

Moisture content determination in solid biofuels by dielectric and NIR reflection methods

Peter Daugbjerg Jensen^{a,*}, Hans Hartmann^b, Thorsten Böhm^b, Michael Temmerman^c, Fabienne Rabier^c, Merete Morsing^a

^aDepartment of Forest and Landscape, The Royal Veterinary and Agricultural University, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark

^bTechnologie- und Förderzentrum für Nachwachsende Rohstoffe (TFZ), Schulgasse 18, D-94315 Straubing, Germany

^cDepartement Genie Rural, Chee de Namur 146, B-5030 Gembloux, Belgium

Received 17 November 2005; accepted 9 June 2006

Available online 7 September 2006

Abstract

One near infrared (NIR) reflectance and five dielectric moisture meters were tested for their capability of measuring moisture content (MC) in solid biofuels. Ninety-eight samples were tested at up to eight moisture levels covering the MC range from fresh fuel to approximately 10% MC (w.b.). The fuel types ranged from typical solid biofuels such as coniferous and deciduous wood chips over short rotation coppice (SRC) to sunflower seed and olive stones. The most promising calibrations were obtained with the NIR reflection method and two dielectric devices where the sample is placed in a container integrated in the device. The calibration equations developed show that there is a profound influence from both laboratory and fuel type. It is suggested that individual calibrations that are based on the specific fuel types used at the individual heating plant could be applied.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Moisture content; Solid biofuel; Fuel chips; On-site measurement; Dielectric measurement; NIR

1. Introduction

Solid biofuels are by nature heterogeneous with respect to moisture content (MC), bulk density and particle size. The fuels range from well-defined upgraded materials such as wood or straw pellets used in domestic burners to wood chips produced from thinnings and residues from logging operations. Pellets typically have a MC below 12% (w.b.), a narrow bulk density range and a uniform size distribution. In contrast, the MC of forest chips varies substantially, from approximately 10% to around 60% (w.b.), it has a wide-range bulk density and a size distribution that largely depends on tree species, raw material and type of chipper used.

The price of the fuel is often based on the MC. Combustion optimisation, storage management and handling properties are influenced by the MC [1–4]. Traditionally, MC is measured as weight loss by convection drying

until constant mass in hot air at 103 or $105 \pm 2^\circ\text{C}$ in a drying cabinet. The method is widely accepted and described in a number of standards used for moisture determination of solid biofuels [5–7]. It is considered as being accurate and independent from other parameters such as bulk density or ambient temperature.

However, moisture determination in a drying oven is time and labour consuming. The potential for saving time and obtaining information on the MC prior to incineration is therefore a motivation for using rapid test methods for moisture determination. As reviewed by Nyström and Dahlquist [8], several methods for rapid measurement of MC of solid biofuels exist. Among these, the dielectric- and near infrared (NIR) methods are presently the best alternative to convective drying [9–12]. Common for the devices are that they measure a characteristic of the fuel that which is correlated with the MC.

The dielectric methods are based on electric field changes. The changes are due to the dielectric properties of the material matrix upon radiation with an alternating

*Corresponding author. Fax: +45 35 28 15 12.

E-mail address: pdj@kvl.dk (P.D. Jensen).

current. The dielectric properties of any material are expressed as the relative permittivity, $\varepsilon = \varepsilon' - \varepsilon''$, where ε' is the dielectric constant of the material which expresses the materials capability to polarise and ε'' is the loss factor of electrical energy within the field due to polarisation of the material. Water has a high dielectric constant ($\varepsilon' \cong 80$) compared to wood ($\varepsilon' \cong 4-5$) [13]. In its simplest version, a moisture meter consists of two plates connected to an alternating voltage supply. The volume between the plates contains the dielectric material e.g. wood chips. When an alternating current passes from one plate (emitter) to the other (receiver), the decrease in the effective electric field compared to a situation with air or vacuum between the plates is a measure of the moisture in the sample. Besides MC, temperature and bulk density also influence dielectric measurements [14–16]. Influence from bulk density and temperature may be reduced by calibrating the moisture meters to fuel types within a suitable bulk density range and by defining the ambient temperature.

If the applied wavelength is within the radio frequency (RF) area (<0.3 GHz), the moisture meter is of the capacitance type. A widespread alternative to radio frequencies are microwaves (0.3–20 GHz). Similar to the capacitance meters, the microwave technique measures the MC by sending a wave of a defined frequency through the material. The waves are either absorbed or reflected by the dipole water molecules, which is measured as a transmission or reflection factor. This technique is particularly attractive since influences from ion conductivity are negligible at high frequencies as compared to the dielectric losses.

The NIR reflectometric method is based on the principle that a material illuminated by monochromatic light of a defined wavelength absorbs, transmits or reflects the light. Water has two distinct absorption bands in the NIR part (800–2500 nm) of the electromagnetic spectrum at around 1475 and 1940 nm. This is used in NIR-reflectometry where monochromatic light of either of the two wavelengths is absorbed by the water molecules of the sample. The absorption difference between the absorbed bands and reference bands using wavelengths that are almost entirely reflected provide a quantitative measure of the functional O–H groups of the material (primarily water). Thygesen [17] found no literature describing influence of bulk density, whereas Fassio and Cozzolino [18] showed that

NIR could be sensitive to variances in the colour of the material.

This paper summarises the results of the testing of five rapid moisture meters measuring dielectric properties in the radio and microwaves frequencies and on one optical device based on NIR reflectance. All devices tested are commercially available and two of them are developed particularly for moisture determination of solid biofuels. The study was carried out as a round robin with participants from 11 European laboratories as described in Section 2.3.

2. Materials and methods

2.1. Rapid moisture meters

An overview on the optical and five dielectric moisture meters tested in the study is given in Table 1.

The Pandis and Schaller devices belong to a type where the sample is placed in a container during the measurements (container type). The emitter and receiver are orientated in a way that allows an electrical field to build up within the sample (transmission measurements). Both devices are commercially available only as pre-calibrated versions. The Pandis consists of a cylindrical container (640 × 500 mm) with a filling volume of approximately 60 l. It is designed to measure MC ranging from 0% to 55% (w.b.) on a mixture of fine and medium chips as described in the ÖNORM M7133 [19]. The sample is compacted during filling by shaking the container twice when it is half full. The Schaller has a cubic sample container (150 × 190 × 400 mm) which requires a sample size of 1700 ± 10 g. It is designed to measure fine and medium chips [19], at a MC range from 0% to 40% (w.b.) and an optimum measuring range between 10% and 25% (w.b.). With the Schaller, the influence from bulk density is reduced due to the application of a defined sample volume and mass.

ACO, Wile and the microwave type Moist are all hand-held devices. The Wile has a probe (length $\cong 190$ mm) that is inserted into the sample, while ACO and Moist have a flat sensor head (ACO, $\varnothing = 50$ mm; Moist, $\varnothing = 80$ mm), that is placed on the surface of the sample during measurements (reflective measurements). The sensor heads of the hand-held devices thus unite emitter and receiver.

Table 1
Description of the tested rapid moisture meters

Method	Principle	Manufacturer: type	Name	Range	MC range (%) ^a
Dielectric	Capacitive	Pandis: FMG 3000	Pandis	<0.3 GHz	0–55
		ACO: MMS-0-1-2-0	ACO		0–80
		Farmcomp: Wile25	Wile		13–85
		Schaller: FS 2002-H	Schaller		0–40
Optical	Microwave	hf sensor: Moist 100	Moist	0.3–20 GHz	0–80
	NIR reflection	Mesa: MM710	Mesa	800–2500 nm	10–40

^aAs recommended by the supplier.

The ACO and Wile compensate for bulk density differences by pressing the sensor head with a defined force onto the material during measurements. The ACO and Moist are available only in non-calibrated versions, whereas the Wile is pre-calibrated for MC measurements in silage. Except the Schaller, only non-calibrated versions of the dielectric methods were tested.

The optical Mesa equipment is developed for on-line measurements. It comprises a gauge with a filter wheel that releases monochromatic light of the desired wavelength (measuring beam) onto the sample and measures the reflected light. A reference beam with a wavelength, which is not absorbed by free water, is used to eliminate variations caused by the environment (e.g. distance to sample or colour differences between the particles). Furthermore, a correction beam, which follows the normal radiation paths of the sensor head without leaving the system, enables corrections for any measuring drift (e.g. caused by ageing of the light source, changes in sensitivity of the detector, temperature changes). In this study, the gauge was equipped with a filter for measuring in the range from 10% to 40% MC. For the testings, the sample was placed in a cylindrical steel container that was rotating horizontally during the measurements, thus imitating a moving stream of fuel on a conveyor belt.

For reference MC determination triplicates of 500 g from each sub-sample were measured in drying ovens at 105 °C [20]. The ovens of all partners were tested for temperature accuracy and distribution prior to the round robin. This was done using thermocouples connected to a Testo 177 data logger. Areas in the drying ovens where the temperature exceeded the tolerance of 105 ± 2 °C were avoided for the moisture determinations.

2.2. Fuel conditioning and sample preparation

A broad variety of 98 solid biofuel types were used for this study (Table 2). From each fuel type, samples of minimum 1 m³ were collected and divided into sub-samples of equal size (eight for wood chips, up to five for the others) using the coning and quartering technique. Approximately equidistant moisture steps were produced for each sample ranging from fresh fuel to approximately 10% moisture (w.b.). The target moisture steps were achieved by determining the MC of the fresh sample [20] followed by floor drying of the sub-samples until the pre-defined MC step was achieved. During the drying process, the moisture level of the sub-samples was monitored on small samples (500–1000 g), which were dried parallel to the sub-samples. When the small sample reached a pre-defined weight corresponding to a desired MC level, the drying of the sub-sample was terminated. The floor drying was performed by spreading the sub-samples on a layer of wooden plates covered by plastic or fine meshed net. Using fine net allowed forced ventilation, which accelerated the drying process. The sub-sample had a height of approximately 5–7 cm and was turned and mixed frequently to achieve a

Table 2
Applied fuels for the test of rapid moisture meters

Fuel type	Bulk density range (kg/m ³)	No. of samples
Wood chips		
Coniferous	111.7–228.6	30
Deciduous	154.2–248.2	25
Mixed	177.8–213.3	2
Short rotation coppice	129.9–156.5	6
Bark	121.57–219.2	6
Sawdust	91.5–162.4	9
Shavings	95.2	1
Pellets		
Wood	600.5–668.0	6
Straw	511.5–636.0	3
Stones/shells	212.34–522.5	5
Olive cake	622.4	1
Grain		
Triticale	647.4	1
Energy grass		
Miscanthus	82.0–138.4	2
Peat	142.0	1

uniform drying process. The conditioning procedure secured that all fuel samples were represented by sub-samples covering the widest possible moisture range. Furthermore, it secured that one of the sub-samples had an MC of $30 \pm 3\%$; these samples were for determine bulk density. After conditioning, the sub-samples were stored in airtight plastic bags at a cool, dry and dark location for a minimum of 2 weeks, in order to ensure a uniform moisture distribution within the sub-samples.

2.3. Measuring procedure

The 11 participating European laboratories were divided into two groups. Each laboratory prepared up to 10 test fuels as described above (2.2). Two sets of the rapid-MC equipment were procured and each circulated within a group of laboratories. Pre-tests were performed on the dielectric equipment to identify optimal settings during the round robin. Prior to the round robin tests, detailed guidelines describing the measuring procedure were developed to ensure uniform trial conditions. Further, the handling of all devices tested was demonstrated at a workshop which was attended by representatives of all participating laboratories.

The MC of the sub-samples of each fuel was measured with the six rapid test devices starting with the driest moisture level and proceeding with increasing moisture levels until all levels were measured. Prior to the measurements, the sub-sample was poured on a clean surface (e.g. a plastic sheet), homogenised twice and split into four portions by coning and quartering. Three of the newly obtained portions were put together in a transparent plastic bag. The fourth portion was split into three small plastic bags, which were closed airtight to avoid moisture changes.

The measurements started with the Moist device. In 20 replicate measurements, the measuring head was held at the exterior of the bag at the middle of the filling height. Then 10 replicate measurements with the Wile were performed, plunging the probe into the material from the top of the open bag. Subsequently, three replicate measurements with the Pandis device were made and then the three replicates for reference moisture were sampled and measured according to CEN/TS 14774-1 [20]. Proceeding with the content of three small plastic bags, the measurements were then performed with the Schaller (3 times one measurement), the ACO (3 times five replicates on the surface of a 7 cm sample layer) and the Mesa (3 times five replicates).

The bulk density was determined in triplicates on the sub-sample which had a MC of $30 \pm 3\%$ using a 50-l cylindrical steel container. Forced compaction was applied by dropping the container 3 times from 150 mm height [21]. For fuel types with a maximum MC below 30%, primarily straw and wood pellets, the bulk density was measured at the MC at reception.

2.4. Statistics

All analyses were performed using SAS version 8.2. In order to exclude erroneous data due to sample pre-treatment, all data from samples that varied more than 1% (*t*-test) within the three reference sample measurements were excluded from the analysis. Tests for outliers from measurements with the devices tested were performed using the interactive data analysis program in SAS[®], which compares the studentised residuals to a critical value. Only those outliers that could be explained as handling or procedure errors were excluded from the analysis.

The following model was used to analyse the data:

$$MC_{ijk} = \alpha_0 + \beta_1 \text{value} + \beta_2 BD + A_i + B_j + (AB)_{ij} + \varepsilon_{ijk}, \quad (1)$$

where α_0 , β_1 , β_2 are the parameters for fixed effects, A_i , B_j , AB_{ij} the parameters for random effects, i the Lab, j the Fuel type, k the replication, ε_{ijk} the $\sim N(0, \sigma^2)$, DB the bulk density, Value the reading on device and MC the moisture contents.

Significance levels of fixed and random effects were tested by *t*-test and χ^2 , respectively.

A joint data set from fuel chips of coniferous, deciduous and short rotation coppice was applied to the SAS[®] PROC MIXED procedure to test the variance due to fuel type and laboratory. The contributions of the dimensionless reading from the test device and the bulk density of the fuels were treated as fixed effects whereas the variance due to laboratory and fuel type were considered to be random effects (bulk density is only considered for the dielectric devices). With PROC MIXED, the variance components due to the random factors “lab” (laboratory) and “fuel type” was quantified. The variance that is explained by

laboratory and fuel type respectively in Tables 4–6 indicates the magnitude of the bias for the predicted MC that is expected if the devices are not calibrated specifically to the laboratory (or person) and/or fuel type. This is important, as a bias only can be eliminated by calibration. The remaining part of the variance (residual) describes the ability of the specific device to measure MC under the given circumstances. Since the fuels were not circulated among the laboratories each fuel was unique to the laboratory. Consequently, the variance due to fuel type may include both that of general fuel type and of the laboratory specific fuel. Finally calibrations on selected devices were made by general linear regression methods (SAS[®] PROC GLM), fitting the data to Eq. (1), but excluding the random effects, fuel-type and laboratory, from the model since the calibration was made specifically for each laboratory and fuel type.

The minimum number of replications required to measure MC within a range of $\pm 5\%$ -point at a certain significance level were determined according to Cochran [22]:

$$CL \geq t_{1-\alpha/2} s / \sqrt{n} \Leftrightarrow n \geq t_{1-\alpha/2}^2 s^2 / CL^2, \quad (2)$$

where CL is the confidence limit (5%-point), α the significance level, s the standard deviation, n the number of replicates and t the *t*-value with $n-1$ degrees of freedom.

3. Results and discussion

Significance levels for fixed and random effect tested for the chipped fuels are shown in Table 3. In all cases, the interaction between laboratory and fuel type were significant and thus the effect ‘fuel type’ was always included in the model despite its main effect in some cases was insignificant.

An initial analysis including all fuel samples showed that the variance due to fuel type constitutes a considerably large share of the variance (see “var fuel type” in Table 4).

In order to reduce the influence due to fuel type heterogeneity, further analyses were performed on a reduced data set of wood chips from coniferous, deciduous and short rotation coppice. The result from the analysis on the reduced data set is given in Table 5.

The residual variance shown in Table 5 indicates that the NIR reflectance method is able to measure moisture with a higher accuracy than the dielectric methods. No statistically significant influence from the variance due to laboratory and fuel type was found in the reduced data set.

For the dielectric devices, the residuals are considerably lower for the container type equipment compared to the probe/sensor type equipment. Pandis was more sensitive to inconsistent handling than Schaller (see “var lab” in Table 5). A reason might be that in contrast to Schaller, Pandis prescribes compaction of the sample introducing an additional source of error. Extending the MC range to 0–55% for the Schaller results in higher residual variance (33.45; see

Table 3
Significance levels of fixed and random effects used in Eq. (1)

Device	MC range (%) ^a	Fixed effects		Random effects		
		Value	Bulk density	Lab	Fuel type	Interaction
Pandis	0–55	<0.0001	0.0005	0.12700	0.01165	<0.0001
Moist	0–80	<0.0001	<0.0001	0.03076	0.38786	<0.0001
Wile	13–85	<0.0001	<0.0001	0.02084	0.06814	<0.0001
Schaller	0–40	<0.0001	0.0004	1.0	0.00113	<0.0001
ACO	0–80	<0.0001	<0.0001	0.00508	0.10980	<0.0001
MESA	10–40	<0.0001	^a	0.97227	0.75643	<0.0001

^aBulk density not relevant.

Table 4
Sum of the joint variance components of laboratory and fuel type and the interaction between laboratory and fuel type

Method	Type	Device	Var lab ^a	Var fuel type ^b	Residual ^c	<i>n</i>
Optical	Moving	Mesa	2.94	15.58	9.55	6225
		MM710				
Dielectric	Container	Pandis	8.60	34.25	33.64	1613
		FMG3000				
		Schaller				
	Probe/sensor	FS 2002-H	5.27	15.32	13.32	1171
		ACO	9.13	88.19	83.13	9915
		MMS 0112	22.43	54.14	84.68	5437
		Wile25				
Moist 100	11.48	11.91	65.37	13200		

Data originating from the six moisture meters at the full set of fuels and the MC ranges given in Table 1.

^aSum of variance from lab and the interaction of lab and fuel type.

^bSum of variance from fuel type and the interaction of lab and fuel type.

^cResidual variance.

Table 5
Sum of the joint variance components of laboratory and fuel type and the interaction between laboratory and fuel type

Method	Type	Device	Var lab ^a	Var fuel type ^b	Residual ^c	<i>n</i>
Optical	Moving	Mesa	2.88	3.50	7.84	4470
		MM710				
Dielectric	Container	Pandis	13.09	11.38	20.73	1202
		FMG3000				
		Schaller				
	Probe/sensor	FS 2002-H	3.94	10.25	12.04	895
		ACO	15.99	8.34	32.45	6780
		MMS 0112	31.72	9.87	36.70	3868
		Wile25				
Moist 100	10.22	4.96	65.99	9020		

Data originating from the six moisture meters and the reduced set of fuel types (coniferous, deciduous and short rotation coppice chips) and the MC ranges given in Table 1.

^aSum of variance from lab and the interaction of lab and fuel type.

^bSum of variance from fuel type and the interaction of lab and fuel type.

^cResidual variance.

Table 6) compared to Pandis (20.73; see Table 5). This indicates that the Schaller is less suitable for measuring within the MC range of 40–55% MC, which is common for wood fuels used in heating plants [11,23].

The analyses of ACO, Wile and Moist were all performed on wider moisture ranges than the container types (Table 5). Thus, some variance obtained may be

caused by the presence of large proportions of free water. In order to test whether smaller MC ranges of 0–40% and 0–55% reduced the residual variation, the three devices were also analysed at these MC ranges. However, only a reduction of the upper MC range to 40% leads to a detectable decrease of the residual variance compared to analyses on a wider MC range, whereas the 0–55% range

Table 6
Sum of the joint variance components of laboratory and fuel type and the interaction between laboratory and fuel type

Device	MC range (%)	Var lab ^a	Var fuel type ^b	Residual ^c	<i>n</i>
Schaller FS 2002-H	0–55	10.40	26.28	33.45	1149
ACO	0–40	8.67	1.62	15.69	4980
MMS 0112	0–55	14.48	7.69	29.98	6465
Wile25	0–40	10.35	4.97	21.00	3318
	0–55	24.26	10.98	41.84	4298
Moist 100	0–40	6.40	1.68	36.33	6640
	0–55	7.66	3.13	59.75	8600

Data originating from ACO, Wile and Moist, a reduced set of fuel types (coniferous, deciduous and short rotation coppice chips) and the moisture range of 0–40% and 0–55%. Further, the Schaller was tested at a moisture range of 0–55%.

^aSum of variance from lab and the interaction of lab and fuel type.

^bSum of variance from fuel type and the interaction of lab and fuel type.

^cResidual variance.

gave similar variances as compared to the entire moisture ranges (Tables 5 and 6). For ACO (15.69) and the Wile (21.00) (Table 6), the residual variances are comparable to the ones found for Pandis (20.73) and Schaller (12.04) when the three devices measure within similar moisture ranges (Tables 5 and 6).

The variance related to fuel type does not vary much between Pandis, Schaller, ACO and Wile, whereas the influence from the laboratories varies among the devices (Table 5). In pre-tests, it was found that the inclination of the ACO towards the horizontal plane of the sample influenced the measurement. Furthermore, the results obtained with the ACO and Wile were influenced by the variable forces that were probably applied when the samples were compressed. The high residual variance obtained using Moist (Table 5) reflects its limited ability to measuring MC's of particulate material such as biofuels. The device was originally developed for measurements on materials such as bricks or wooden panels, which offer a plane solid surface for the measurements. This conclusion is supported by the comparably low variance related to laboratory and fuel type, which means that the major part of the total variance is due to the device itself. The relatively low residual variance of the container type devices compared to the probe/sensor type indicates that the first type is superior to the second.

The results from the calibrations of Mesa, Pandis, Schaller and ACO on individual fuel types and laboratories using PROC GLM in SAS[®] are shown in Table 7. To facilitate the comparisons between the two types of dielectric meters, the ACO is calibrated for two moisture ranges (0–40% and 0–55% MC, respectively). Based on the R^2 -value, the regressions confirm the smaller variance obtained with the NIR reflectance method ($R^2 = 0.84$ – 0.99) and the dielectric method using the Pandis ($R^2 = 0.89$ – 0.995). Furthermore, it is seen that the dielectric devices are sensitive towards bulk density variations. This can be read from the number of regressions, marked with an asterisk in Table 7, where a significant bulk density ($\alpha < 0.05$) influence had been determined. Also for the Schaller device, acceptable results were obtained,

although two of the regressions resulted in poor R^2 -values of only 0.75 and 0.31.

The sensitivity of ACO towards variable handling procedures is indicated by the high variation of R^2 -values and standard errors between the 11 laboratories. However, some of the laboratories reach similar regression values as for the container type devices, e.g. labs 4 and 8. Any technical solution, which reduces inconsistent handling, should therefore improve the accuracy of the moisture estimation. As shown by Hartman and Böhm [10], arranging the ACO sensor head steadily and horizontally to the sample surface, e.g. in a test rig that simulates a moving sample stream could considerably reduce the variance in the measurements.

Calibrating the Mesa MM710 to the combined set of three fuel types increased the variation in the measurements compared to a calibration for only one fuel type (Fig. 1, upper plots). For the dielectric devices, it was observed that the variance of the measurements varied for different fuel types and increased with higher MC. This trend was particularly evident above the fibre saturation point, where free water in the cell vacuoles leads to inconsistent measurement (shown for Pandis and ACO in Fig. 1, middle and lower plots) [13].

The analyses of the Pandis data from Fig. 1 exemplify that acceptable calibrations with high R^2 -values are possible with this principle. To measure the MC shown in Fig. 1 with $\pm 5\%$ -points accuracy at a probability level where 99% ($\alpha = 0.01$) of the measurements is within the 5%-points require at least five replicates for both one fuel type and for the three fuel types. Reducing the probability level to 95% ($\alpha = 0.05$) decreases the minimum number of measurements to 3 for one fuel type and 5 for the three fuel types (Eq. (2)).

The bulk density influences the determination with dielectric devices e.g. for the Pandis a bulk density of 100, 150 and 200 kg/m³, respectively, the resulting MC will be biased in the order of 2–3%-point between the consecutive bulk density levels.

When comparing the R^2 -values and standard errors of the calibrations from Fig. 1 with similar statistics from

Table 7

Statistical figures from regression analyses of NIR reflectance method (Mesa MM710), the dielectric container type (Pandis FMG3000 and Schaller FS 2002-H) and the probe/sensor type with the lowest variance given in Table 5 (ACO)

Device	MC (%)	Chips type	Statistics	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6	Lab 7	Lab 8	Lab 9	Lab 10	Lab 11	
Mesa MM710	10–40	Coniferous	R^2	0.88	0.91	0.82	0.99	0.97	0.92	0.93	0.89	0.97	0.99	0.89	
			n	285	165	345	75	360	30	285	240	90	90	150	
			s^2	11.74	3.73	16.86	1.65	2.22	1.80	4.65	5.43	1.95	1.44	8.20	
		Deciduous	R^2	0.97	0.84	0.86	0.99	0.91		0.91	0.94		0.96	0.96	
			n	135	345	360	75	240		465	285		75	90	
			s^2	3.69	10.51	11.59	1.05	5.38		5.48	4.83		2.78	1.89	
		SRC	R^2		0.93			0.98				0.91		0.99	0.98
			n		90			75				165		60	45
			s^2		4.80			1.67				3.87		0.85	1.16
Pandis FMG3000	0–55	Coniferous	R^2	0.89	0.88	0.93	0.96	0.96	0.98	0.91 ^a	0.93 ^a	0.98	0.98		
			n	108	63	117	15	84	12	92	66	20	24		
			s^2	23.92	22.90	14.92	4.29	3.98	1.59	16.14	12.44	2.51	5.01		
		Deciduous	R^2	0.98	0.89	0.93	0.99	0.98 ^a			0.96 ^a	0.96		0.96	
			n	45	95	95	18	66			111	72		24	
			s^2	3.79	18.91	10.82	1.27	2.33			4.20	5.54		5.90	
		SRC	R^2		0.97			0.995				0.93		0.97	
			n		24			21				48		21	
			s^2		4.51			0.89				9.26		9.12	
Schaller FS2002-H	0–40	Coniferous	R^2	0.94 ^a	0.86	0.90		0.92	0.89	0.94 ^a	0.97	0.96	0.94	0.90 ^a	
			n	69	33	84		72	6	63	21	18	18	27	
			s^2	8.47	5.78	12.11		5.44	3.62	5.85	3.17	2.89	6.32	9.46	
		Deciduous	R^2	0.97 ^a	0.75	0.89 ^a	0.97	0.95 ^a			0.96	0.93		0.94	0.98
			n	39	78	72	11	45			99	63		21	21
			s^2	5.38	25.14	9.14	2.01	5.74			2.82	7.53		6.14	1.69
		SRC	R^2		0.93			0.97				0.31		0.97	0.98
			n		15			15				12		14	6
			s^2		3.80			2.46				6.11		3.80	1.76
ACO	0–40	Coniferous	R^2	0.88	0.77	0.81 ^a	0.96	0.85	0.56	0.90 ^a	0.90 ^a	0.90	0.78	0.75 ^a	
			n	345	165	420	75	270	30	315	270	90	90	165	
			s^2	15.40	9.20	22.08	4.75	10.52	10.53	8.54	7.39	7.35	21.54	24.18	
		Deciduous	R^2	0.87 ^a	0.77 ^a	0.84	0.95	0.90 ^a			0.87 ^a	0.92 ^a		0.94	0.85
			n	195	420	375	75	180			495	315		105	105
			s^2	16.63	24.01	15.31	3.88	6.42			8.96	7.63		5.77	10.68
		SRC	R^2		0.88			0.90				0.90 ^a		0.93	0.97
			n		90			75				180		75	60
			s^2		8.65			6.72				7.67		8.92	4.45
	0–55	Coniferous	R^2	0.83 ^a	0.88 ^a	0.83 ^a	0.96	0.84 ^a	0.86	0.90 ^a	0.93 ^a	0.88	0.67	0.77 ^a	
			n	540	315	585	75	330	60	465	330	105	120	225	
			s^2	38.47	23.41	38.40	4.75	19.33	18.10	17.59	10.82	13.41	72.11	40.23	
		Deciduous	R^2	0.89 ^a	0.84 ^a	0.85 ^a	0.95	0.92 ^a			0.90 ^a	0.94 ^a		0.94	0.87
			n	225	480	480	90	225			555	360		120	120
			s^2	22.27	26.42	22.51	6.29	8.86			10.02	8.70		7.35	12.04
SRC	R^2		0.84			0.94				0.91 ^a		0.95	0.97		
	n		120			105				240		105	90		
	s^2		26.62			10.37				11.88		13.32	7.50		

Data from the 11 participating laboratories and three fuel chips types; coniferous, deciduous and short rotation coppice (SRC).

^aBulk density significant in the calibration.

other laboratories (Table 7) confirmed that within a specific fuel type the performance of the laboratory is quite decisive for the overall quality of the calibration. This is true for all tested combinations of moisture ranges and fuel types for both the NIR reflectance and the dielectric methods. Thus, the decision on the number of fuel types and the applied moisture range for the calibration will always be made as a trade-off between the intended accuracy of the subsequent

measurements and the workload of providing and applying individual calibrations for each fuel type. If such a calibration regards bulk density as an additional input parameter for the MC estimation, it should be measured along with the MC. Furthermore, it should be determined for all unknown fuels to ensure that the tested samples are within the range of bulk density for which the device was calibrated.

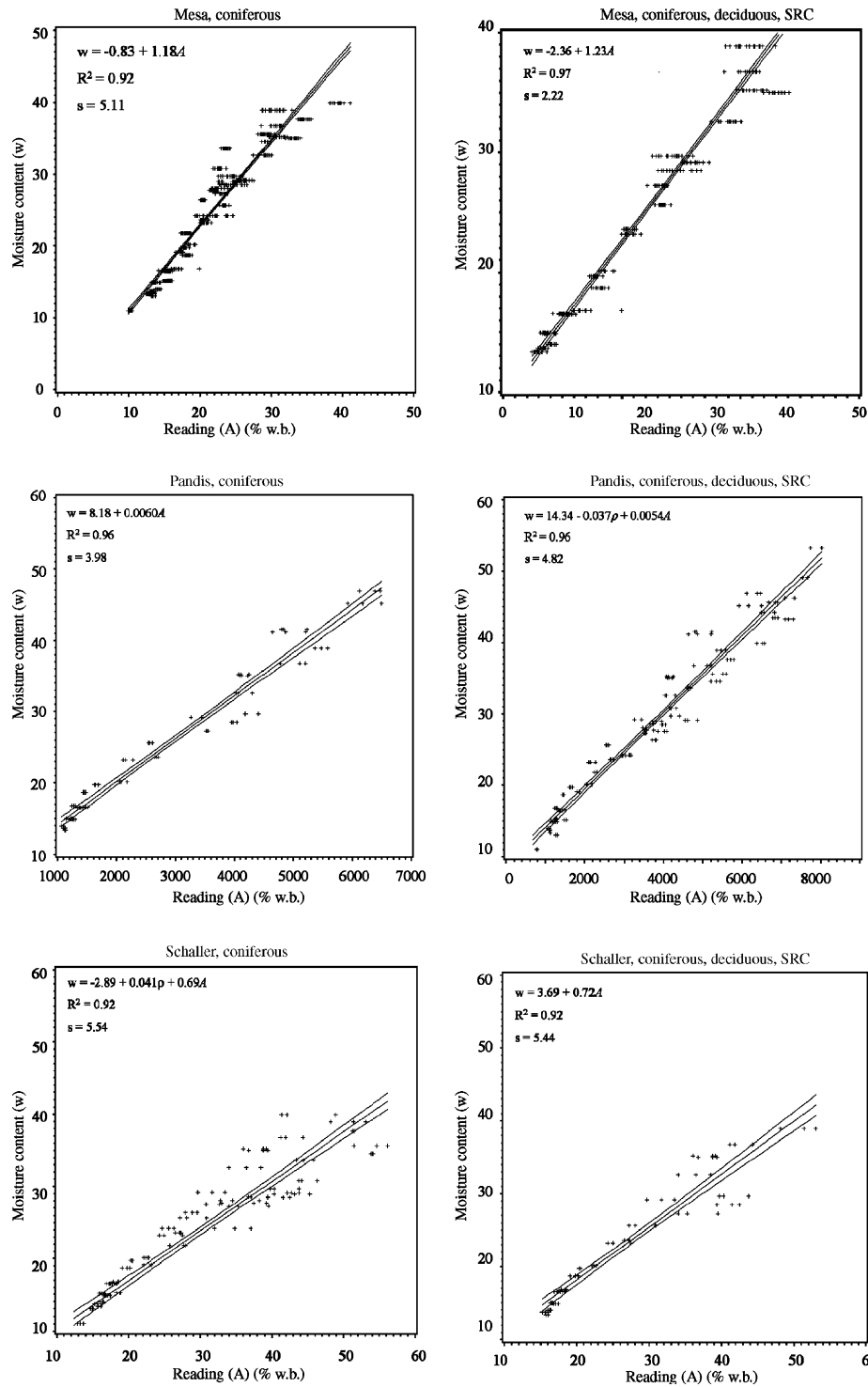


Fig. 1. Example of calibration functions for Mesa MM710, Pandis FMG3000 and Schaller FS 2002-H. Data shown are from Lab 5 in Table 7. The upper and lower lines in each plot represent the confidence intervals ($\alpha = 0.05$). The black dots represent the original data pairs.

4. Conclusions

Rapid moisture meters enable instantaneous moisture determination of solid biofuels. Among the instruments tested (one NIR reflectance and five dielectric devices),

several promising applications were identified. The main conclusions are as follows:

- The NIR reflectance method (Mesa MM710) and the dielectric devices of the container type (Pandis

FMG3000 and Schaller FS2002-H) have clear advantages compared to the other systems tested. They can be operated at higher accuracy with less sensitivity towards variable fuel types or calibration procedures.

- For the dielectric devices, it was shown that the fuel bulk density influences the measurements. This variable should therefore always be considered in calibrations for dielectric devices when several fuel types are involved.
- Due to the usually higher precision it is advisable to apply an individual calibration for the prevailing fuel base at a site, rather than using a global calibration function for all wood fuels of different properties and origin.
- The application of calibrations from other laboratories implies the risk of non-suitable data fit, as shown by the significant laboratory influences.

Acknowledgements

The research was conducted within the European project “Pre-normative work on sampling and testing of solid biofuels for the development of quality assurance systems” (BioNorm) ENK6-CT-2001-00556. The authors would like to thank the following laboratories and persons, which participated in the round robin:

- Swedish University of Agricultural Sciences, Umeå and Uppsala, Sweden (J. Burvall and R. Jirjis),
- Ingenieurbüro HERSENER, Wiesendangen, in cooperation with Agroscope FAT Tänikon, Switzerland (J.-L. Hersener),
- Bundesanstalt für Landtechnik (BLT) Wieselburg, Austria (J. Rathbauer),
- Forest Contracting Association, UK (B. Hudson),
- EC Baltic renewable energy centre, Poland (M. Pisarek and L. Jamowics),
- AFOCEL, France (M. Lecourt),
- INETI, Portugal (D.H. Boavida),
- Comitato Termotecnico Italiano, Italy (J.A. Calzoni).

References

- [1] Evald A, Jacobsen HH. Facts on installation, operation and economy for wood chips fired district heating plants in Denmark. Centre of Biomass Technology; 1993.
- [2] Jirjis R. Effects of particle size and pile height on storage and fuel quality of comminuted *Salix viminalis*. Biomass and Bioenergy 2005;28:193–201.
- [3] Mattsson JE. Basic handling characteristics of wood fuels: angle of repose, friction against surfaces and tendency to bridge for different assortments. Scandinavian Journal of Forest Research 1990;5:583–97.
- [4] Jensen PD, Mattsson J-E, Kofman PD, Klausner A. Tendency of wood fuels from whole trees, logging residues and roundwood to bridge over openings. Biomass and Bioenergy 2004;26:107–13.
- [5] SS 18 71 70. Biofuels and peat—determination of total moisture content. Sweden: Swedish Standards Institute, Stockholm; 1997.
- [6] DIN 51718. Feste Brennstoffe—Bestimmung des Wassergehaltes und der Analysenfeuchtigkeit. Deutsches Institut für Normung EV, editor, Berlin, Germany, Beuth Verlag; 1995.
- [7] ASTM E 871–82. Standard test methods for analysis of wood fuels. USA: American Society for Testing and Materials (ASTM); 1992.
- [8] Nyström J, Dahlquist E. Methods for determination of moisture content in wood chips for power plants—a review. Fuel 2004;83:773–9.
- [9] Trabelsi S, Krazewski AW, Nelson SO. New density independent calibration function for microwave sensing of moisture content in particulate materials. IEEE Transactions on Instrumentation and Measurements 1998;47(3).
- [10] Hartmann H, Böhm B. Rapid moisture content determination of wood chips—results from comparative trials. In: Proceedings of the first World conference on biomass for energy and industry, 5–9 June 2000, in Sevilla, Spain: James & James Ltd.; London UK; 2001. p. 571–4.
- [11] Nyström J, Axrup L, Dahlquist E. Långtidsutvärdering av nya on-line fukthaltsmätare för biobränsle. Värmeforsk Anläggsteknik 2002;763.
- [12] Skoglund A, Kessler W, Kessler RW, Brundin A, Mandenius C-F. On-line spectroscopic measurements of wood chips before a continuous digester. Chemometrics and Intelligent Laboratory Systems 2004;70:129–35.
- [13] Skaar C. Wood–water relations. New York: Springer; 1988.
- [14] Nelson SO. Review of factors influencing the dielectric properties of cereal grain. Cereal Chemistry 1981;58(6):181–92.
- [15] Trabelsi S, Krazewski AW, Nelson SO. Microwave dielectric sensing of bulk density of granular materials. Measurement Science and Technology 2001;12:2192–7.
- [16] Nelson SO. Review of factors influencing dielectric properties of cereal grains. Cereal Chemistry 1981;58:487–92.
- [17] Thygesen LG. Indirect methods for determination of dry matter content and basic density of pulp wood. Copenhagen: The Royal Veterinarian and Agricultural University; 1994.
- [18] Fassio A, Cozzolino D. Non-destructive prediction of chemical composition in sunflower seeds by near infrared spectroscopy. Industrial Crops and Products 2004;20:321–9.
- [19] ÖNORM M7133 Energiehackgut Anforderungen und Prüfbestimmungen. Österreichisches Normungsinstitut; 1988.
- [20] CEN/TS 14774-1 Solid biofuels—methods for determination of moisture content—part 1—oven dry method. 2004.
- [21] prCEN/TS 15103 Solid biofuels—methods for determination of bulk density. Final draft, 2004.
- [22] Cochran WG. Sampling techniques. 3rd ed. New York, NY: Wiley; 1977 428pp. (p. 77f).
- [23] Suadcani K, Gamborg C. Fuel quality of whole-tree chips from freshly felled and summer dried Norway spruce on a poor sandy soil and a rich loamy soil. Biomass and Bioenergy 1999;17:199–208.