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TRANSVERSE DIMENSIONS OF WOOD PULP FIBRES AND THEIR IMPLICATIONS FOR END USE

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ABSTRACT

The transverse dimensions of pulp fibres influence strongly their response to the papermaking process, and most end-use properties of products. However, fibre transverse dimensions are difficult to measure. Confocal microscopy combined with image analysis has been used for rapid and accurate measurement of fibre wall cross-sectional area, perimeter, and thickness. Results on kraft pulp fibres obtained from a variety of wood species are presented. They demonstrate how fibre transverse dimensions are distributed within a species, and can be described analytically. Comparison between different species shows that species with coarse or thick-walled fibres are likely to be more heterogeneous. Implications for pulp quality and fibre selection for end-use requirements are discussed.

INTRODUCTION

The morphology of wood pulp fibres, particularly their transverse dimensions influence strongly the response of pulps to papermaking treatments, and most end-use properties of paper and board products [1-5]. For instance, the collapse behaviour of fibres depends on their transverse dimensions and the rigidity of the fibre wall material [6]. For a given wall rigidity, fibres with large perimeters and thin walls collapse more readily and are, therefore, more conformable. Conformable fibres bond better in a sheet structure, and make denser, stronger and smoother sheets. Fibre coarseness, which is defined as fibre mass per unit length, is simply proportional to the cross-sectional area of the fibre wall. Fibres with small cross-sectional areas are considered fine. Specific surface area, which is the surface area of fibres per unit mass, equals the ratio of fibre perimeter to its coarseness. The importance of fibre fineness and specific surface area for papermaking and product properties has been established [1].

Fibre transverse dimensions are difficult to measure. Although fibre coarseness can now be measured easily as a population average with a fibre length analyzer [7], the method provides no information on how coarseness is distributed within that population. Moreover, fibre coarseness alone is insufficient to define and predict pulp quality, as two fibres of similar coarseness can have quite different wall thicknesses if their perimeters are different. There is as yet no easy method for measuring fibre wall thickness and its distribution in a pulp. The distributions of transverse dimensions are likely to be more important than their mean values in controlling pulp quality as they define the extent of heterogeneity in the papermaking material. Two pulps can have similar mean wall thicknesses, but one may have a proportion of very thick-walled fibres. As they will be difficult to collapse in the sheet structure, such fibres could unduly increase sheet surface roughness.

Recently, we have developed procedures for obtaining cross-sectional images of wood pulp fibres by using the optical sectioning ability of confocal laser scanning microscopy (CLSM) [8]. Combined with image analysis, we are able to accurately obtain fibre transverse dimensions and other features, such as lumen area. In this report we will present results on pulp fibres obtained from a variety of wood species, and show how fibre transverse dimensions are distributed within a species, and vary between different species. The implications of these results for pulp quality and fibre selection for end-use requirements will be discussed.

METHODS AND MATERIALS

A Bio-Rad MRC-500 confocal laser scanning system attached to a Zeiss Axiophot microscope was used to generate fibre cross-sectional images. Observations were made in fluorescence mode with a 100x oil immersion Plan-Apochromatic objective with a numerical aperture of 1.3. The system was later replaced by a Bio-Rad MRC-600 attached to a Nikon Optiphot-2 microscope using a 60x objective with a numerical aperture of 1.4. Fibres were first lightly dyed with a fluorochrome dye. They were deposited on glass slides, dried, and mounted in Permount mounting medium under cover slips. During measurement, each fibre was oriented perpendicular to the laser scanning direction, and its optical section through the thickness was obtained. In this way cross-sectional images of several hundred different fibres were randomly obtained for each pulp. Image analysis was used to quantify these images. The details of specimen preparation, optical sectioning with confocal microscopy, and image analysis have been reported earlier [9]. Figure 1 shows a typical fibre cross-sectional image obtained with a CLSM, and its processed binary image. The fibre transverse dimensions such as those defined in Figure 2 were thus obtained. The pulps investigated were mostly laboratory made, low-yield, unbleached kraft (Table I). Some commercial dried bleached pulps were also examined.

Our laboratory pulps were made from composites of chips from several different logs of each species, but because of the inherent variation within a species, our results on transverse dimensions should be considered only illustrative, and not representative of the species.

RESULTS

Validity of measurements

The primary measurement obtained from the confocal images is the cross-sectional area A of the fibre wall (Figure 2). Since the coarseness of a fibre is proportional to its wall cross-sectional area, we have plotted in Figure 3 mean pulp coarseness against mean A for several pulps. The pulp coarseness was obtained with Kajaani-FS100 or FS-200 fibre length analyzers [7]. The slope of the line in Figure 3 is expected to be the density of the fibre wall material for these pulps. It is nearly 1.5 g/cm^3, which is close to the accepted value. The results in Figure 3 demonstrate that our measurement of A is valid.

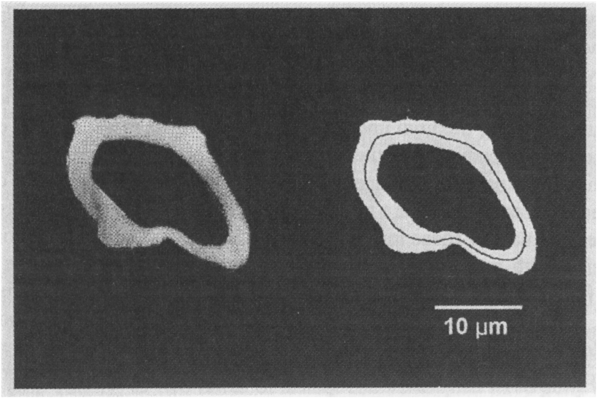

Figure 1. Typical confocal cross-sectional image of a fibre and its processed binary image with the centre-line perimeter drawn.

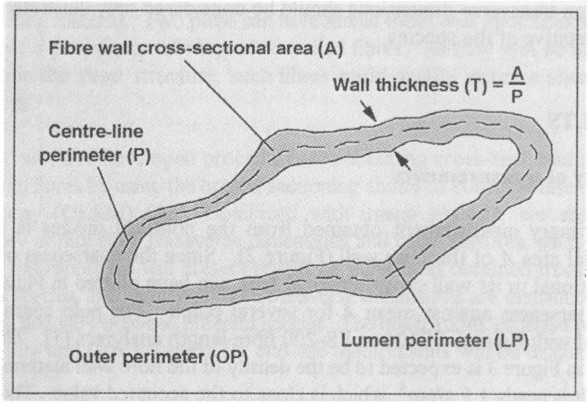

Figure 2. Fibre dimensions measured from a cross-sectional image by image analysis. *A* – fibre wall cross-sectional area; *P* – centre-line perimeter; *T* – mean wall thickness *(A/P)*; *LP* – lumen perimeter; *OP* – outer perimeter.

TABLE I: Pulp yield and kappa number of various unbleached softwood kraft pulps of this investigation

Species	Yield, %	Kappa number
Western spruce	47.6	29.4
Western hemlock	44.2	30.3
Western red cedar	46.4	29.6
Douglas fir	45.7	28.1
Black spruce	47.1	29.0
Balsam fir	46.2	31.2
Juvenile Douglas fir [10]	45.4	33.3
Mature Douglas fir [10]	46.6	33.3
Black spruce thinnings [11]	48.3	35.8
Young western hemlock [12]	43.0	33.0

Further information on pulps in references 10 through 12 is available from the authors.

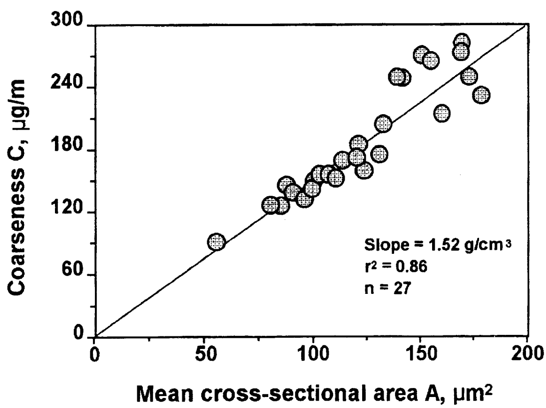

Figure 3. Relationship between fibre wall cross-sectional area and coarseness.

Variability within and between species

We have defined the mean thickness of the fibre wall T as the cross-sectional area A divided by the fibre's centre-line perimeter P; that is, $T = A/P$.

It is instructive to examine the relationships between the three fibre transverse dimensions A, P and T. Figures 4 through 6 show (A vs P), (A vs T) and (P vs T) plots for fibres of three different wood species. What is immediately apparent from these plots is that fibre transverse dimensions within each species are highly variable.

If we assume that fibres with transverse dimensions above or below certain values such as $A > 120$ µm^2, $P < 60$ µm and $T > 2$ µm will be less desirable for papermaking, then there are several ways their proportion can be recognized. Figures 4 through 6 show some examples. It is clear that the proportion of such fibres in Figure 6 for this Douglas fir is very large. It is worth noting that fibres in a population that tend to have thicker walls and smaller perimeters are typically latewood fibres. They tend to be coarser as well, and difficult to collapse.

In Figures 4 through 6, while A and T, and P and T may appear to be somewhat correlated, there is hardly any correlation between A and P; at a given A, P is widely distributed. This is typical of all pulps. Therefore, for a given fibre coarseness, fibre wall thickness can have a range of values depending on the fibre perimeter.

The distributions of A, P and T for fibres of another three different wood species, balsam fir, western hemlock and western spruce, are shown in Figures 7 through 9. The shapes of the distributions are typical, and seem to fit a three-parameter Weibull function (Appendix I). It is interesting to note that while these three pulps have similar mean fibre cross-sectional areas, the mean wall thicknesses are different. This is because their fibre perimeters are different.

In Figure 10, we have plotted the standard deviations of A, P and T against their respective mean values for the above six pulps. While the range for A and T for these pulps is wide, it is relatively narrow for P. Further, while the standard deviations for P are relatively constant, those for A and T are proportional to their respective means. This implies that species with coarse or thick-walled fibres are likely to be more heterogeneous.

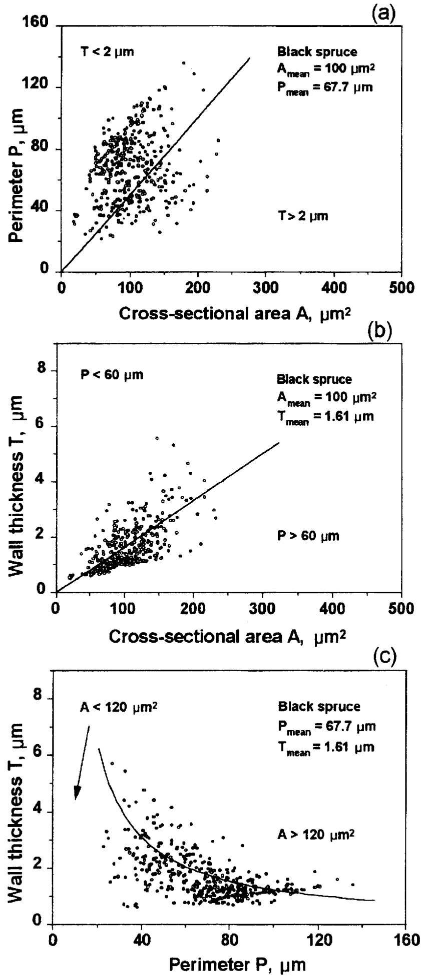

Figure 4. Relationships between various fibre transverse dimensions for eastern Canadian black spruce kraft pulp. The lines through the data points are lines of constant *T*, *P* and *A* of 2 µm, 60 µm and 120 µm² respectively, and show fibres above or below these values.

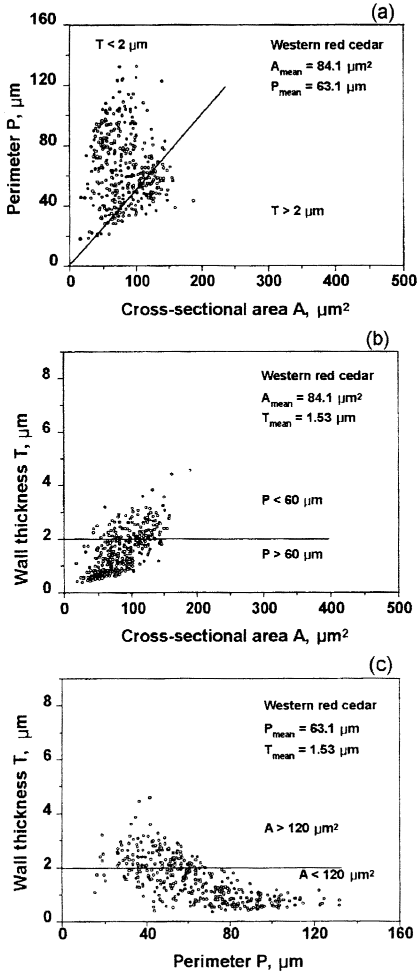

Figure 5. Relationships between various fibre transverse dimensions for western red cedar kraft pulp. The lines through the data points are lines of constant T of 2 µm, and show fibres above or below this value.

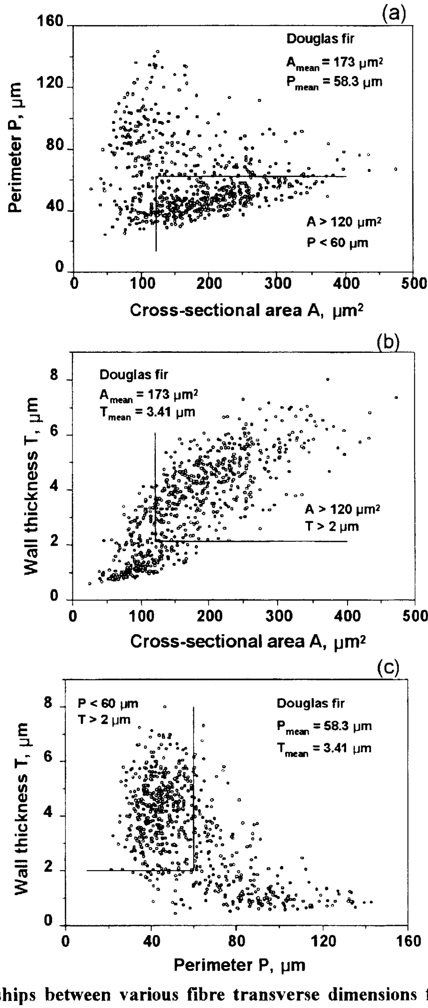

Figure 6. Relationships between various fibre transverse dimensions for Douglas fir kraft pulp. The quadrants show the proportion of fibres with A >120 μm², P<60 μm and T>2 μm.

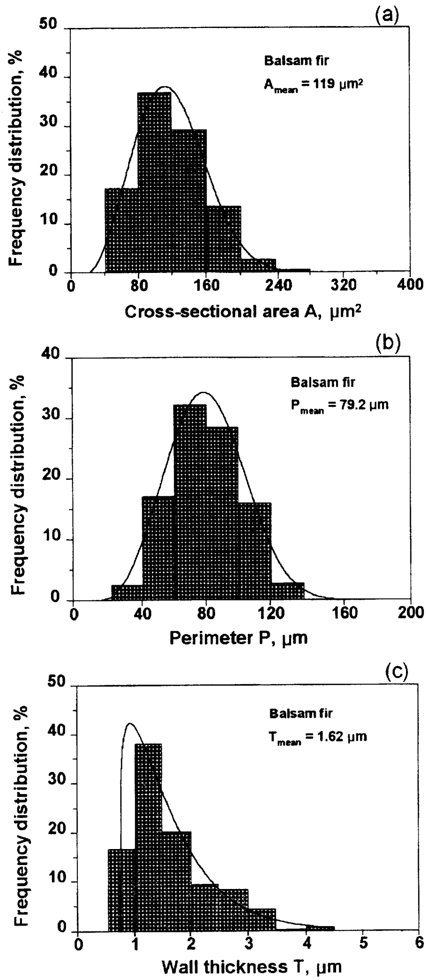

Figure 7. Distributions of A, P and T for fibres of eastern Canadian balsam fir kraft pulp. The curve shows the fitted Weibull function.

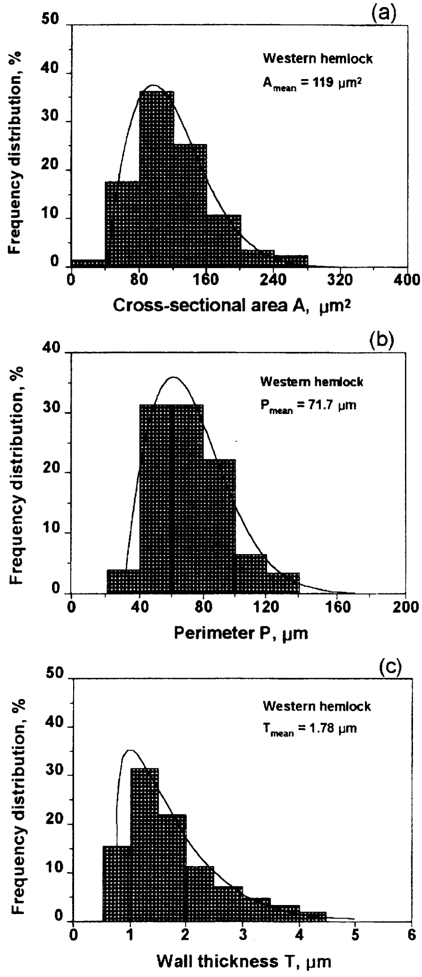

Figure 8. Distributions of *A*, *P* and *T* for fibres of western hemlock kraft pulp. The curve shows the fitted Weibull function.

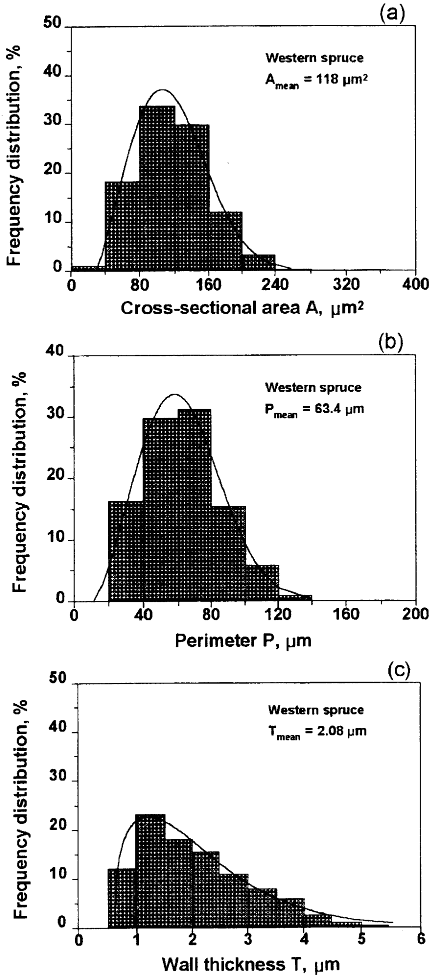

Figure 9. Distributions of A, P and T for fibres of western spruce kraft pulp. The curve shows the fitted Weibull function.

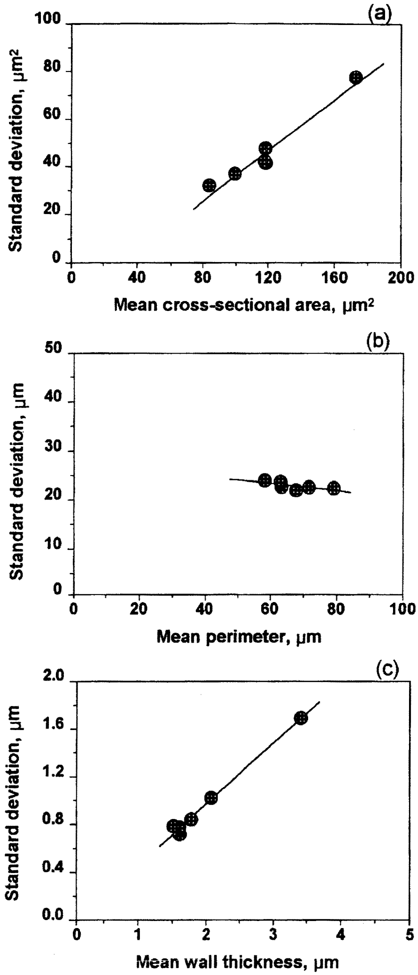

Figure 10. Relationship between standard deviations and mean values for *A*, *P* and *T*.

Comparison within and between species by weight

Previous work [6] showed that the fibre (transverse) geometry factor that determines collapse is *($LP/2\pi T$)*, where *LP* is the total lumen perimeter (Figure 2). The larger this factor is, the more readily the fibres collapse. Since papermaking fibres are used by weight, we have calculated the weight fractions of *A*, *T*, and *($LP/2\pi T$)* for various species, and compared them in Figures 11 through 17. The amount of undesirable fibres by weight in each population can now be determined from these plots.

Figure 11 shows a comparison of the four western Canadian species. These pulps were prepared to similar yields (~ 46%) and to similar kappa numbers (~29) as shown in Table I. The percentage of fibres by weight above certain *A* and *T* values, for instance 120 μm^2 and 2 μm respectively, is apparent from these plots. For example, while Douglas fir in Figure 11b has only about 15% fibres with wall thickness below 2 μm, both red cedar and hemlock have nearly 60%, and spruce has nearly 45%. Furthermore, over 50% of the fibres in this Douglas fir sample have wall thickness above 4 μm. If we arbitrarily assume that fibres with *($LP/2\pi T$) <5* will be extremely difficult to collapse in these pulps, then the proportion of such fibres in this Douglas fir sample is the highest (nearly 85%), and the lowest is this hemlock (nearly 40%). Similarly, if we assume that fibres with *($LP/2\pi T$) >10* will collapse readily, then the proportion of such fibres in this Douglas fir is the lowest (nearly 10%), and highest is this red cedar (nearly 30%). This type of pulp ranking was not practical before, but now can be carried out readily with confocal microscopy and image analysis.

In Figure 12, comparison is made between eastern Canadian black spruce and balsam fir fibres of Figures 4 and 7. The pulps once again had similar yields (~ 47%) and similar kappa numbers (~ 30) as shown in Table I. These two pulps have similar wall thickness distributions (Figure 12b), but the balsam fir fibres are nearly 18% coarser than black spruce fibres (Figure 12a). This also implies that balsam fir fibres have larger perimeters, and will be more collapsed, as confirmed in Figure 12c. It is also worth noting that over 60% of the black spruce fibres have their cross-sectional areas below 120 μm^2 compared with about 40% for balsam fir (Figure 12a).

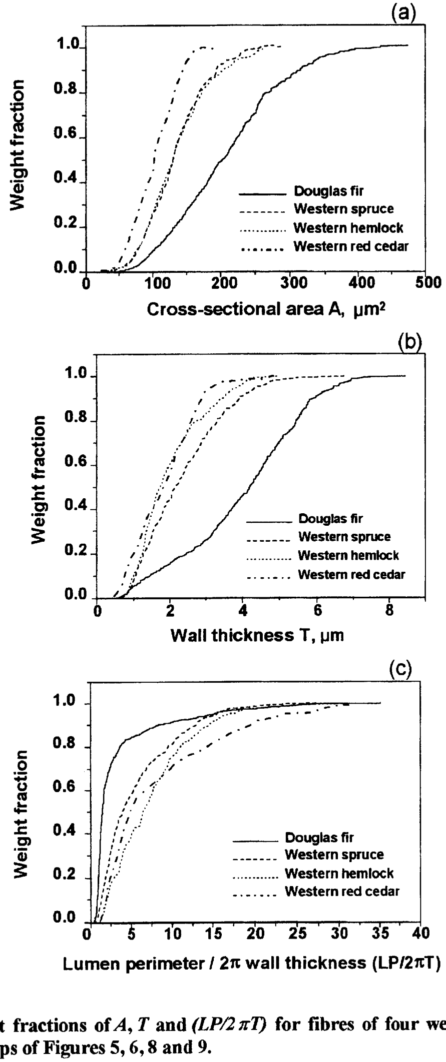

Figure 11. Weight fractions of *A*, *T* and *(LP/2πT)* for fibres of four western Canadian softwood kraft pulps of Figures 5, 6, 8 and 9.

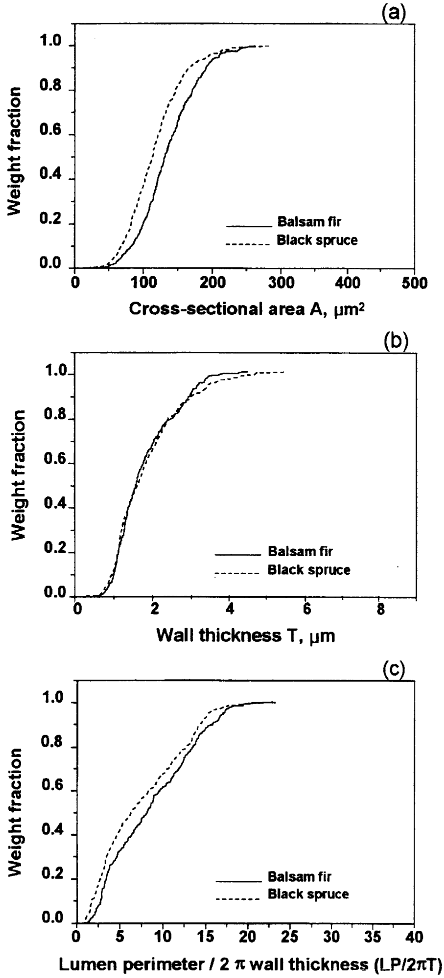

Figure 12. Weight fractions of A, T, and $(LP/2\pi T)$ for fibres of eastern Canadian black spruce and balsam fir kraft pulps of Figures 4 and 7.

We have compared in Figure 13 black spruce fibres of Figure 12 and western red cedar fibres of Figure 11; both are thin-walled species, but from two different geographical regions of Canada. Both species have fibres with similar wall thickness, but the red cedar fibres are somewhat finer. Further, there are more fibres with $A < 120\ \mu m^2$ and $(LP/2\pi T) < 5$ in red cedar than in black spruce.

Figure 14 shows a comparison of juvenile and mature wood fibres of Douglas fir. Juvenile wood was defined as the innermost 20 years growth within a tree [10]. The juvenile wood fibres have been shown to be somewhat shorter, finer, and have different pulping and papermaking characteristics [10]. Figure 14a shows that, for any fibre fineness, there are more fine fibres in juvenile wood than in mature wood. Furthermore, only about 20% of juvenile wood fibres have walls thicker than 3 μm, whereas the mature wood has nearly 50% (Figure 14b). Similarly, there are more fibres with $(LP/2\pi T) < 5$ in mature wood, that could be more difficult to collapse, than in the juvenile wood (Figure 14c). It is for these reasons that the juvenile wood fibres of an otherwise thick-walled species are more acceptable for papermaking when strength and smoothness in the sheet are desired [13].

In Figures 15 and 16, fibre properties from old and young trees are compared. Young trees and thinnings contain primarily or entirely juvenile wood. In Figure 15, fibres of black spruce thinnings from an eastern Canadian plantation are compared against those of mature trees shown in Figure 12. Similarly, fibres of plantation-grown young western hemlock trees are compared in Figure 16 against those of mature trees of Figure 11. The yields and the kappa numbers of kraft pulp of black spruce thinnings and western hemlock fibres are given in Table I. The results in Figures 15 and 16 are similar to those in Figure 14 for juvenile and mature woods; the juvenile wood fibres in general are finer, have thinner walls and are more collapsible.

In Figure 17, we have compared two bleached hardwood kraft market pulps A and B. Although the two pulps have nearly similar mean wall thickness and distributions (Figure 17b), fibres of pulp A are coarser (Figure 17a), and more collapsible (Figure 17c), implying that they are wider or have larger lumen perimeters.

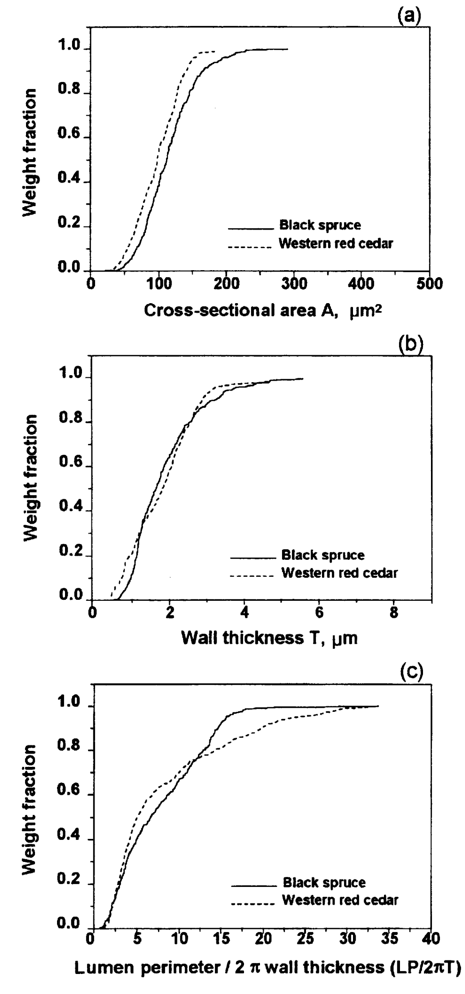

Figure 13. Weight fractions of *A*, *T*, and *(LP/2πT)* for fibres of eastern Canadian black spruce and western Canadian red cedar kraft pulps of Figures 4 and 5.

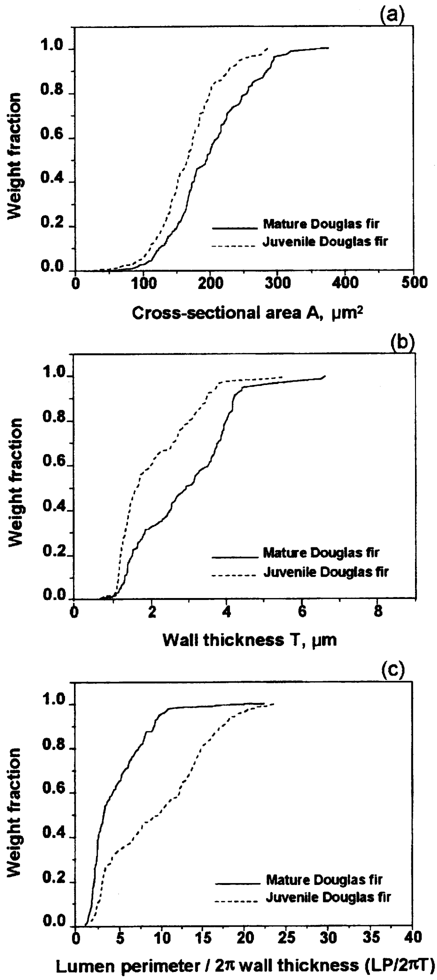

Figure 14. Weight fractions of A, T, and ($LP/2\pi T$) for fibres of juvenile and mature Douglas fir kraft pulps. The mean A, P and T for the juvenile and mature wood fibres respectively are 149 µm², 89.2 µm, 1.84 µm and 179 µm², 77.3 µm and 2.65 µm.

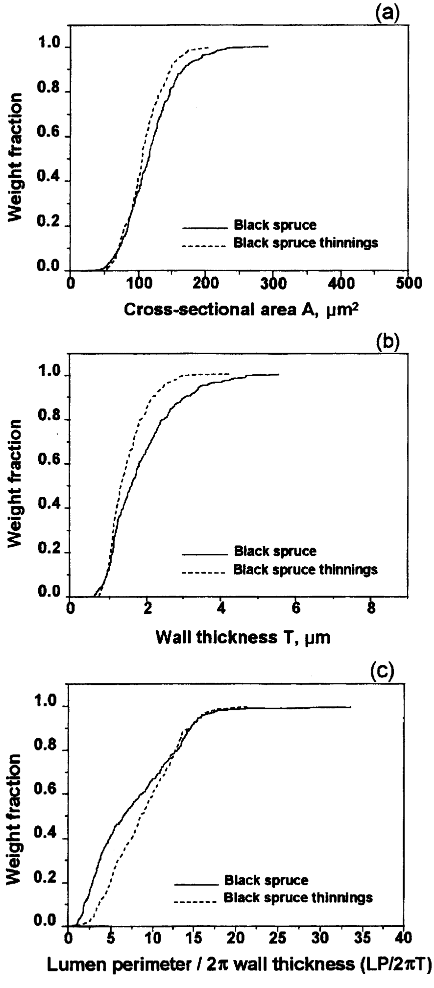

Figure 15. Weight fractions of A, T, and $(LP/2\pi T)$ for fibres of black spruce of Figure 12 and of kraft pulps of black spruce thinnings from an eastern Canadian plantation. The mean A, P and T for the fibres of thinnings are 96.0 μm², 72.5 μm and 1.38 μm.

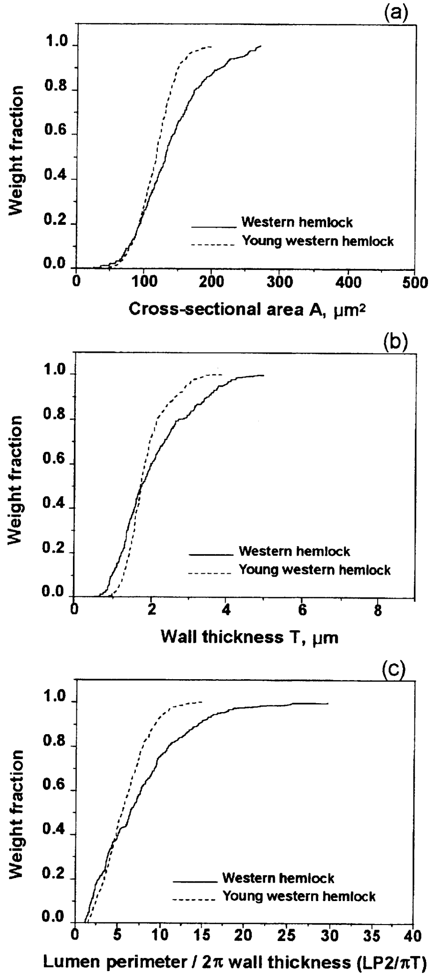

Figure 16. Weight fractions of A, T, and ($LP/2\pi T$) for fibres of western hemlock of Figure 11 and of kraft pulps of plantation-grown young western hemlock trees. The mean A, P and T for the fibres of young trees are 109 μm², 63.5 μm and 1.78 μm.

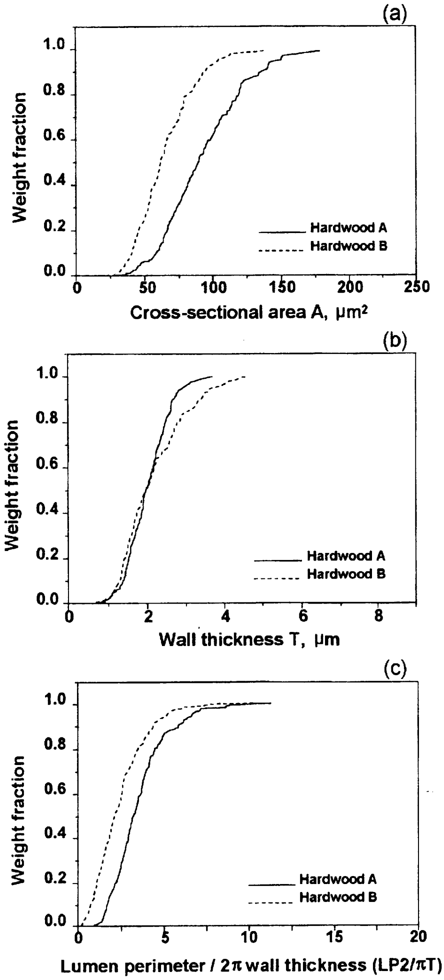

Figure 17. Weight fractions of *A*, *T*, and *(LP/2πT)* for fibres of two bleached hardwood kraft market pulps.

DISCUSSION

Confocal microscopy has been used to measure the transverse dimensions of wood pulp fibres, and to determine both qualitatively and quantitatively the extent of variability in them. As examples, we have provided measurements on kraft pulp fibres of various wood species, and have given comparisons between different species. We have examined only the transverse dimensions and suggested ways to identify or quantify fibres with undesirable dimensions. However, the response of fibres to papermaking treatments, and the resulting product properties do not depend on the morphology alone, but also on the physical and the chemical properties of the fibre wall material. We have not considered these aspects, as they were not within the scope of this investigation. If, however, fibres with less desirable dimensions could be separated, they could be post-treated to change their dimensions and the properties of the wall material, and thus made more acceptable for papermaking. Alternatively, fibre resources with fewer such fibres could be identified and grown.

The information on fibre transverse dimensions helps us to select fibre sources for various end use requirements. For instance, if high sheet opacity is desired, fibres must have thin walls. The reasons are as follows. For a given sheet grammage, opacity depends on the sheet's light scattering and absorption coefficients. While the absorption coefficient depends on the pulp's light absorptive properties, the scattering coefficient is controlled by the available fibre surface area within the sheet. This area is large if the specific surface area, *SSA*, the fibre surface area per unit mass, is large. For an uncollapsed fibre, considered as a cylindrical tube of wall thickness T, the specific surface area $SSA=(OP + LP)/\rho A = 2/\rho T$, where OP and LP are the outer fibre and lumen perimeters (Figure 2), and ρ is the density of the fibre wall material; the surface area of the tube ends is ignored. If the tube is completely collapsed, $SSA \approx 1/\rho T$, assuming that T is much smaller than the fibre perimeter. Thus, for high opacity, fibres must have thin walls. This was first pointed out by Scallan and Borch [14], and is well demonstrated [1, 14-16]. Large *SSA* also leads to a high sheet tensile strength [17], simply because there is more (outside) surface area available for fibres to bond [1].

If high sheet bulk is desired, fibres must resist collapse, that is, their ratio $(LP/2\pi T)$ for a given wall rigidity should be small. This implies that the fibres should have narrow lumens and thick walls. But, thick-walled fibres will give a low sheet opacity.

Both high bulk and high opacity are generally desired in sheets of hardwood fibres. However, the requirements for these two properties appear to be contradictory. For a given wall thickness, fibres will resist collapse and give a high sheet bulk only if they have small $(LP/2\pi T)$, that is, small lumen perimeters. This implies that fibres should be narrow and have small wall cross-sectional areas, or they should be fine. Thus, it is fine and thin walled fibres that will give high bulk and high opacity to the sheet. But these fibres can have a higher drainage resistance. It is worth noting that the hardwood pulp B of Figure 17 has finer fibres, but has wall thickness similar to pulp A (Table II). Therefore, the sheets of the pulp B are bulkier, have a higher light scattering coefficient and opacity, but the pulp has a lower freeness. On the other hand, fibres of pulp A, being wider, collapsed more, bonded better, and therefore gave sheets a higher tensile strength.

TABLE II: Comparison of fibre and handsheet properties of bleached hardwood market pulps of Figure 17.

	Pulp A	Pulp B
Fibre Properties		
A, μm^2	80.8	56.0
P, μm	43.3	30.0
T, μm	1.88	1.96
$(LP/2\pi T)$	3.59	2.57
Pulp and Handsheet Properties		
Pulp freeness, mL	463	392
Sheet bulk, cm^3/g	1.50	1.72
Tensile strength, km	5.30	4.64
Air resistance, s/100mL	18	7.9
Scattering coefficient, cm^2/g (at 681 nm)	275	389
Opacity, %	70.9	77.5

Handsheet properties were measured after beating the pulps to 3000 revolutions in a PFI mill.

If $(LP/2\pi T)$ is the fibre geometry factor that controls collapse and conformability, then for a given wall thickness T, how large should the LP be? The answer is just large enough for the fibre to collapse, because a large perimeter will mean a large cross-sectional area A, or a high fibre coarseness. Coarse fibres are less desirable for papermaking simply because, for a given length, they are fewer per unit pulp mass [1]. For a given sheet grammage, finer fibres being more numerous, make more fibre-fibre contacts per unit area, and therefore make stronger wet webs [18], and dry sheets [17]. Because of their abundance, they form more layers within the sheet giving it a better formation [19]. The sheet formation is also better because finer fibres have a greater mobility, and a lower tendency to flocculate [20]. It seems, therefore, that whether from hardwoods or softwoods, fine fibres with thin walls are more desirable for papermaking. For a given wall thickness, hardwood fibres, generally being finer and narrower, resist collapse, and therefore provide bulk and opacity to the sheet. However, because they are shorter and have a lower bonded area in the sheet, they give poor sheet strength, and therefore require reinforcement. Softwood fibres, on the other hand, are relatively coarser and wider for a given wall thickness. Therefore, they collapse readily. Because they are much longer and bond better, softwood fibres give high sheet strength, and therefore provide reinforcement; their contribution to opacity is relatively less. If hardwood fibres could be grown longer, they would require less reinforcement. Fine, thin-walled fibres in general make smoother sheets, but offer somewhat higher resistance to drainage [1].

In summary, the knowledge of fibre dimensions allows us to identify and select resources with fibres most desirable for end-use requirements. The challenge is to grow them.

CONCLUDING REMARKS

The measurement of fibre transverse dimensions such as wall cross-sectional area, perimeter and thickness is essential for predicting pulp quality. Fibre transverse dimensions in wood are highly variable, and are poorly correlated with one another. Therefore, each has to be measured. Optical sectioning with confocal microscopy combined with image analysis provides a rapid and accurate method; all fibre transverse dimensions are simultaneously obtained from the confocal cross-sectional images. The proportion of fibres by weight above or below a certain dimension, considered undesirable for papermaking, can now be determined. Future work on tree improvement could be directed towards reducing the proportion of such fibres. Wood species with finer and thinner-walled fibres were found to be more homogeneous.

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APPENDIX I

The Weibull distribution

The three-parameter Weibull[1] probability density function (PDF) for a random variable x is expressed as

$$f(x) = (c / b)\,[(x - a) / b]^{c-1} \exp\left(-[(x - a) / b]^{c}\right), \tag{A1}$$

where $a \geq 0$, b, $c > 0$, and $x \geq a$. The cumulative distribution function (CDF) is

$$F(x) = 1 - \exp\left(-[(x - a) / b]^{c}\right), \tag{A2}$$

such that $d/dx\,[\,F(x)\,] = f(x)$.

The Weibull parameter a is the location or the threshold parameter, and is determined by the smallest value of x in the distribution. For fixed values of b and c, changes in a simply shift the distribution along the x-axis. Parameter b is the scale parameter. For $x = a + b$, $F(x) = 1 - e^{-1} = 0.632$. The point, $x = a + b$ corresponds approximately to the 63rd percentile of the distribution. Parameter c determines the shape of the distribution. The Weibull distribution is very flexible because it can assume different shapes depending on the value of c. For instance, when $c = 1$, it becomes the negative exponential distribution. For $c \approx 3.6$, the Weibull distribution is similar in shape to the normal distribution. When c is between 1 and 3.6, the Weibull distribution is positively skewed; when $c > 3.6$, it is negatively skewed.

Many biological growth phenomena, such as the distribution of the diameters of trees in a forest stand, can be quantified by the Weibull function. We have found that the Weibull function describes well the distribution of fibre transverse dimensions in wood pulps.

The results on fibre transverse dimensions were first expressed as cumulative distributions. The Weibull CDF (Equation A2) was then fitted to the results using

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[1] Weibull, W., J. Appl. Mech. 18:293(1951).

the Lavenberg - Marquardt method for non-linear least-squares curve fitting. The parameters *a*, *b* and *c* for the best fit were thus determined. The goodness of the fit was examined graphically, as well as from the chi-squared values, and the standard errors of the estimates (Figure A1). These values of the parameters were then used to generate the Weibull PDF's (Equation A1) shown in Figures 7 through 9.

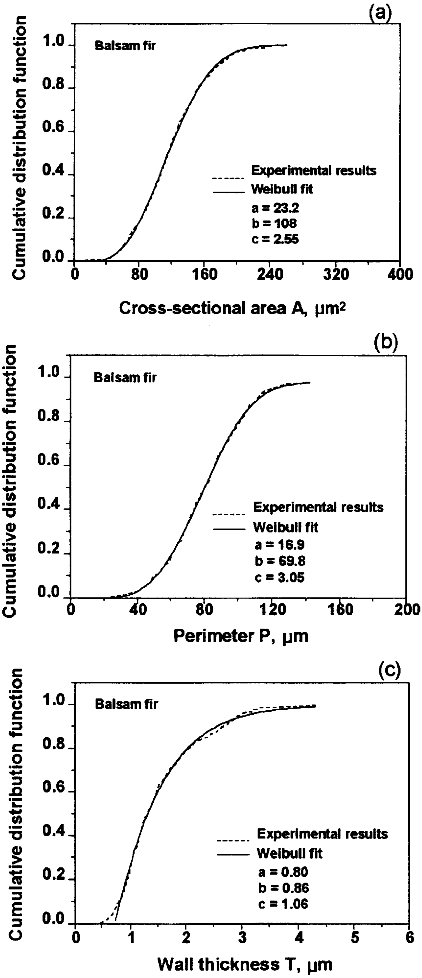

Figure A1. Experimental results on *A*, *P* and *T* for balsam fir fibres, and the Weibull CDF fitted to them.

Transcription of Discussion

Transverse Dimensions of Wood Pulp Fibres and their Implications for End Use

Dr Raj S Seth, Principal Scientist, Paprican, Canada

Theo van de Ven, Director, Paprican/McGill, Canada

I have a question about the observation you mentioned that fibres are more heterogeneous if they are more coarse. I guess that depends on the definition of heterogeneous. If I express your data as relative standard deviations then there is almost no effect of heterogeneity. Is that not a more natural way of defining it?

Raj Seth

Yes, you are right. But, it depends on how you define heterogeneity. Why can't coarse fibres have a narrow distribution? The fact that the standard deviation is proportional to the mean is the way fibres grow in the tree, as shown by our results.
I should point out that plotting standard deviation against the mean was suggested to us by Kit Dodson.

Professor C T J (Kit) Dodson, UMIST, UK

On another point, the Weibull distribution requires three parameters. In fact there are very many similar distributions needing only two parameters, can you justify needing three?

Raj Seth

I think here I will need Dr Jang to answer, but let me add something in the meantime while he comes to the podium. Dr Jang tried many distributions but the Weibull gave the best fit. We also found a body of work which showed that the distribution of tree cross-sectional areas at a given height in a forest stand also followed the Weibull function. Further, we believe that the Weibull function has a physical basis, and may well be derived from a growth phenomenon.

Dr Ho Fan Jang, Scientist, Paprican, Canada

First of all I would like to say that we expected questions on our use of the Weibull distribution. What I said was we need three parameters to describe the distribution. First we need a parameter to describe the threshold of the distribution, the second to describe the spread of the distribution, and the third to describe the shape of the distribution. Weibull is a simple function that meets this need. Both the density and the cumulative distribution functions of the Weibull are in closed form. I also want to add that its shape parameter, c, is related to the coefficient of variation. We found $c \approx 2$ for the distributions of the fibre cross-sectional areas for various species. Interestingly, the distribution of tree cross-sectional areas also had $c \approx 2$.

Dr Kari Ebeling, Director, UPM Kymmene Group, Finland

Thank you for a very nice presentation. I have a question concerning the coarser fibres. With today's technology you can pull the coarser fraction apart and give it a special treatment so that you can end up with a fairly homogeneous stream of fibres after combining the fractions. Is it a fact of life that you need the coarser fibres to get the higher growth rate per hectare? If we consider papermaking to be a money making operation then we have to live with the coarser fibres in the fast growing trees.

Raj Seth

I agree. The technology exists to separate fibres. We are looking at what kind of separation occurs. There is no way to get rid of the latewood, but if we can identify a tree which has a minimum amount of the undesirables, then maybe it should be propagated. The other point is - it is up to the user to define the undesirables depending on his needs.

Mark T Kortschot, Associate Professor, University of Toronto, Canada

I notice that in the process of converting the confocal image into a binary image the surface seemed to have a rough shape so that every so often you find a pixel sticking up, that must affect the calculation of the perimeter. How do you filter or handle that?

Ho Fan Jang

I am not sure what you are asking - are you talking about the accuracy of the perimeter measurement?

Mark Kortschot

Is it a nominal perimeter that you are trying to calculate? I presume the binary image is produced by some kind of thresholding operation. I noticed that the surface of the fibre in the binary image wasn't smooth anymore.

Ho Fan Jang

I think you are talking about the accuracy of the cross-sectional area measurement.

Raj Seth

I can answer that. The measurements are accurate. One evidence is the relationship between the fibre wall cross-sectional area and fibre coarseness as shown in figure 3 in the text.

Dr Derek Page, IPST, USA

I think Mark's question is 'Are you using modern up-to-date methods of image analysis to determine fibre dimensions?', and I believe the answer is 'yes'?

Ho Fan Jang

Yes. When we do the image processing from a raw image to a binary image, we use an operator which allows us to find the edge at the maximum gradient. In fact this effectively does a deconvolution on the image so that we get a better resolution than the scan allows.

Raj Seth

I can add here that these details were given in an earlier paper which is referenced in the text. These details were very carefully worked out.

Stuart Loewen, Associate, LSZ Paper Tech Inc, Canada

The use of the confocal laser scanning microscopy is, I presume, to orient the image in order to obtain the cross-sectional measures. So that's in place of using mechanical orientation and more conventional image techniques. Is that a correct understanding?

Raj Seth

This is true in a sense that we are taking optical cross-sections perpendicular to the fibre axis. Have I answered your question?

Stuart Loewen

Yes, in terms of implementation of the analysis methods of papermaking processes would you recommend a paper mill getting a confocal laser microscope?

Raj Seth

No. But what we are doing at present is to help the papermakers or the pulp suppliers evaluate the quality of their fibres. Whether this technology will become easy and fast enough for the mills to use it is another matter.

Petri Kärenlampi, Champion Int Corp, USA

Professor Ebeling raised the argument that one of the prices of high growth rate is high coarseness. This to some degree disagrees with observations I have read from literature where, with regard to spruce species, increasing the growth rate increases the proportion of early wood which decreases coarseness and with pine species that relative proportions of early wood and late wood remain about constant when you increase growth rate. Maybe Professor Ebeling referred to differences between tree species in Southern and Northern areas, where coarseness differences are well established. I would like to ask, do you have observations about Canadian tree species, is there a significant effect of growth rate on coarseness or other fibre properties?

Raj Seth

Petri, can you repeat your question for Dr Jang?

Petri Kärenlampi

Is there a significant effect of growth rate on the cross-sectional area, cell wall thickness, coarseness or possibly other properties?

Ho Fan Jang

You mean fibre properties with respect to the growth rate?

Petri Kärenlampi

Are these fibre properties sensitive to growth rate?

Ho Fan Jang

We have looked at this aspect for western hemlock. At this stage, all I can say is that the work is in progress.