ABSTRACT
Density-independent high moisture content measurement is required in actual production line. In this paper, the experimental results for high moisture content measurement using microwave free-space technique are presented. The method is based on a ratio of phase shifts at two microwave frequencies after propagating through a sample. The experiments were performed with three kinds of sawdust named Momizai, Cedar and Douglas Fir. In the high moisture content above 130%, the root mean square error (RMSE) of moisture determination by the method for three kinds of sawdust are 9.0%, 17.0%, 22.8%, respectively.

KEYWORDS: High moisture content, density-independent, measurement, microwave phase shift, sawdust.

INTRODUCTION
Density-independent high moisture content measurement is required in actual production line. For example, it is necessary to measure high moisture content of tea leaves in green tea production line, where the fresh tea leaves with moisture content as high as above 350% on a dry basis are dried to be green tea product with 8% moisture content [Okamura et al., 1998; Zhang et al., 2006]. The moisture measurement method is also expected to be able to determine the moisture content independent of sample density because variation of sample density is the main error source in the moisture measurement by the microwave techniques [Meyer et al., 1981; Nyfors et al., 1989; Kraszewski et al., 1996; Trabelsi et al., 1998; Zhang et al., 1999].

Microwave free-space technique has received great attention in the moisture content measurement, because the technique is contactless, nondestructive, and requires no special preparation of the sample. A useful method using the microwave free-space technique to determine moisture content independent density and thickness is based on the measurement of attenuation and phase shift at a microwave frequency [Meyer et al., 1981; Nyfors et al., 1989; Kraszewski et al., 1996;]. It was shown to be able to determine the moisture content for many materials such as wheat, wool, corn etc. [Meyer et al., 1981; Nyfors et al., 1989; Kraszewski et al., 1996;]. A dielectric-based method was reported recently to measure the moisture content and density [Trabelsi et al., 1998; 2005]. The reported method was proved with the microwave free-space technique, and the good results have been shown on the material of wheat, soybeans, corn and etc. We have proposed a new method for density-independent moisture measurement.
using the microwave free-space technique [Zhang et al., 1999]. The method uses phase shifts only to determine moisture content. It has been made sure that the method is valid to measure the moisture content for timbers, tea leaves [Zhang et al., 1999; 2000]. However, less report could be found on high moisture measurement, especially on density-independent high moisture measurement. This paper presents the experimental results on the measurement of high moisture content above 130% on a dry basis. The method measure phase shifts of microwave at 12 GHz and 9 GHz, and the moisture content is density-independent determined according to the ratio of phase shifts. The material under test is the sawdust with high moisture content. Three kinds of sawdust named Momizai, Cedar and Douglas Fir are used for the experiments of high moisture content measurement.

MEASUREMENT PRINCIPLE

The moisture content on a dry basis, $M$, is usually defined as following, where $W_w$ and $W_d$ are the masses of water and dry material, respectively.

$$M = \frac{W_w}{W_d} \times 100\% \quad (1)$$

Moisture content measurement by the microwave free-space technique uses a microwave signal transmitted through a layer of the material under test. Changes of microwave signal after propagating the material can be expressed by attenuation and phase shift, and they are mainly caused by the moisture contained in the material. Thus from the attenuation or the phase shift, it is possible to determine the moisture content of the material [Meyer et al., 1981; Nyfors et al., 1989; Kraszewski et al., 1996].

The phase shift of microwave through a layer of material is mainly caused by the moisture content $M$, affected by the material density $\rho$, and is proportional to the layer thickness $d$. The phase shift is also related to the frequency of the microwave and the temperature. Under the conditions of a certain frequency and a certain temperature, the phase shift is simplified to be a function of $M$, $\rho$, $d$. In general, the phase shifts $\Delta \phi_1$, $\Delta \phi_2$ at two different frequency $f_1$, $f_2$ can be expressed in following functional forms respectively,

$$\Delta \phi_1 = \Psi_1(M, \rho) \cdot d \quad (2)$$

$$\Delta \phi_2 = \Psi_2(M, \rho) \cdot d \quad (3)$$

where $\Psi_1(M, \rho)$, $\Psi_2(M, \rho)$ are functions of $M$, $\rho$. It has been shown the ratio of the phase shifts can be used for density-independent moisture measurement [Zhang et al., 1999; 2000]. The moisture content is determined as,

$$M = g\left(\frac{\Delta \phi_2}{\Delta \phi_1}\right) \quad (4)$$

The method has been used for density-independent moisture measurement in the range from about 4% to 40% [Zhang et al., 1999; 2000]. In this paper, the method will be tested for the measurement of high moisture above 130%.

EXPERIMENTAL METHOD

The block diagram of the moisture measurement setup using the microwave free space technique is shown in Figure 1. Two rectangular horn antennas with 10.9 cm x 7.9 cm apertures and 20±2 dB gain were used as transmitting and receiving elements. The distance between the antennas was 26 cm. A plastic case was used to contain the sawdust sample. The phase shifts used in the method were measured at 9 GHz and 12 GHz, which are in the single frequency range of waveguide WR90. The phase shifts were measured by a vector network analyzer (HP8720ES).

Sawdust was used as the material under test in the experiments, because the sawdust sample can contain the moisture contents as high as 350%. Additionally sawdust sample is decay-resistant, suitable to the experiments...
repeated during a period of some weeks. Three kinds of sawdust named Momizai, Cedar and Douglas Fir were used. The volume of each kind of sawdust was changed 3 times to obtain the samples with different density, to investigate the possibility of the method to determine the moisture content independent of sample density. The values of dry material density for all samples are listed in Table I.

The samples with high moisture content were prepared. At first, the sample was oven dried to 0% moisture content to obtain the mass of dry material \( M_d \). Then the tap water was added into the sample till the maximum moisture content which the sawdust can contain. The sample was stored in a sealed plastic-case for 3 days to obtain a uniform moisture distribution, and the first measurement was performed. After the first measurement, the sample was gradually dried at room temperature to be next moisture content. Then the sample was again stored in the plastic-case. After 24 hours to obtain a uniform moisture distribution, the measurement at next moisture content was performed. The processes of store, measurement, dry were repeated till the moisture content we interested. The phase shift at every moisture content level for one sample was measured twice to obtain an average value.

**EXPERIMENTAL RESULTS**

Microwave phase shift at 9GHz for Momizai sawdust normalized by the sample thickness is shown in Figure 2. The results are those of #1, #3 Momizai samples with different density. The dry material density of #1 sample was 0.066g/cm\(^3\), and that of #3 sample was 0.044g/cm\(^3\).

The phase shift increase with the moisture content increasing, and they are affected by the density of sample. The #1, #3 samples at the same moisture content cause different phase shift because of their different density.

Figure 3 shows the values of \( \Delta \Phi_2 / \Delta \Phi_1 \) for the two Momizai samples with different density with respect to oven moisture content. \( \Delta \Phi_1 \) and \( \Delta \Phi_2 \) are the phase shifts at 9 GHz and 12 GHz respectively. The values of \( \Delta \Phi_2 / \Delta \Phi_1 \) of the samples at the same moisture content have similar ratio value although the sample densities are different. The result shows the proposed method are able to measure the high moisture content independent of sample density.

| Table I. Dry material density of the samples (g/cm\(^3\)) |
|-----------------|-----------------|-----------------|
| Sample No.      | Momizai         | Cedar           | Douglas Fir    |
| #1              | 0.044           | 0.070           | 0.112          |
| #2              | 0.052           | 0.084           | 0.134          |
| #3              | 0.066           | 0.105           | 0.168          |

Figure 2. Phase shift at 9 GHz for Momizai sawdust normalized by the sample thickness with respect to oven moisture content.
density. From the result the calibration curve was obtained as,

\[ M = -4902.6\xi^2 + 11317\xi - 6216.6 \quad (5) \]

where \( \xi \) is the ratio of \( \Delta\Phi_2/\Delta\Phi_1 \).

The calibration equation obtained from #1 and #3 Momizai samples was used to predicate the moisture content of #2 Momizai sample, which dry density is different to #1, and #3, as shown in Table 1. The moisture content calculated from the \( \Delta\Phi_2/\Delta\Phi_1 \) value versus the oven moisture content is shown in Figure 4, in which the straight line corresponds to the ideal relation.

The root mean square error (RMSE) is calculated to evaluate how well the moisture content is predicated. RMSE for #2 moisture content determination shown in Figure 4 is 9.0%. We also tested to determine #1 moisture content using the calibration curve obtained from #2, #3, and to determine #3 moisture content using the calibration curve based on #1, #2. Similar result was obtained, and the values of RMSE for #1 and #3 moisture measurements are 12.5% and 8.7%, respectively.

The measurement results of high moisture content for sawdust of Cedar, Douglas

![Figure 3](image1.png)

**Figure 3.** Values of \( \Delta\Phi_2/\Delta\Phi_1 \) for two Momizai samples with respect to oven moisture content.

![Figure 4](image2.png)

**Figure 4.** Moisture content predicated by \( \Delta\Phi_2/\Delta\Phi_1 \) with respect to oven moisture content for Momizai sawdust.

![Figure 5](image3.png)

**Figure 5.** Moisture content predicated by \( \Delta\Phi_2/\Delta\Phi_1 \) with respect to oven moisture content for Cedar sawdust.

![Figure 6](image4.png)

**Figure 6.** Moisture content predicated by \( \Delta\Phi_2/\Delta\Phi_1 \) with respect to oven moisture content for Douglas Fir sawdust.
Fir sawdust are shown in Figures 5 and 6, respectively. The values of RMSE for Momizai, Cedar, Douglas Fir sawdust respectively are summarized in Table II. They are based on the #2 sample moisture prediction using the calibration curve obtained from #1, #3 samples.

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<thead>
<tr>
<th>Table II RMSE of moisture measurement</th>
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<td>Moisture range (%)</td>
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<td>RMSE(%)</td>
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CONCLUSIONS
The experimental results for density-independent high moisture measurement are presented. The method uses the microwave free-space technique, and determines the high moisture according to the ratio of phase shift at 12 GHz to that at 9 GHz. The experiments were performed with three kinds of sawdust named Momizai, Cedar and Douglas Fir. In the high moisture content range, the root mean square errors by the method for three kinds of sawdust are 9.0%, 17.0%, 22.8%, respectively. The results show that the method using the ratio of phase shift can be used for density-independent high moisture measurement.

REFERENCES


