position became clearer. In addition, during RF/VP drying test, the phenomenon of moisture condensation was also observed on the ground plate side of the top of the dryer. It was assumed that the difference in drying rate according to the stacking position during RF/VP drying was caused by permittivity characteristics of wood, use of fixed frequency, and moisture condensation phenomenon at the top of the dryer.

These results provide valuable insights for improving RF/VP drying technology and suggest that further studies are needed to address the problem of non-uniform MC depending on the stacking position in the dryer during RF/VP drying. This study provides a basis for future research on optimizing RF/VP drying technology for different wood species and stacking positions.

Table 5 Analysis of the relationship between various factors and drying rate of Douglas-fir and Radiata pine during RF/VP drying

	Dependent variable: drying rate (%/day)							
	Layer[1]	**Full model[2]**	**1 day**	**2 days**	**3 days**	**4 days**	**5 days**	**6 days**
Layer2	− 0.750[3] (1.755)[4]	− 0.805 (1.411)	1.043 (2.388)	− 2.342 (2.353)	− 4.143 (3.257)	− 6.484 (4.110)	− 0.107 (3.267)	0.936 (1.219)
Layer3	1.215 (1.755)	0.645 (1.412)	3.332 (2.388)	− 0.902 (2.355)	− 1.299 (3.262)	− 5.329 (4.124)	− 1.999 (3.310)	1.607 (1.240)
Layer4	− 2.417 (1.755)	− 1.700 (1.413)	5.310** (2.407)	− 0.054 (2.375)	− 6.478* (3.267)	− 10.621** (4.092)	− 9.835*** (3.371)	1.424 (1.398)
Layer5	− 2.207 (1.755)	− 1.916 (1.411)	2.173 (2.397)	− 2.871 (2.360)	− 4.571 (3.258)	− 8.975** (4.100)	− 11.618*** (3.449)	1.740 (1.525)
Layer6	1.138 (1.755)	0.106 (1.416)	2.189 (2.390)	− 1.419 (2.359)	− 2.832 (3.273)	− 7.486* (4.179)	− 9.375** (3.592)	2.216 (1.738)
Layer7	− 0.380 (1.755)	− 1.353 (1.415)	− 0.305 (2.387)	− 4.288* (2.357)	− 6.271* (3.278)	− 7.404* (4.191)	− 13.298*** (3.759)	2.231 (2.102)
Layer8	− 0.268 (1.755)	− 1.496 (1.418)	0.709 (2.387)	− 4.452* (2.358)	− 6.714** (3.283)	− 12.272*** (4.272)	− 19.124*** (4.190)	3.675 (2.501)
Layer9	− 1.435 (1.755)	− 2.309 (1.414)	1.330 (2.386)	− 4.012* (2.353)	− 6.694** (3.267)	− 12.000*** (4.209)	− 24.385*** (4.297)	2.434 (3.112)
Layer10	− 3.673** (1.755)	− 5.053*** (1.420)	− 4.584* (2.388)	− 9.964*** (2.355)	− 12.792*** (3.297)	− 16.936*** (4.398)	− 31.837*** (5.139)	2.753 (4.489)
Species-Radiata		7.092*** (0.689)	11.862*** (1.337)	6.057*** (1.260)	6.974*** (1.655)	8.111*** (1.948)	4.597*** (1.480)	1.526*** (0.559)
MC		0.137*** (0.016)	0.038** (0.019)	0.127*** (0.021)	0.242*** (0.038)	0.476*** (0.078)	2.651*** (0.277)	− 0.041 (0.355)
Drying time		0.485** (0.241)						
Constant	10.650*** (1.241)	1.998 (1.464)	1.686 (1.888)	4.805** (1.835)	4.926* (2.506)	6.079* (3.093)	− 13.192*** (2.886)	3.016** (1.352)
Observations	600	600	100	100	100	100	100	100
R^2	0.024	0.372	0.678	0.639	0.591	0.510	0.600	0.174
Adjusted R^2	0.009	0.360	0.638	0.593	0.540	0.448	0.550	0.070
Residual SE	9.613 (df = 590)	7.727 (df = 587)	5.335 (df = 88)	5.261 (df = 88)	7.281 (df = 88)	9.141 (df = 88)	7.243 (df = 88)	2.680 (df = 88)
F statistic	1.595 (df = 9; 590)	29.018*** (df = 12; 587)	16.840*** (df = 11; 88)	14.132*** (df = 11; 88)	11.549*** (df = 11; 88)	8.315*** (df = 11; 88)	12.003*** (df = 11; 88)	1.682* (df = 11; 88)

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

Layer[1] predicted value of dependent variable for only the stacking position in the independent variables, Full model[2] predicted values of dependent variables including independent variables, [3]drying rate difference compared to Layer-1, [4]standard error, Dependent variable; drying rate, Independent variables; stacking position (Layer 1–10), species (Douglas-fir and Radiata), moisture content on a day before (MC on day n-1), and drying time, Species—Radiata; value compared to Douglas-fir, MC; moisture content on a day before, Constant; the predicted value of the dependent variable when all independent variables are 0, i.e. when there are no other effects (if this value is statistically significant, it can be interpreted that the constant term plays a significant role in the model)

Table 6 Relationship between drying rate and factors for Radiata pine at different MC levels

Radiata pine	Dependent variable: drying rate (%/day)						
	Full model	MC > 30%	MC ≤ 30%	MC ≤ 25%	MC ≤ 20%	MC ≤ 15%	MC ≤ 10%
Layer-2	− 0.729[1] (2.323)[2]	− 4.264 (2.910)	2.027 (2.636)	− 0.968 (1.728)	− 0.470 (1.376)	− 0.592 (0.733)	1.040** (0.388)
Layer-3	0.365 (2.325)	− 0.478 (2.870)	2.200 (2.699)	− 1.500 (2.295)	− 1.667* (0.969)	− 0.788 (0.691)	0.935** (0.412)
Layer-4	− 0.775 (2.345)	− 1.339 (3.222)	0.514 (2.767)	− 1.316 (1.715)	− 2.154** (0.850)	− 1.716** (0.652)	0.960** (0.412)
Layer-5	− 1.823 (2.341)	− 4.016 (3.219)	− 0.293 (2.357)	− 1.067 (1.711)	− 3.010*** (0.819)	− 2.117*** (0.714)	0.910* (0.514)
Layer-6	0.020 (2.333)	− 3.436 (2.770)	0.127 (2.961)	0.348 (2.325)	− 1.689 (1.049)	− 2.590*** (0.780)	0.960 (0.672)
Layer-7	− 2.421 (2.324)	− 8.201*** (2.836)	− 3.536 (2.415)	− 1.790 (1.688)	− 3.604*** (1.180)	− 2.078** (0.851)	
Layer-8	− 2.313 (2.332)	− 7.371*** (2.780)		− 1.964 (1.647)	− 4.026*** (1.005)	− 3.678*** (0.895)	
Layer-9	− 2.523 (2.323)	− 4.709 (2.957)	− 2.202 (2.622)	− 4.111** (1.584)	− 5.356*** (0.978)	− 3.911*** (0.895)	
Layer-10	− 5.730** (2.323)	− 13.648*** (2.850)	− 4.829* (2.213)	− 5.761*** (1.628)	− 7.015*** (1.178)		
MC	0.211*** (0.017)						
Drying time	1.624*** (0.417)	4.539*** (0.494)	2.786*** (0.609)	2.452*** (0.371)	2.689*** (0.403)	1.653*** (0.513)	
Constant	1.064 (2.426)	20.944*** (2.182)	3.014 (2.003)	0.596 (1.519)	− 1.896 (1.507)	− 0.286 (2.108)	3.740*** (0.275)
Observations	300	161	16	32	35	35	21
R^2	0.422	0.421	0.931	0.754	0.790	0.531	0.392
Adjusted R^2	0.400	0.383	0.827	0.637	0.702	0.363	0.189
Residual SE	8.996 (*df* = 288)	8.096 (*df* = 150)	1.909 (*df* = 6)	1.874 (*df* = 21)	1.186 (*df* = 24)	0.960 (*df* = 25)	0.614 (*df* = 15)
F statistic	19.142*** (*df* = 11; 288)	10.911*** (*df* = 10; 150)	8.988*** (*df* = 9; 6)	6.435*** (*df* = 10; 21)	9.028*** (*df* = 10; 24)	3.150** (*df* = 9; 25)	1.932 (*df* = 5; 15)

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

[1] Drying rate difference compared to Layer-1, [2]standard error, Dependent variable; drying rate, Independent variables; stacking position (Layer 1–10), moisture content on a day before (MC on day n-1), and drying time, MC; Previous moisture content (MC on day n-1), Constant; the predicted value of the dependent variable when all independent variables are 0, i.e. when there are no other effects (if this value is statistically significant, it can be interpreted that the constant term plays a significant role in the model)

Table 7 Relationship between drying rate and factors for Douglas-fir at different MC levels

Douglas-fir	Dependent variable: drying rate (%/day)						
	Full model	**MC > 30%**	**MC ≤ 30%**	**MC ≤ 25%**	**MC ≤ 20%**	**MC ≤ 15%**	**MC ≤ 10%**
Layer-2	− 0.634[1] (0.456)[2]	− 4.448** (1.993)	− 1.132 (0.798)	− 1.053 (0.773)	− 0.205 (0.368)	0.318 (0.249)	0.780*** (0.155)
Layer-3	− 0.396 (0.462)	− 3.926** (1.765)	0.108 (0.911)	− 0.242 (0.818)	− 0.099 (0.378)	0.105 (0.290)	1.480*** (0.155)
Layer-4	− 0.939** (0.458)	− 6.092*** (1.738)	− 1.103 (0.979)	− 1.360 (0.827)	− 0.521 (0.387)	− 0.211 (0.274)	1.333*** (0.179)
Layer-5	− 1.083** (0.474)	− 5.611*** (1.692)	− 1.136 (0.979)	− 0.677 (0.853)	− 0.409	0.040 (0.321)	1.400*** (0.269)
Layer-6	− 1.595*** (0.462)	− 7.248*** (1.738)	− 1.272	− 1.723** (0.830)	− 0.929** (0.439)	− 0.506 (0.317)	
Layer-7	− 1.561*** (0.480)	− 5.082*** (1.710)	− 1.171 (0.848)	− 1.570	− 1.369*** (0.439)	− 0.495 (0.350)	
Layer-8	− 2.124*** (0.464)	− 7.744*** (1.741)	− 1.270	− 2.417*** (0.853)	− 1.883*** (0.422)	− 0.955** (0.350)	
Layer-9	− 2.829*** (0.482)	− 7.319*** (1.702)	− 2.666*** (0.868)	− 3.557*** (0.853)	− 2.458*** (0.503)	− 1.185*** (0.415)	
Layer-10	− 4.716*** (0.482)	− 11.923*** (1.661)	− 4.027*** (1.049)	− 4.196*** (1.155)	− 3.257*** (0.600)		
MC	0.252*** (0.016)						
Drying time	1.395*** (0.102)	2.632*** (0.307)	1.374*** (0.271)	1.469*** (0.290)	1.331*** (0.188)	0.573** (0.213)	
Constant	− 3.129*** (0.627)	10.323*** (1.508)	4.213*** (0.552)	2.729*** (0.768)	0.749 (0.565)	2.571*** (0.832)	3.600*** (0.110)
Observations	300	93	49	44	53	42	19
R^2	0.532	0.645	0.505	0.577	0.614	0.461	0.887
Adjusted R^2	0.514	0.602	0.375	0.448	0.523	0.309	0.855
Residual SE	1.765 (df = 288)	2.606 (df = 82)	1.311 (df = 38)	1.152 (df = 33)	0.635 (df = 42)	0.407 (df = 32)	0.245 (df = 14)
F statistic	29.706*** (df = 11; 288)	14.924*** (df = 10; 82)	3.882*** (df = 10; 38)	4.495*** (df = 10; 33)	6.693*** (df = 10; 42)	3.035*** (df = 9; 32)	27.450*** (df = 4; 14)

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

[1] Drying rate difference compared to Layer-1, [2]standard error, Dependent variable; drying rate, Independent variables; stacking position (Layer 1–10), moisture content on a day before (MC on day n-1), and drying time, MC; Previous moisture content (MC on day n-1), Constant; the predicted value of the dependent variable when all independent variables are 0, i.e. when there are no other effects (if this value is statistically significant, it can be interpreted that the constant term plays a significant role in the model)

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CL designed the study, collected the experimental data, analyzed the results, and wrote the manuscript. The author read and approved the final manuscript.

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