DIRECT SCANNING DENSITOMETRY: AN EFFECT OF SAMPLE HETEROGENEITY AND APERTURE AREA

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ABSTRACT

Direct scanning radiation densitometry is finding increased application in forestry and wood products research. Radiation densitometry is often used for tree ring analysis and density profile analysis of reconstituted panel products. This paper discusses some limitations to accuracy in the use of a scanning or stepping densitometry system. The effect of aperture area and sample heterogeneity on accuracy of the density determination is discussed. The "edge effect" in the densitometry of panel products is discussed.

Keywords: Gamma densitometry, densitometry, density.

BACKGROUND

Direct scanning radiation densitometry using gamma or X-rays has become of increasing interest both for tree ring analysis (Woods and Lawhon 1974; Cown and Clement 1983; Hoag and McKinney 1988) and for density profile analysis of reconstituted wood products (Ferraz 1976; Laufenberg 1986; Winistorfer et al. 1986; Winistorfer and Moschler 1987). A major impetus for the increased use of direct scanning densitometers is that the technique eliminates the intermediate steps involving photographic film and optical densitometry. The direct determination of density makes data immediately available so that it may be used in process control or manufacturing situations where immediate density feedback is important. Another advantage of direct scanning techniques is that most systems utilize a scintillation detector with standard radiation pulse shaping and counting equipment that allow the user to select the energy range actually counted, thereby allowing closer evaluation of the mass attenuation coefficient and improving calibration (Olson and Arganbright 1981; Olson et al. 1988).

The principle of scanning densitometry is to pass a collimated photon beam (X-ray or gamma ray) through a sample material (wood) and into a radiation sensing device, usually a photoscintillation detection system. An aperture positioned in front of the source serves to collimate the photon beam. An aperture in front of the detector delimits the area of the sample for which the density determination is actually made. Many densitometry systems employ a stepping arrangement. In a stepping system, the area defined by the aperture (usually a slit)

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is counted, the sample or source-detector combination is moved a preset distance, and the new area under the aperture is counted.

Interest in the factors affecting accuracy of the density determination has increased since direct scanning densitometry has come into more general use. Olson and Arganbright (1981), Liu et al. (1988), and Olson et al. (1988) have established a sound theoretical foundation for X-ray densitometry. However there remain some practical limitations to accuracy in the use of a gamma scanning or stepping densitometry system that need to be considered.

Liu et al. (1988) describe modeling a system with "good architecture," i.e., collimated, monochromatic beam perpendicular to the sample surface. A condition of this "good architecture" is that the density of the sample material must be uniform over the length and width of the aperture area through which each individual density determination of the sample is made. In a densitometry system using an X-ray source, this problem is usually addressed by making the beam area very small, i.e., a point.

In a low energy gamma densitometry system, the intensity of the incident radiation beam is limited by collimation, by air attenuation, and by self-absorption of the gamma source. The counting of a radioactive source follows a Poisson distribution. At low count rates the error in each individual determination of density is increased. With all other parameters constant, one way to increase the count rate is to increase the beam area passed through the sample, thus increasing the probability of nonuniform density distribution within the aperture area.

OBJECTIVE

The objective of this paper is to provide information on the error caused by density variations within the aperture area of a gamma densitometer. The problem of density variation within the aperture area arises in low-energy gamma densitometers and in other density measuring situations where it is necessary to determine density through an aperture larger than a point. Examples are presented to show the cause and magnitude of this error. Several situations in which this error occurs in applied work are discussed, and suggestions for reducing this error are presented.

FUNDAMENTAL RELATIONSHIPS

Most direct radiation densitometry techniques are based on the relationship between count rates obtained through the detector system and density as shown in Eqs. (1) and (2).

$$I = I_0 e^{-\mu_\ell t} \tag{1}$$

where:

I = intensity of the radiation beam after passing through the wood (counts)
I_0 = intensity of the radiation beam before passing through the wood (counts)
t = sample absorbed thickness (cm)
μ_ℓ = linear attenuation coefficient (cm^{-1})

Once I and I_0 are measured experimentally for wood of thickness t, μ_ℓ is calculated. The linear attenuation coefficient is dependent on 2 factors [Eq. (2)].

$$\mu_\ell = \mu_m \times \rho \tag{2}$$

where:

μ_m = mass attenuation coefficient (cm^2/g)
ρ = density (g/cm^3)

Substituting (2) into (1) gives the basic equation relating density to counting data.

$$\rho = -\frac{1}{\mu_m t}\ln\left(\frac{I}{I_0}\right) \tag{3}$$

The mass attenuation coefficient, μ_m, is a material property. The values of t, I, and I_0 are determined at each sample location within the density scan.

A NUMERICAL EXAMPLE

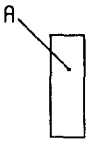
An example is presented to illustrate the error that can be caused by density variation of materials within the measuring aperture. The photoscintillation detector records a total number of counts proportional to the total amount of radiation passing through the aperture area. The density is, however, proportional to log (I/I_0), not to I [Eq. (3)]. The operational nature of the counting equipment therefore influences the determination of sample density. Assume an aperture of area A, an I_0 of 5,000 counts, 2 samples of wood of 0.9 and 0.2 specific gravity (G), a sample thickness of 0.3 cm, and an Fe^{55} source with a 6 KEV energy peak (Fig. 1). Let us assume for this illustration a typical value of 17.7 cm^2/g for μ_m (Olson and Arganbright 1981; Moschler and Dougal 1988). Using these values in Eq. (1) and solving for I, for the wood of 0.9 specific gravity I_1 = 42 counts, and for the wood of 0.2 specific gravity I_2 = 1,729 counts. If we consider an aperture of 2A size, the beam intensity becomes ($I_0 + I_0$) = (5,000 + 5,000) = 10,000 and the sample counts become ($I_1 + I_2$) = (42 + 1,772) = 1,779 (Fig. 1). Using these values to calculate a density from Eq. (2) gives ρ = 0.33. However, the mean specific gravity of the material within the 2A aperture is (0.2 + 0.9)/2 = 0.55. Because the counter summed the counts from the two different density areas as defined by the aperture, a 40% error in density determination occurred when the two areas of differing density were both included in the aperture area.

The above example can be written in more general terms. The density calculated for each area separately is:

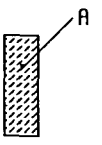
$$I_1 = -\frac{1}{\mu_m t}\ln\left(\frac{I_1}{I_0}\right)$$

$$I_2 = -\frac{1}{\mu_m t}\ln\left(\frac{I_2}{I_0}\right)$$

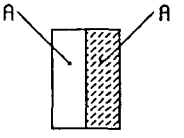
When the 2 areas are combined within the aperture, the counter will interpret the density as:



aperture area = A
specific gravity = 0.9
I_o = 5000
μ_m = 17.7
thickness = 0.3 cm
$I_1 = I_o e^{-\rho_1 \mu_m t} = 42$



aperture area = A
specific gravity = 0.2
I_o = 5000
μ_m = 17.7
thickness = 0.3 cm
$I_2 = I_o e^{-\rho_2 \mu_m t} = 1729$



aperture area = 2A
specific gravity = (0.9 + 0.2)/2 = 0.55
μ_m = 17.7
t = 0.3 cm
$I_o = 5000 + 5000 = 10{,}000$
$I = I_1 + I_2 = 42 + 1729 = 1771$
$\rho_{calc} = \frac{1}{\mu_m t} \ln(I/I_o) = 0.33$
error = 40%

FIG. 1. Calculated density for two different homogeneous samples, with a given aperture area, sample thickness, count rate and mass attenuation coefficient. Calculated error in density determination when a heterogeneous sample occupies the aperture area.

$$\rho_{calc} = -\frac{1}{\mu_m t} \ln\left(\frac{I_1 + I_2}{2I_0}\right)$$

The true average density of the combined area is:

$$\bar{\rho} = \tfrac{1}{2}(\rho_1 + \rho_2)$$

The error may be calculated by substituting the measured density for the true average density, yielding:

$$\text{error} = \frac{1}{2\mu_m t} \ln\left\{\frac{(I_1 + I_2)^2}{4I_1 I_2}\right\} \quad (4)$$

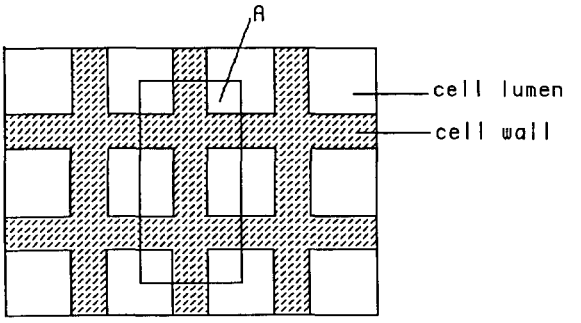
Equation (4) applies only when the aperture area contains equal portions of material of each density. However the main point of Eq. (4) is to present a quick method to evaluate the potential error in an applied situation by taking counts through adjacent high and low density areas of the sample material.

APPLIED EXAMPLES

Scanning densitometry can be used for tree ring density analysis. In those conifers with an abrupt springwood to summerwood transition, and in ring porous hardwoods, the specific gravity within and between growth rings varies greatly. Unless the detector aperture is very small, there exists a possibility of including material of different densities within the area of the aperture, resulting in the measurement error previously described. However, decreasing the aperture size decreases the count rate, thus lowering the precision with which I and I_0 can be determined when using the same count interval. Restrictions on reducing aperture size might also apply to X-ray systems if a very narrow energy band is selected as suggested by Olson et al. (1988). The usual solution for tree ring scanning is to use an aperture shaped like a slit, narrow in the sample radial direction and long in either the sample longitudinal or tangential direction depending upon sample orientation. By this method the aperture area may be increased substantially without any apparent decrease in resolution along the scanned direction. The scan then consists of a number of determinations of density, many with homogeneous wood under the slit, and some with enough heterogeneity to cause an appreciable error.

Any curvature of the growth rings or misalignment of the aperture with the growth rings will result in more measurement error. Verification of accuracy should be made for any change in aperture size or shape, sample thickness, or growth ring pattern. For example, with a fixed aperture geometry, the wide growth rings from a thinned plot might produce a different density error bias than the narrow growth rings from an unthinned plot.

A second implication of the effect of sample heterogeneity is the case of scanning thin sections with the radiation beam passing through the longitudinal section of the sample. Softwood tracheids can range from 1 mm to 5 mm in length. A 1-mm cross section then will contain areas where the cell lumens are completely open across the thickness of the sample (longitudinal direction) and other areas where the cell wall is continuous across the thickness. Using the model of Siau (1984), the porosity, P, is equal to the fractional cross-sectional area of the lumens and may be calculated by $P = 1 - G(0.685)$. Assume a dry cell-wall specific gravity of 1.46 (Kellog and Wangaard 1969) and a conifer with a specific gravity of 0.4. In this idealized model 73% of the total area will be lumens (voids) and 27% will be cell-wall material. Figure 2 shows an aperture imposed upon this hypothetical piece of wood. The density value for a typical aperture opening can be calculated by using (1) to calculate values for I_1 through the cell walls and I_2 through the lumens, and then weighting I_1 and I_2 by their proportional fractional areas. From



thickness = 1 mm

specific gravity (G) = 0.4

porosity = void % = 1 - 0.685G = 73%

cross section consists of 73% void and 27% cell wall

dry cell wall density = 1.46

let I_o = 5000 for aperture area A

I_1 through walls = $I_o e^{-\mu_m \rho_1 t}$ = 377

I_2 through lumens = 5000

$I = 0.27\ (I_1) + 0.73\ (I_2) = 3752$

$$\rho_{calc} = \frac{1}{\mu_m t} \ln[(I_1 + I_2)/I_o] = 0.16$$

error = 59%

FIG. 2. Density determination for an idealized wood cross section of a given porosity.

Fig. 2 the calculated density is 0.16, which is an error of almost 60% from the true value of 0.4.

In practice the error will not be this large because the cell elements are not as well defined or aligned as in this idealized model. Because of the effect illustrated in Fig. 2 our laboratory procedure for scans of thin sections is to pass the radiation beam through the wood in the tangential direction. An additional consideration of this orientation is that a radial section is easier to prepare than a transverse section, resulting in less density disturbance caused by tearing and folding of the cell walls at the sample surface.

The first scanning densitometry studies done in our laboratory were on cross sections of fertilized yellow-poplar (Ross et al. 1979). Yellow-poplar is a diffuse porous, medium to low density hardwood with a gradual density change across the growth ring. A slit aperture about 1 mm wide by 3 mm high was used. Ross reported the density scans to be "reproducible" and "acceptable." The same technique was later applied to loblolly pine from a thinning study. Loblolly pine is an abrupt transition, medium to high density softwood with an abrupt density change across the growth ring. Average sample densities calculated from density scans were in error up to as much as 15% to 20% or more, primarily on samples

with slow growth and very curved growth rings. The system was judged to be not useful in this configuration. Re-orientation of the sampling to scans with the radiation beam passing in the tangential direction, attention to slit-growth ring alignment, and reduction of the slit width to less than 0.5 mm produced density scans that provided a useful correlation with basic specific gravity determined by measuring the volume and weight of the increment cores from which the samples for the densitometer were cut (McRae 1981).

In the densitometry of panel and board products, there are several considerations that can make the use of large aperture sizes desirable. One reason for a large aperture is that samples from board products are usually thick and of relatively high density. Another reason for using a large aperture would be found in the case where the density determination is part of a production process control system, in which the measurement must be made rapidly. In these two cases using a large aperture could be the only way to get the transmitted radiation intensity I high enough for rapid, accurate determination.

The density profile of panel products has been studied with a scanning densitometry system (Winistorfer et al. 1986; Laufenberg 1986; Winistorfer and Moschler 1987). At the edges of panel samples, there is an abrupt density transition between the panel and the air around it. Locating the edge of the panel partly in and partly out of the slit opening will cause an error. If the panel is tilted slightly in relation to the radiation beam, the error will be spread over several density determinations. This error may account for some of the "edge effect" noted by Laufenberg (1986).

Another contributing factor to the edge effect is that with thick material the density determination is probably affected by material on each side of the collimated beam. Since attenuation is a combination of scattering and absorption, and since the collimation of our source is not perfect, some of the incident and scattered radiation is rescattered back into the detector by material surrounding the aperture area being measured. One way to reduce both types of edge effects mentioned above is to sandwich the sample being measured between material of approximately the same density as each face of the panel sample. For example, if the density profile is being determined for several 2 in. by 2 in. internal bond samples from the same panel, samples could be stacked "face-to-face" and a single continuous scan made across all samples. A dial indicator or a linear variable displacement transducer may then be used on the carriage to locate the true faces of the density sample from the scan of the sandwich.

RECOMMENDATIONS

1) The effect of abrupt variations in sample density must be considered when evaluating the overall performance of a scanning densitometer. Equation (4) can be used to help determine the potential error.

2) The mass attenuation coefficient, μ_m can be in error on thin cross sections. The amount of this error will depend on the species, thickness, source strength, and aperture geometry.

3) The "edge effect" noted in some previous studies of panel densitometry may in part be caused by the operational nature of the counting system and the aperture-sample surface geometry. This "edge effect" may be reduced by sandwiching the sample between layers of material with similar surface density.

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