TECHNICAL NOTE: EQUILIBRIUM MOISTURE CONTENT OF NORWAY SPRUCE AT LOW PRESSURE

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Abstract. The EMC of Norway spruce (*Picea abies*) was determined at various levels of temperature and RH under low pressures. EMC corresponded to temperature and RH and was strongly related to vapor pressure inside the chamber. The amount of air present in the vacuum chamber did not significantly affect the EMC. The Hailwood-Horrobin model can be used to estimate the EMC of wood under vacuum, although it is about 2 – 3% MC less than the actual EMC of wood during initial desorption.

Manufacturers of furniture, cabinets, and interior woodwork are faced with the need to dry varying amounts of small pieces of wood. Vacuum drying offers a means to do that economically and without degrade. However, such drying requires knowing the EMC of the wood under specific conditions of humidity, temperature, and pressure. Those relationships have been established for drying at atmospheric pressure, but data on their effects under vacuum conditions are limited. The Hailwood-Horrobin model (FPL 1999) offers a means to calculate EMC under various conditions of pressure. We conducted a study of MC, temperature, and pressure relationships to evaluate the effectiveness of that approach.

The Hailwood-Horrobin (Hailwood and Horrobin 1946) sorption theory considers wood as a polymer and has been applied to relate water vapor pressure and EMC. Simpson (1973) used the Hailwood-Horrobin model to calculate the EMC of (apparently) Sitka spruce (*Picea sitkensis*) at

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atmospheric pressure within about 0.9% MC with a standard deviation of 0.1% MC from values published in standard RH/temperature/MC tables (FPL 1999). The model is expressed as:

$$\mathrm{EMC} = \left(\frac{KK_1h + 2K^2K_1K_2h^2}{1 + K^2K_1K_2h^2 + K_1Kh} + \frac{Kh}{1 - Kh} \right) \times \frac{1800}{W} \quad (1)$$

where

$$W = 349 + 1.29T + 0.0135\,T^2 \quad (2)$$

$$K = 0.805 + 0.000736T - 0.00000273\,T^2 \quad (3)$$

$$K_1 = 6.27 - 0.00938T - 0.000303\,T^2 \quad (4)$$

$$K_2 = 1.91 + 0.0407T - 0.000293\,T^2 \quad (5)$$

EMC is EMC (%); T is temperature (°C); and h is the RH (%).

In a vacuum drying system using pure water vapor, there are only two independent parameters: the absolute pressure and the temperature. The RH (h) in the vacuum system is defined as the ratio of the absolute pressure (p) in this system to the saturated vapor pressure (p_0) at a given temperature (T). The RH under vacuum is:

$$h = \frac{p}{p_0} \times 100\% \quad (6)$$

In this study, we measured and calculated the EMC of Norway spruce (*Picea abies*) as a function of RH and wood temperature and determined the effect of pressure. Values of EMC for the specimen material were calculated by the Hailwood-Horrobin model (Table 1). Specimens were dried from the green condition and

Table 1. *Vacuum EMCs of Norway spruce at various temperatures and pressures.*

Temperature (°C)	RH (%)	Average measured EMC (%)	Standard deviation	EMC (%) calculated from Hailwood-Horrobin model	Difference between the measured EMC and calculated EMC (%)	Total pressure (kPa)	Vapor pressure (kPa)	Air pressure (kPa)
40	36	8.9	0.2	6.5	2.4	11.7	2.53	9.17
40	67	12.2	0.2	11.4	0.8	11.7	4.72	6.97
40	71	14.0	0.2	12.4	1.7	11.5	5.04	6.46
40	77	17.5	0.4	13.9	3.6	13	5.45	7.54
40	89	22.5	2.8	18.9	3.5	13.3	6.35	6.95
40	95	27.4	2.5	22.5	4.9	17.7	6.73	10.97
45	31	7.5	0.2	5.7	1.8	11.4	2.86	8.54
45	38	8.5	0.1	6.7	1.8	11.6	3.5	8.1
45	54	10.0	0.1	8.9	1.1	12	4.95	7.05
45	60	10.3	0.2	9.9	0.3	13.4	5.53	7.87
45	67	13.3	0.2	11.3	2.1	13.4	6.18	7.22
45	84	17.9	0.5	16.1	1.8	12.5	7.76	4.74
50	34	7.5	0.1	5.9	1.6	11.3	4.01	7.29
50	50	9.0	0.2	8.1	0.9	12.3	5.9	6.4
50	75	14.7	1.0	12.9	1.8	15.9	8.96	6.94
50	79	17.4	0.8	14.0	3.3	18	9.42	8.58
50	82	17.4	0.4	15.1	2.4	15.6	9.78	5.82
55	23	6.2	0.1	4.3	1.9	11.3	3.56	7.74
55	35	7.1	0.2	5.8	1.3	13.1	5.26	7.84
55	40	8.3	0.3	6.5	1.8	13.9	6.04	7.86
55	46	8.5	0.1	7.3	1.2	14.7	6.93	7.77
55	60	12.6	0.3	9.5	3.1	17.4	9.18	8.22
55	62	10.0	0.2	9.7	0.3	16.2	9.39	6.81
55	70	14.8	1.0	11.2	3.5	15.7	10.59	5.11
55	78	15.5	0.6	13.3	2.3	17.5	11.82	5.68
					2.0			

weighed continuously in a superheated steam kiln; they were finally weighed in the oven-dry condition to calculate MC. We compared measured and calculated EMC using specimens 15 mm in the grain direction, 200 mm long, and 60 mm wide. Sets of 10 specimens each were dried to equilibrium at 95 – 23% RH and 40, 45, 50, and 55°C, which are common vacuum-drying conditions. We determined effects of air pressure on EMC using sets of 15 specimens of the same dimensions. They were dried to equilibrium in a special laboratory kiln at the described RH and temperature levels at total pressures of 11.3 – 17.5 kPa.

The measured EMCs and standard deviations at the various temperatures and RH levels are given in Table 1. EMCs in the table are the average of 10 specimens. Table 1 also shows the vapor pressure and air pressure at each drying condition. The EMC/RH relationship for each level of temperature (Fig 1) is similar to that at atmospheric pressure. The measured EMCs were greater than the calculated EMCs by about 2% MC and were larger at higher RH for each temperature. The difference may be from the use of Norway spruce rather than Sitka spruce for the Hailwood-Horrobin model constants. The phenomenon that the measured EMCs were larger than the calculated EMCs can also be explained by sorption hysteresis in that the EMC attained during desorption is always greater than adsorption. Furthermore, EMC from initial desorption from the green condition is higher than in any subsequent desorptions (FPL 1999). The greater difference between measured and calculated EMC at higher RH has also been reported for EMC at atmospheric pressure (FPL 1999).

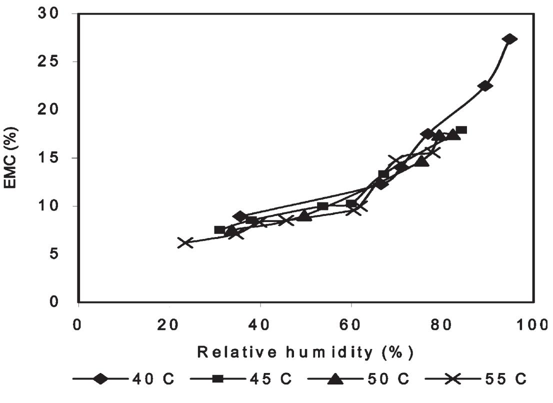

Figure 1. Wood vacuum EMC as a function of temperature and humidity.

At equal levels of temperature and RH, total pressure or air pressure does not significantly affect EMC. Experiments were designed to support this conclusion and results are presented in Table 2. During vacuum drying, air and water vapor inside the wood are removed from the total pressure difference. As drying proceeds, the residual air and air pressure are reduced, and vapor and vapor pressure are increased. Results show that wood EMCs under low pressure are not affected by the air pressure in the system. With little air left inside the chamber, total pressure approximately equals the vapor pressure and can be used in Eq 6 to estimate wood EMC inside the chamber.

Table 2. *Average of vacuum EMCs at various total pressures and temperatures.*

		Total pressure (kPa)	50	30	15
Temperature (°C)	50	Vapor pressure (kPa)	9.2	9.2	9.2
		Air pressure (kPa)	40.8	20.8	5.8
		RH (%)	75	75	75
		Average EMC (%)	12.8	13.2	13.0
	60	Vapor pressure (kPa)	10.9	10.5	10
		Air pressure (kPa)	39.1	19.5	5
		RH (%)	55	53	50
		Average EMC (%)	8.7	7.3	7.1

Our conclusion is that knowing RH and wood temperature, the Hailwood-Horrobin model can be used to estimate the EMC of wood under vacuum. This estimated EMC will be about 2 – 3% less than the actual EMC of wood during initial desorption. If there is no air present inside the chamber, total pressure can be used as an equilibrium to control the system.

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