Measuring Moisture Content of Wood Using a Transient Hot-Wire Technique

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Wood easily acquires a large amount of moisture when it is exposed to high-humidity conditions. The high moisture content influences the service life of wood. Thus, there is a need for an accurate, rapid, nondestructive, and simple measurement technique for wood's moisture content. This investigation proposes a method to measure the moisture content of wood by the wood volumetric heat capacity using a transient hot wire (THW) technique. The moisture content was inferred from the change of the volumetric heat capacity before and after the wood acquired moisture; the volumetric heat capacity is the ratio of the thermal conductivity to the thermal diffusivity. The results were validated by the gravimetric method, displaying good agreement, with discrepancies within 4%.

Keywords: Hot wire; Moisture content; Uncertainty analysis; Volumetric heat capacity; Wood

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INTRODUCTION

Wood or wood-based products are susceptible to deformation and decay if they are exposed to high-humidity conditions for long periods of time. Especially for wood structures in engineering, the acquired moisture may directly result in the reduction in mechanical properties and even influence the service life. To ensure structure safety, it is necessary to monitor the moisture content of the wood on a regular basis. Therefore, an accurate, convenient, *in situ*, and nondestructive means of measuring moisture content is needed.

Numerous methods have been developed to measure moisture content based on different principles (Phillipson *et al*. 2007). These methods can be generally categorized into direct and indirect types. The gravimetric method is a direct measurement and is the main measuring method in the fields of engineering application and lab investigation. In this method, the researcher weighs the mass change before and after wood acquires moisture (Cai *et al*. 2005). This simple and accurate method still has problems, such as a lack of timeliness and efficiency. Additionally, employing this method may result in the destruction of the material during sample preparation. Hence, the gravimetric method is not suitable for routine moisture monitoring in many engineering applications, *i.e.*, wooden structures. To overcome the inherent deficiencies of the gravimetric method, timely, nondestructive, and even non-contact methods are being developed, which are usually referred to as indirect methods.

Indirect methods allow the determination of moisture content based on the main signal from any of the following: thermal, electrical, optical wave, *i.e.*, X-ray, microwave, ultrasonic, near infrared spectroscopy (NIR), and nuclear sources (Forest Products Laboratory 1999). Among the indirect methods, only the nuclear method can provide temporal and continuous spatial moisture information; however, this method is comparatively expensive and inconvenient (Asli-Ardeh *et al.* 2009; Senni *et al.* 2010). Although the optical wave method provides an alternative approach for determining moisture content, this method does not perform well in practice (Moschler *et al.* 2007; Esteves and Pereira 2008; Hansson and Cherepanova 2012; He and Qi 2013; Kim *et al.* 2015). Currently, the electrical method is relatively popular, and it has been widely applied to lab investigations and industrial applications (Pan *et al.* 2007; Zhou *et al*. 2011; Fredriksson 2013a, b; Fu *et al*. 2016). However, the problem with this method is limited measuring range. Generally, measurement accuracy is good under fiber saturation point (FSP), but it is bad above FSP. In short, all of the methods mentioned above have some limitations for use in real-world applications.

Strangely, the thermal method that takes advantage of relationship between moisture content and wood thermal properties is only infrequently reported in wood science. In this method, moisture content is inferred from the change of thermal properties, *i.e.*, thermal conductivity, thermal diffusion, and volumetric heat capacity. The latter is the ratio of the thermal conductivity to the thermal diffusivity, before and after the wood acquires moisture. By measuring the temperature response subject to an instantaneous line heat input, the parameters of these thermal properties can be obtained. For example, Trcala *et al.* (2015) proposed that measuring the moisture content of wood using thermal properties is feasible. The accuracy of the calculated moisture content based on the relationship between thermal conductivity and moisture content needs further improvement.

Zhang *et al.* (2015) confirmed that measuring the moisture content using the material's volumetric heat capacity has higher precision than other parameters related to thermal properties. The discrepancies are within 4% between a hot-wire method and the gravimetric method.

When a parameter related to thermal properties (volumetric heat capacity in the present study) is selected, a stable heat source is needed. Compared with the pulse and plate heat source that generally requires elaborate calibration before use, the transient hot wire (THW) technique has been widely successfully used in many scientific fields, and it does not require a relative complex instrumentation or experimental equipment (Salmon 2001; Ham and Benson 2004).

The hot wire technique originated in the 1780s. It was applied to study gas heat conduction (Healy *et al.* 1976). Benefiting from modern hardware and a more fully developed theory, this THW technique features an extremely low uncertainty of less than 1% for measuring the thermal conductivity of gases, liquids, and solids and less than 2% for nano-fluids (Assael *et al.* 2010; Su and Lee 2012; Lee *et al.* 2015). The method exhibits good performance in various applications (Labudova and Vozárová 2002; Santos 2008; Su and Lee 2012). Thus, this hot wire method is very suitable for producing a stable heat source in the wood industry.

The main objective of this study was to measure moisture content using the wood volumetric heat capacity with the THW technique to conduct routine moisture monitoring in engineering applications. The moisture content was inferred from the change in the volumetric heat capacity before and after moisture is acquired. The final objective was to evaluate the quality of the measurements and to implement an uncertainty analysis.

EXPERIMENTAL

Materials and Methods

Oak (*Quercus mongolica*) was collected in a larch plantation in Heilongjiang Province, China. Specimens obtained from a sapwood tangential cut had dimensions of 100 × 30 × 10 mm^3, initial moisture content 40 ± 1.9%, and basic density 750 ± 23 kg, which is obtained using weighing method and drainage method, respectively. Several specimens were slowly dried to a moisture content near 0%, 5%, 10%, 15%, and 25% in the convectional chamber. Prior to the experiment, a thermocouple measuring point and the front end of a hot wire was placed in the core of the plane of symmetry of each specimen and were fixed with glass cement. The prepared specimens were insulated with asbestos insulation and aluminum tape. Figure 1 shows a schematic of the hot wire and sensor layout used to measure the moisture content. During the experiment, the recording interval was 10 seconds, with a total sample measurement of 600 s. The specimen was then placed in a drying oven at 103 ± 2 °C to measure oven-dry weight. The determination of five levels of moisture content using different specimens was repeated three times at each level, for a total of 15 specimens. The initial temperature of each specimen was 17 to 19 °C.

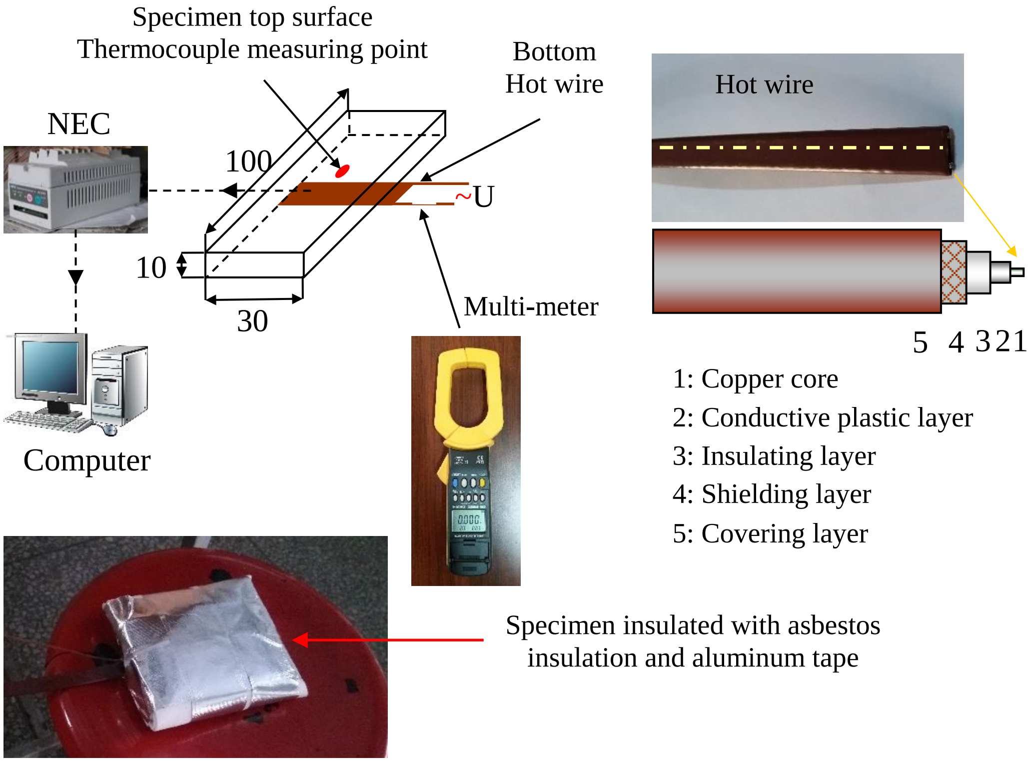

Fig. 1. Schematic of the hot wire and sensor layout used to measure moisture content

The temperature was recorded using a NEC Remote Scanner Jr. DC3100 (Nec-Sanei, Ltd., Tokyo, Japan; accuracy 0.1 °C and error ± 0.5 °C). A multi-meter (Model 3286-20, HIOKI, Tokyo, Japan) with an accuracy of 0.01 A and error of ± 0.02 A was used to record the electric current and hence the heat generation rate of the hot wire per unit length. A hot wire (Type: ZWK-JX, An-Hui Xiaoxiang Electric Heating Material Co., Ltd., An-Hui, China) had the following characteristics: nominal power, 45 W; width, 4 mm; length, 8 mm; internal copper wire diameter, 0.32 mm; and conductive plastic resistance, 0.6 Ω. In addition, a digital precision balance (Model LD-1001, Shen-Yang Longteng Electronics Co., Ltd., Shen-Yang, China) with a resolution of 0.01 g and an accuracy of ± 0.02 g was used to determine the mass of the specimens.

BASIC PRINCIPLES

The correlations between the moisture content and the volumetric heat capacity are addressed first, followed by an overview of the hot wire technique to measure the volumetric heat capacity. Finally, the measurement procedure is presented.

Relating Moisture Content to the Volumetric Heat Capacity

Wood is a biological porous material that consists of wood matrix, water (free and bound water, water vapor), and air. Because the density and specific heat of air is relatively small compared with the former, the volumetric heat capacity of the air in the voids of the wood is negligible. Thus, the relationship between moisture and the volumetric heat capacity can be expressed as follows,

$$\rho_{dry}c_{dry} + \rho_w c_w x_w = \rho_{wet}c_{wet} \tag{1}$$

where *dry* refers to oven-dry wood, *wet* is wet wood, and *w* is water. The parameter x_w is the volumetric fraction (%) given by Tremblay *et al.* (1999).

Equation 1 shows that once the change in the volumetric heat capacity before and after the acquisition of moisture is known, the moisture content can be inferred. Then, the moisture content can be calculated from the volumetric heat capacity as,

$$M = \frac{\rho_w x_w}{\rho_{dry}} = \frac{\rho_{wet}c_{wet} - \rho_{dry}c_{dry}}{\rho_{dry}c_w} \tag{2}$$

where ρ_w is 1000 kg m^{-3}, c_w is 4183 J kg^{-1} K^{-1}, and ρ_{dry} is 750 kg m^{-3} (Pan *et al.* 2007).

Overview of the THW Technique

The THW technique provides a prompt means to measure both the thermal conductivity and the thermal diffusivity from the temperature response subject to a sudden line heat source. The detailed theory and historical evolution can be found in Healy *et al.* (1976) and Assael *et al.* (2010). The ideal analytical model treats the hot wire as an infinitely thin and long line heat source. The medium is an infinitely large, homogenous, and isotropic material with a uniform initial temperature. The temperature rise due to pure heat conduction can be expressed as Eq. 3,

$$\Delta T(r,\tau) = -\frac{q}{0.1\pi\lambda} Ei\left(-\frac{r^2}{4a\tau}\right) \tag{3}$$

where ΔT is temperature rise (°C), r is distance between the hot wire and the temperature sensor (m), τ is heating time (s), q is heat generation rate per unit length (W m^{-1}), a is the thermal diffusivity (m^2 s^{-1}), and λ is the thermal conductivity (W m^{-1} K^{-1}). *Ei* is the exponential integral function that can be expanded into Eq. 4,

$$-Ei(-x) = -\beta - \ln x + \sum_{i=1}^{\infty} \frac{(-1)^{i+1} x^i}{i \cdot i!} \tag{4}$$

where β is the Euler constant equaling to 0.5772. If x is small enough, the last term on the right hand side of the above equation can be neglected. That is, when $r^2/(4a\tau)$ is sufficiently small, the temperature rise can be simplified into Eq. 5,

$$\Delta T(r,\tau) \approx \frac{q}{0.1\pi\lambda}\left[-\beta - \ln\left(\frac{r^2}{4a\tau}\right)\right] = \frac{q}{0.1\pi\lambda}\left[\ln\tau + \ln\left(\frac{4a}{r^2 C_E}\right)\right] \tag{5}$$

where $C_E = \exp(\beta) = 1.781$. Rewriting the temperature rise in coordinates of ΔT *versus* $\ln \tau$ yields Eq. 6,

$$\Delta T(r,\tau) = A \ln\tau + B \tag{6}$$

where A is the slope of the temperature curve and B is the intercept, such that λ and a can be expressed by Eqs. 7 and 8, respectively.

$$\lambda = \frac{q}{0.1\pi A} \tag{7}$$

$$a = 0.25 r^2 C_E \exp\left(\frac{B}{A}\right) \tag{8}$$

Finally, the volumetric heat capacity can therefore be obtained as follows,

$$\rho c \equiv \frac{\lambda}{a} = \frac{q}{0.025 C_E \pi r^2 A \exp(\frac{B}{A})} \tag{9}$$

where ρ is density (kg m^{-3}) and c is specific heat (J kg^{-1} K^{-1}).

The Measurement Procedure

To apply the THW technique to detect moisture content in wood, the following rational assumptions should be established to assure the validity of the proposed method:

1. A uniform initial temperature and moisture content distribution in the test medium.
2. No change of temperature and moisture content at the outer boundary of the test medium.
3. One-dimensional heat conduction from the hot wire to the temperature sensor.
4. Negligible radiation heat transfer and thermal inertia of the temperature sensor.
5. A thin hot wire long enough to be treated as a line source.
6. Subject to a sudden constant heat flux.

The assumptions 1, 2, and 3 are commonly valid due to special experimental handling, *i.e.*, slow drying to ensure uniform moisture content and the use of thermal insulation materials to reduce the heat loss. Meanwhile, assumptions 4, 5, and 6 are also valid and very common in papers about hot wire method (Zhang *et al.* 2015). The intact calculation process is as shown in Fig. 2.

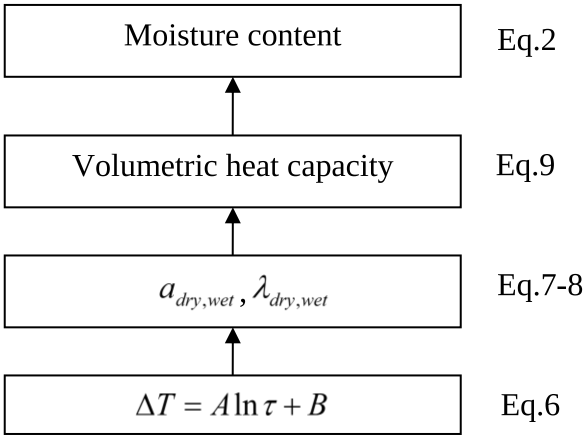

Fig. 2. The moisture content calculation process

RESULTS AND DISCUSSION

Figure 3 shows the recorded temperature response from specimens with different moisture content subjected to 600 s of hot wire heating in the first test. The curved nature of the temperature response decreased as the moisture content increased. The difference in heating rate is likely related to the different moisture content of the specimens. For example, the heating rate is related to thermal conductivity and volumetric heat capacity, so the heating rate is also affected by moisture content. Hence, moisture content is inferred from these phenomena using hot wire proposed in the study.

To further illustrate this phenomenon, Fig. 4 includes logarithmic graphs of the temperature response with variations in moisture content *versus* time. It took approximately 400 s to reach a linear temperature response over the logarithmic time scale (Fig. 4a). The linear sections of the temperature rise *versus* the logarithmic time were extracted from the recorded temperature responses (Fig. 4b). To obtain the slope and the intercept of the temperature response in the linear section, the data in this section was fitted to a straight line. An R^2 value was used to quantify the goodness of fit, in which an R^2 of 1 means that all the data points are located on the fitted straight line.

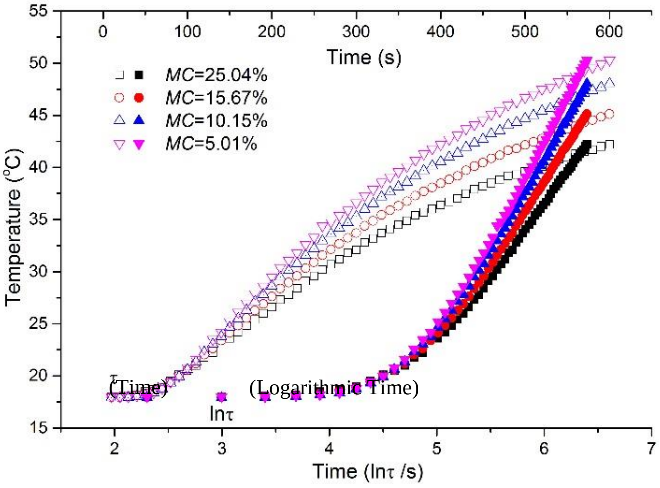

Fig. 3. The recorded temperature response of a specimen subjected to hot wire heating in the first test *versus* logarithmic time ($\ln\tau$) and time (τ)

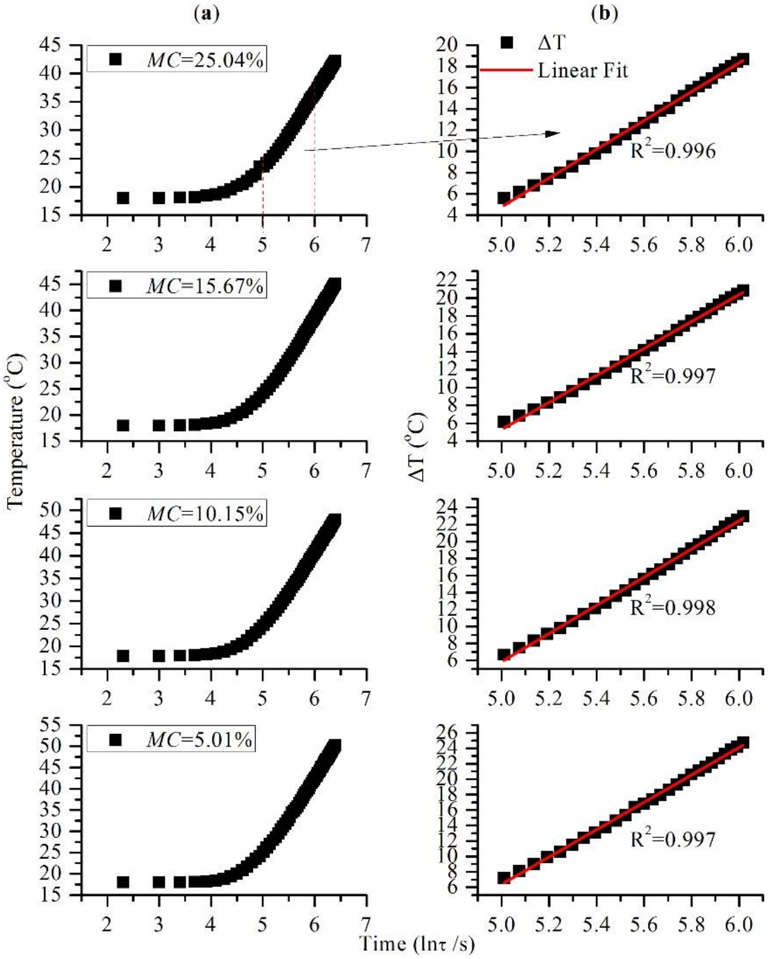

Fig. 4. The recorded temperature response and extraction of the linear section in the first test

Based on the obtained slope and intercept, the volumetric heat capacity was calculated with Eq. 9. Finally, the moisture content was inferred by Eq. 2. The calculated parameters, *i.e.*, thermal conductivity, thermal diffusivity, volumetric heat capacity, and calculated moisture content using the hot wire method and the measured parameters, *i.e.*, heat generation rate and measured moisture content using gravimetric method, are given in Table 1. The discrepancies were within 3.8% and the standard uncertainty ranges were from 3.02% to 4.57%, which indicated that measuring moisture content of wood using the proposed hot wire method is feasible. The major factors contributing to the discrepancies were attributed to some assumptions in the THW model, *i.e.*, the heterogeneous distribution of the moisture and temperature, thermal inertia, and differences of wood properties. Nevertheless, the proposed hot wire method should suffice for engineering applications (Pan *et al.* 2007).

Table 1 also shows that volumetric heat capacity increased with increasing moisture content. However, the change was not obvious for thermal conductivity and thermal diffusivity; in addition, it was somewhat volatile for thermal diffusivity. Thus, the volumetric heat capacity selected in the THW model is reliable, in agreement with Zhang *et al.* (2015).

Table 1. Measured Parameters and Moisture Content Using the Hot-Wire Method and its Comparison to the Gravimetric Method

A	*B*	λ W m^{-1} K^{-1}	*a*,10^{-7} m^2 s^{-1}	ρc,10^5 J m^{-3} K^{-1}	$u_c(\rho c)$,10^5 J m^{-3} K^{-1}	M_G %	M_{HW} %	ε $\|M_G$-$M_{HW}\|$ %	$u_c(M)$ %
20.561	**-90.562**	**0.155**	**6.584**	**2.349**	**1.422**	**0.00**^{a}	**-**	**-**	**-**
Test 1									
13.558	-63.011	0.443	4.107	10.795	1.221	25.04	26.92	1.88	3.66
15.640	-72.626	0.384	4.546	8.456	1.049	15.67	19.47	3.80	3.15
16.580	-77.582	0.243	3.995	6.075	1.522	10.15	11.88	1.73	4.57
17.721	-82.241	0.179	4.219	4.252	1.356	5.01	6.07	1.06	4.07
Test 2									
13.053	-59.015	0.461	4.940	9.323	1.159	24.86	22.23	2.63	3.48
14.932	-69.545	0.270	4.311	6.252	1.098	15.27	12.44	2.83	3.29
16.723	-78.234	0.241	5.099	4.719	1.329	9.98	7.56	2.42	3.99
18.418	-80.363	0.218	5.671	3.853	1.251	5.19	4.79	0.40	3.75
Test 3									
13.550	-64.237	0.367	3.880	9.449	1.005	24.03	22.63	1.40	3.02
15.632	-73.519	0.257	3.917	6.572	1.553	15.07	13.46	1.61	3.76
16.893	-78.267	0.239	4.310	5.527	1.298	10.58	10.13	0.45	3.89
18.253	-80.573	0.220	5.522	3.992	1.341	4.89	5.24	0.35	4.02

M_G: measured moisture content, M_{HW}: calculated moisture content, a: data for oven-dry specimens from the average value of three tests

Table 2. List of Standard Uncertainties for the Measurement of Moisture Content

No.	Uncertainty source	M_G			
		25.04%	15.67%	10.15%	5.01%
1	u_A(A)	0.154	0.133	0.193	0.171
2	u_B(A)	0.004	0.004	0.008	0.005
3	u_C(A)	0.878	0.754	1.098	0.975
4	u_A(B)	0.864	0.742	1.081	0.960
5	u_B(B)	0.017	0.017	0.038	0.023
6	u_C(B)	0.018	0.018	0.039	0.023
7	$u_B(q)$	7.621×10^{-4} W/m	7.621×10^{-4} W/m	7.621×10^{-4} W/m	5.543×10^{-4} W/m
8	$u_B(r)$	1.155×10^{-5} M	1.155×10^{-5} m	1.155×10^{-5} m	1.155×10^{-5} m
9	$u_C(\rho c)$	1.221×10^5 J/(m^3·K)	1.049×10^5 J/(m^3·K)	1.522×10^5 J/(m^3·K)	1.356×10^5 J/(m^3·K)

u_A: type A uncertainty, u_B: type B uncertainty, u_C: the combined uncertainty

Uncertainty analysis was implemented to evaluate the quality of the measurement. A detailed definition and application of type A and B uncertainty can be found in Ni (2013). Tables 2 and 3 list the standard and combined standard uncertainties for each variable in the model. The calculated process of standard uncertainty is found in Zhao (2016). Table 3 shows that the slope contributed significantly to the uncertainty of the volumetric heat capacity, but the combination of both the slope and intercept contributed less than the slope alone. This occurs because the slope and intercept have a negative correlation coefficient.

In other words, if the slope is overestimated, the intercept is underestimated. In addition, the heat generation rate of the hot wire and its distance from the temperature sensor contributes little. Thus, the slope has a significant effect on the calculation precision and stability. In the future, the THW model may be improved by determining the slope more accurately. For example, research is needed to explore how to more reasonably extract the linear sections of the temperature rise from the recorded temperature responses *versus* the logarithmic time.

Table 3. Final Standard Uncertainty Source

No.	Final uncertainty source	M_G			
		25.04%	15.67%	10.15%	5.01%
1	$\left\lvert\frac{\partial(\rho c)}{\partial A}\cdot u_c(A)\right\rvert$	1.227 $\times10^5$	1.055 $\times10^5$	1.535 $\times10^5$	1.364 $\times10^5$
2	$\left\lvert\frac{\partial(\rho c)}{\partial B}\cdot u_c(B)\right\rvert$	0.061 $\times10^4$	0.060 $\times10^4$	0.013 $\times10^4$	0.080 $\times10^4$
3	$\begin{pmatrix}\left[\frac{\partial(\rho c)}{\partial A}\cdot u_c(A)\right]^2+\left[\frac{\partial(\rho c)}{\partial B}\cdot u_c(B)\right]^2+\ldots \\ 2\xi A,B\cdot\frac{\partial(\rho c)}{\partial A}\cdot\frac{\partial(\rho c)}{\partial B}u_c(A)\cdot u_c(B)\end{pmatrix}^{1/2}$	1.221 $\times10^5$	1.049 $\times10^5$	1.522 $\times10^5$	1.356 $\times10^5$
4	$\left\lvert\frac{\partial(\rho c)}{\partial q}\cdot u_B(q)\right\rvert$	0.045 $\times10^4$	0.045 $\times10^4$	0.045 $\times10^4$	0.033 $\times10^4$
5	$\left\lvert\frac{\partial(\rho c)}{\partial r}\cdot u_B(r)\right\rvert$	0.012 $\times10^4$	0.012 $\times10^4$	0.012 $\times10^4$	0.012 $\times10^4$

Generally, the expanded uncertainty is the product of the coverage factor with standard uncertainty. The relationship between the coverage factor and coverage probability is listed in Table 4. If a coverage factor of three for a confidence level of 99.73% is chosen, all of the differences of the measured moisture content between both methods fall within the uncertainties. The uncertainty analysis thus confirms that the proposed method has generally good accuracy.

Table 4. The Relationship between the Coverage Probability and Factor

p (%)	50	68.27	90	95	95.45	99	99.73
k_p	0.675	1	1.645	1.960	2	2.576	3

CONCLUSIONS

1. This investigation proposes a method to measure the moisture content of wood by the volumetric heat capacity using a transient hot wire (THW) technique. The moisture content is inferred from the change of the volumetric heat capacity before and after the wood acquires moisture. The results indicated that the hot-wire method measures moisture content of wood with reasonably good accuracy.

2. The deviation between the hot wire method and the gravimetric method was less than 4%. For a confidence level of 99.73%, all the differences in the measured moisture content from both methods fall within the uncertainties. Additionally, measuring the moisture content using volumetric heat capacity had higher precision and stability than other parameters related to thermal properties.
3. The corresponding devices related to the method proposed in this study may be developed in the future.

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