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THE EFFECT OF CELL SNIPPET POSITION ON LASERSCAN DIAMETER MEASUREMENT

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SUMMARY

The effect of wool fibre snippet position within the Laserscan measurement cell and its impact on calibrated diameter distribution measurements has been investigated using Monte Carlo techniques in conjunction with a Fresnel diffraction model of the optical system. Raw effects are found to cause a downward shift on distribution mean fibre diameter while standard deviations are essentially unaffected. Although raw effects are found to be significant for mean fibre diameters greater than about 20 μm calibration of the instrument reduces errors to an insignificant level.

INTRODUCTION

The Laserscan measures diameter by transporting a dilute slurry of 2mm snippets in an isopropanol/water carrier past a measurement laser beam. The measurement cell shown in Figure 1 consists of a 2mm wide expanding channel which leads to turbulent fluid flow in the vicinity of the measurement beam. As a consequence of this turbulence both the angular presentation and the axial position (in the beam direction) of a snippet within the cell at the instant of measurement are random in nature.

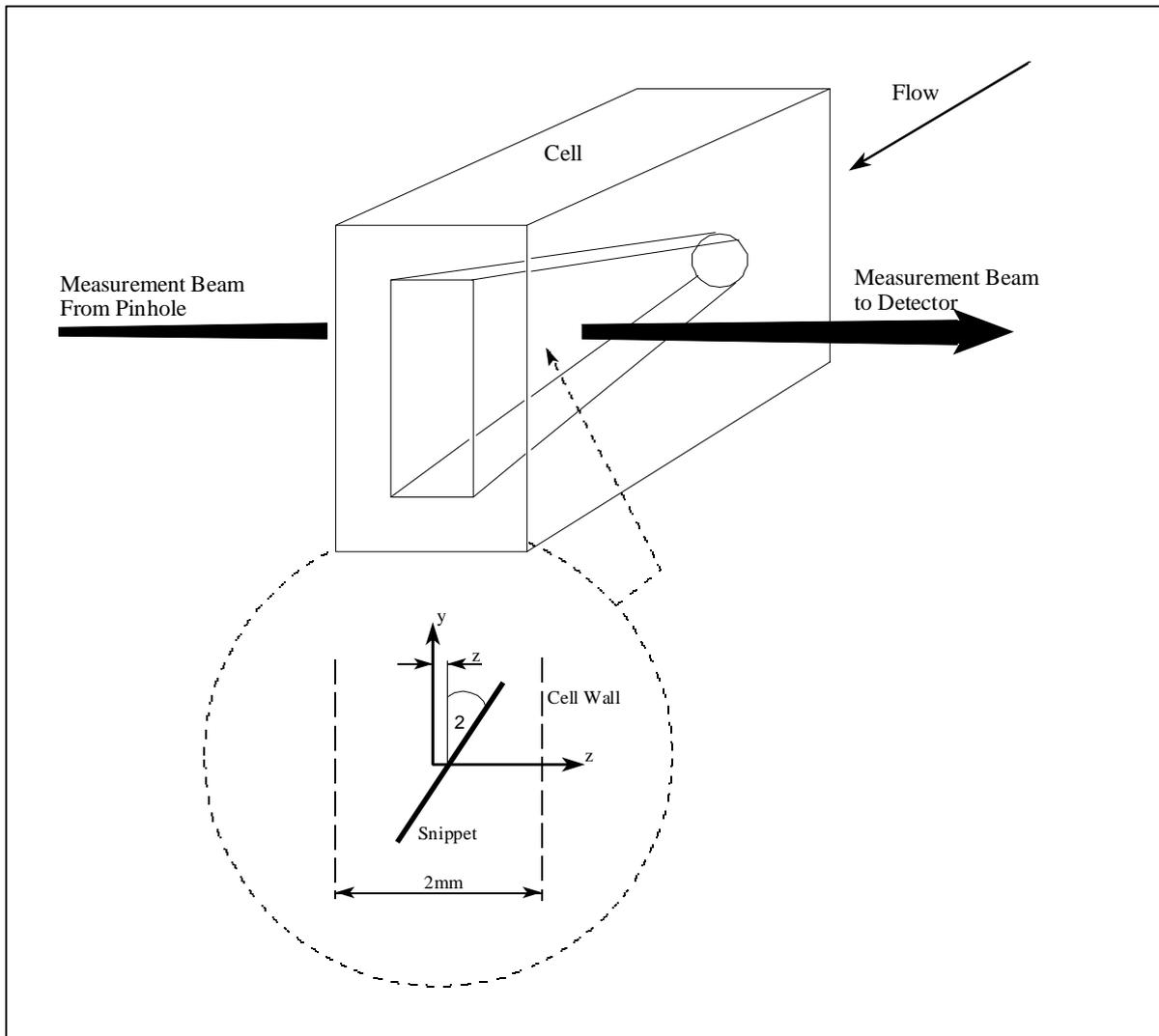


Figure 1. Random snippet orientation and axial position within the Laserscan measurement cell.

The use of a pinhole in the Laserscan causes the beam to expand ($\sim 0.3^\circ$ full angle) as it propagates through the cell and towards the detector. In terms of a simple geometrical optics model a snippet on the left side of the cell channel shown in Figure 1 will obscure more of the smaller diameter beam than it will on the right side of the cell where the beam size is a little larger. The beam occlusion for a given diameter snippet within the cell channel is thus dependant on the axial position of the snippet within the measurement beam. The error, which this axial position dependence introduces when measuring typical wool diameter distributions, is the subject of the following investigation.

THE MONTE CARLO MODEL

A Broad Outline of the Procedure

Although geometrical optics gives a conceptually simple basis for understanding the axial position dependence described above it is inadequate for a more precise quantitative assessment of the magnitude of errors involved. The optical response of the Laserscan is well described by a model based on Fresnel diffraction¹⁻³. Using the theoretical response of Laserscan to snippets at the cell centerline, shown in Figure 2, the apparent “raw” diameter error is first investigated as the snippet is moved axially ($\pm z$) along the beam towards either inside cell wall.

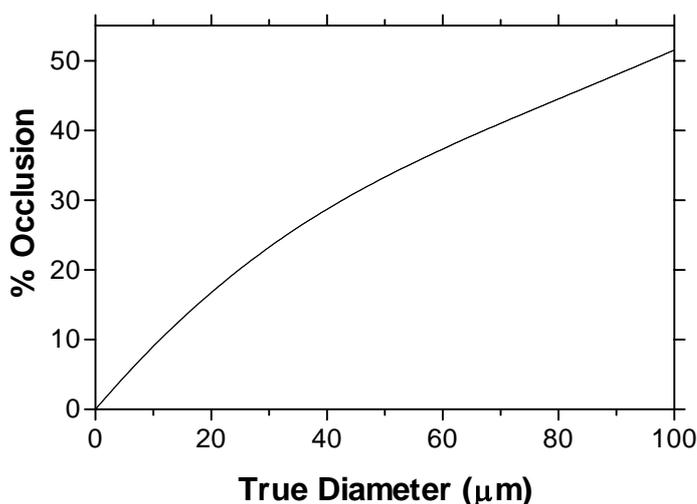


Figure 2. Theoretical Laserscan calibration curve for snippets on the cell centerline

As outlined above, in practice the turbulent flow within the cell causes each snippet to cut the measurement beam with a random angular orientation θ in the y - z plane as well as a random axial beam position z . For a given fibre diameter distribution the Monte Carlo technique⁴ can be used to randomly select a snippet diameter, orientation and axial position. These three parameters lead to an apparent or “measured” occlusion that will be different from the occlusion for the snippet on the beam centerline.

The distribution of apparent occlusions so generated can be used to examine shifts in the fibre diameter distribution mean and standard deviation (SD) in two different ways. Assuming the Laserscan response is governed by the theoretical occlusion versus diameter curve for $z=0$ is equivalent to assuming that the Laserscan has been calibrated with snippets, which travel *only down the cell centerline*, and whose assigned mean/SD are known precisely. Using this theoretical curve to convert the apparent occlusion distribution to an apparent diameter distribution allows computation of the raw mean/SD of the shifted diameter distribution.

Although these raw errors are useful to elucidate overall trends they overestimate what happens in practice. Since snippets from the Interwoollabs tops normally used for calibration are subjected to the same random effects within the cell as wools subsequently measured, raw errors are to a large extent effectively calibrated out. As a means of exploring the effect of calibration the apparent occlusion distribution from each of the calibration tops is used to generate linear files which are the initial step in a normal Laserscan calibration. These are then used to produce a calibration using normal Laserscan software and allows a more realistic estimate of errors encountered in practice.

Optical Response and Single Snippet Raw Error with Axial Position

The optical response and hence calibration curve of the Laserscan changes shape with changes in pinhole to snippet distance and snippet to detector distance^{1,2}. The pinhole-snippet distance a and snippet-detector distance b , for a snippet parallel to but displaced from the y axis of Figure 1 by a distance z , are given by

$$\begin{aligned} a &= 79.744 + 0.726z \\ b &= 106.944 - 0.726z \end{aligned} \quad (1)$$

where a , b and z are measured in mm. Here nominal pinhole-cell and cell-detector distances have been used with appropriate corrections made for beamsplitter and cell wall thicknesses and isopropanol/water thickness in the inclined 2mm wide cell channel (cf. reference 1). For each snippet position z the unobstructed field at the snippet and detector plane changes slightly and must be recalculated prior to computing the power on the detector and hence occlusion for any given snippet true diameter. The theoretical calibration curve, for $z=0$, can then be used to transform this apparent occlusion to an apparent diameter and hence generate curves of raw diameter error versus true diameter for various axial z positions. The result of performing this procedure is shown in Figure 3 below.

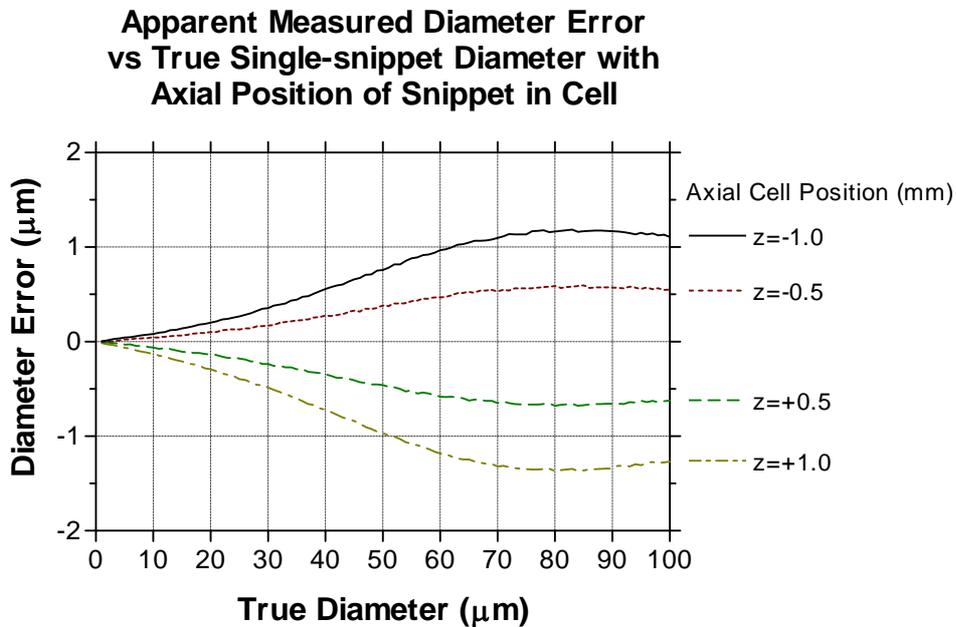


Figure 3. Apparent raw diameter error for a single snippet with a theoretical $z=0$ calibrated Laserscan.

Notice that these curves display a small amount of asymmetry around the cell centerline position with the diameter error flattening out above about $60\mu\text{m}$.

Raw Errors with Diameter Distributions

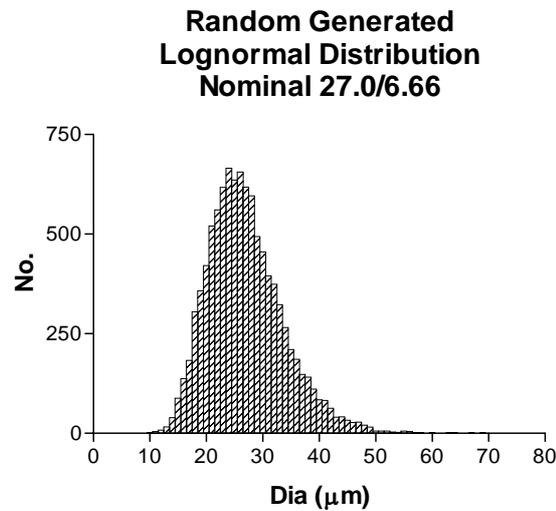
Typical wool fibre diameter distributions are fairly well represented by the lognormal distribution⁵. Also distribution SD's are well correlated with the mean diameter D and related by⁶

$$SD = -4.86 + 0.54D - 0.0042D^2. \quad (2)$$

Standard techniques⁴ can be used to generate a lognormally distributed random variable with given mean and SD fixed using correlation of equation (2). Figure 4 shows the result of generating 10000

lognormally distributed random numbers with a nominal distribution mean/SD of 27.00/6.66 μm . The actual mean/SD of this distribution is 26.96/6.67 μm .

Figure 4. Computer generated random lognormal distribution with 10000 fibres and nominal



mean/SD of 27.00/6.66 μm .

For a 2mm long snippet with a random angular orientation θ the possible range within which z may be chosen randomly is limited by the 2mm wide cell channel. With straight snippets the maximum available displacement (in mm) from the cell centerline is given by

$$z_{\max} = 1 - \sin \theta . \quad (3)$$

As a result of the turbulence it is reasonable to assume that both the angle θ , and position z within the available z_{\max} range, can be chosen as independent random variables with rectangular probability density. Although in practice snippets may tend to hug the center of the cell flow channel, using a rectangular probability density function (PDF) rather than for example a parabolic shape makes almost no difference to the Monte Carlo simulations which follow.

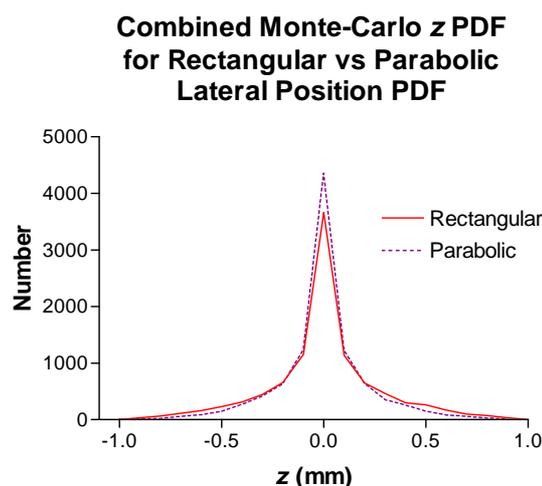


Figure 5. Comparison of combined Monte Carlo PDF for z with rectangular versus parabolic PDF for axial position.

Figure 5 shows the resulting PDF with 10000 randomly chosen (rectangular PDF) angles θ and subsequent random choice of z in the available range, with either rectangular or parabolic PDF's. The

differences apparent in the PDF's are small and subsequent diameter histogram statistics showed it was irrelevant which PDF shape is used for z in the Monte Carlo simulations.

Since the beam intensity is greatest near its center we can expect the occlusion from an angled snippet to be well approximated to the first order by the occlusion from a snippet parallel to the y axis located at the same z position as the centre of the angled snippet. With this understanding the raw errors, as they apply to a distribution of fibre diameters with given mean and SD from equation (2), are calculated as follows:

- (i) Generate a true snippet diameter randomly from a lognormal distribution.
- (ii) Generate a snippet orientation θ randomly from a rectangular distribution.
- (iii) Generate a snippet axial position z in the range $-z_{\max} \leq z \leq z_{\max}$ randomly from a rectangular distribution.
- (iv) The data used to derive Figure 3 is in the form $d_{\text{apparent}} = f(d_{\text{true}}, z)$ and can be interpolated in two dimensions to arrive at an apparent diameter for each "measured" snippet. Note that the "calibration" used here is the Laserscan theoretical response for $z=0$.
- (v) Each true diameter and apparent diameter is binned into separate histograms with 1 wide bins centered on $0.5\mu\text{m}$ positions. Any diameters which are greater than $81\mu\text{m}$ are added to an overs bin in each distribution and subsequently excluded from the distribution statistics.
- (vi) After generating 20000 snippets randomly in this manner the mean and SD of the true and apparent diameter distributions are calculated.

The result of carrying out the above procedure for a range of true distribution nominal mean diameter from 15 to $50\mu\text{m}$ is shown in Table 1 and Figure 6 below.

Nominal Mean	True Mean	True Overs No.	Apparent Mean	Apparent Overs No.	Nominal SD	True SD	Apparent SD
15.00	15.00	0	14.91	0	2.30	2.33	2.31
20.00	20.01	0	19.87	0	4.26	4.29	4.26
25.00	25.00	1	24.83	1	6.02	6.04	5.99
30.00	30.00	2	29.78	2	7.56	7.57	7.51
35.00	34.98	7	34.72	7	8.90	8.87	8.8
40.00	39.94	29	39.62	25	10.02	9.89	9.81
45.00	44.80	99	44.44	89	10.94	10.57	10.51
50.00	49.41	319	49.04	286	11.64	10.75	10.72

Table 1. Raw distribution mean and SD errors with a theoretical calibration response for $z=0$.

Notice in Table 1 that above $40\mu\text{m}$ the number of snippets falling in the overs bin starts to pull the binned true mean and SD significantly below their nominal values. In Figure 6 it is the difference of apparent and true (rather than nominal) mean/SD which has been plotted since the Laserscan excludes overs from its statistics. Raw error in the distribution mean becomes significant ($\sim 0.1\mu\text{m}$) above about $20\mu\text{m}$ and at $40\mu\text{m}$ is $\sim 0.3\mu\text{m}$. The distribution raw SD errors are insignificant being less than $0.1\mu\text{m}$ across the range of SD tested. These trends are due to a combination of the asymmetry evident in Figure 3 and the long coarse tail of the lognormal fibre diameter distribution. The asymmetry causes a slight overall downward shift of the apparent diameter distribution resulting in a lowering of the mean. The downward shift in the long coarse tail of the lognormal diameter distribution evidently compensates the SD for any broadening of the distribution due to "spreading" of apparent diameter.

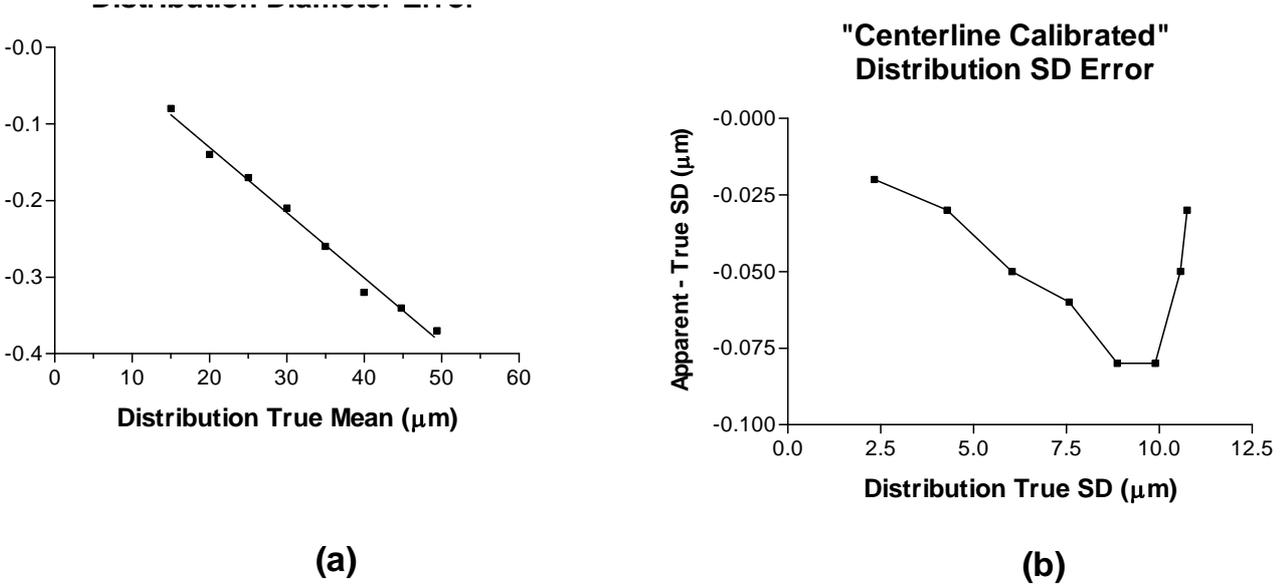


Figure 6. Raw distribution errors for a theoretical, centerline $z=0$ calibration. (a) Differences of apparent and true means, and (b) differences of apparent and true SD's.

Distribution Errors after Normal Calibration

Snippets from the Interwoollabs tops normally used for calibration are subjected to the same random effects within the cell as wools subsequently measured and consequently raw errors are to a large extent calibrated out. This effect is explored here by performing an artificial calibration from Monte Carlo generated measured or apparent diameter distributions.

Laserscan has the ability to collect data in the form of raw analog-to-digital converter (ADC) units that can later be used to test any calibration model⁷. By converting each apparent occlusion from the Monte Carlo simulation to its equivalent ADC value, histograms of ADC values for each of the IH calibration tops can be subsequently used to generate a standard Laserscan calibration. This in turn can be used to perform a validation on ADC values collected in a separate Monte Carlo simulation on validation tops.

To better utilise the full analog-to-digital converter capability the Laserscan electronics linearly transforms the measured occlusion O_c (or signal voltage) to an equivalent baseline voltage v_b (0-10 volts) given by

$$\begin{aligned}
 v_b &= -O_c / (0.1 + 1/V_0) \\
 &= 20.303O_c
 \end{aligned}
 \tag{4}$$

where the standard nominal unoccluded detector voltage, $V_0 = -6.7$ volts, has been used. For a 12 bit analog-to-digital (A/D) converter spanning an input voltage range of -10 to $+10$ volts the ADC value (ADV) for any given baseline voltage is

$$ADV = (v_b + 10) 4096/20 - 2048 .
 \tag{5}$$

A full-scale baseline voltage $v_b = 10$ volts gives an ADV reading of 2048 corresponding to full-scale occlusion of 49.3% and maximum measurable diameter of about 94 μm. For any given occlusion, and hence baseline voltage, the ADV from equation (5) must be converted to an integer using the normal transform rules for A/D converters⁸.

The calibrated errors, using Monte Carlo generated apparent ADC distributions, are investigated as follows:

- (i) Using the PM assigned mean/SD of each Interwoollabs IH12 series top in turn, generate a true snippet diameter randomly from a lognormal distribution representing each calibration top.
- (ii) Generate a snippet orientation θ randomly from a rectangular distribution.
- (iii) Generate a snippet position z in the range $-z_{\max} \leq z \leq z_{\max}$ randomly from a rectangular distribution.
- (iv) The forerunner to the data shown in Figure 3 is of the form $O_{c,\text{apparent}} = f(d_{\text{true}}, z)$ and is interpolated in two dimensions to arrive at an apparent occlusion for each “measured” snippet.
- (v) Each apparent occlusion is used to generate an *ADV* integer using equation (4) and (5) and thus the ADC file is accumulated, with 20000 snippets randomly generated for each IH12 calibration top.
- (vi) A similar process (i)-(v) is carried out in turn for each top from the Interwoollabs IH11 series and the ADC files accumulated are later used for validation.
- (vii) The ADC file from each IH12 calibration top is used to generate a linear file on the 0-80 μm range, this being the initial step in a normal Laserscan calibration.
- (viii) The standard “means calibration” technique is applied to the eight IH12 linear files using the currently implemented rational function model⁷.
- (ix) The ADC files from each of the eight IH11 validation tops is applied to the calibration file generated in (viii) to determine a measured mean/SD for each validation top.

The result of carrying out the above procedure using IH12 for calibration and IH11 for validation is shown in Figure 7 below.

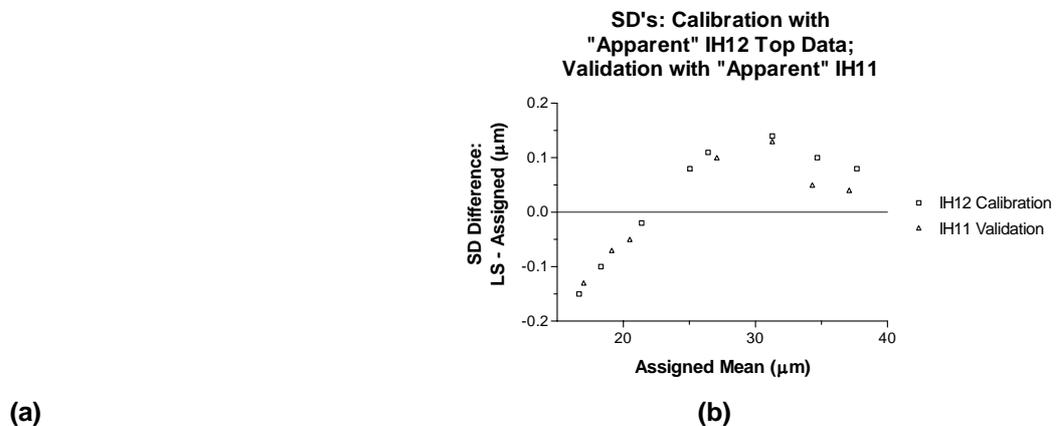


Figure 7. Distribution errors after calibration with IH12 and validation with IH11 series tops. (a) Differences of “measured” and assigned means, and (b) differences of “measured” and assigned SD’s.

The plotted differences shown in Figure 7 indicate that, after calibration, errors in the distribution means due to axial position effects are less than 0.1 μm across the range of diameter tested. Although errors in the SD’s appear a little higher peaking at $\pm 0.15\mu\text{m}$ the average error is about 0.03 μm and the overall impact of axial position effects is still small.

FURTHER DISCUSSION

Figure 7 indicates that both the IH12 calibration tops and IH11 validation tops show similar systematic trends in the differences of both means and SD's. These systematic trends are evidently due to differences in shape between the theoretical response (at $z=0$) and the rational function model⁷ used in the calibration process. This is illustrated in Figure 8, which shows the two curves for direct comparison, as well as plots of the differences in particular over the mean diameter range of the IH tops. Although there is a similar shape visible in Figure 8(b) to Figure 7(a) vertical shifting of the differences occurs during the means calibration process in order to minimise the overall difference in means.

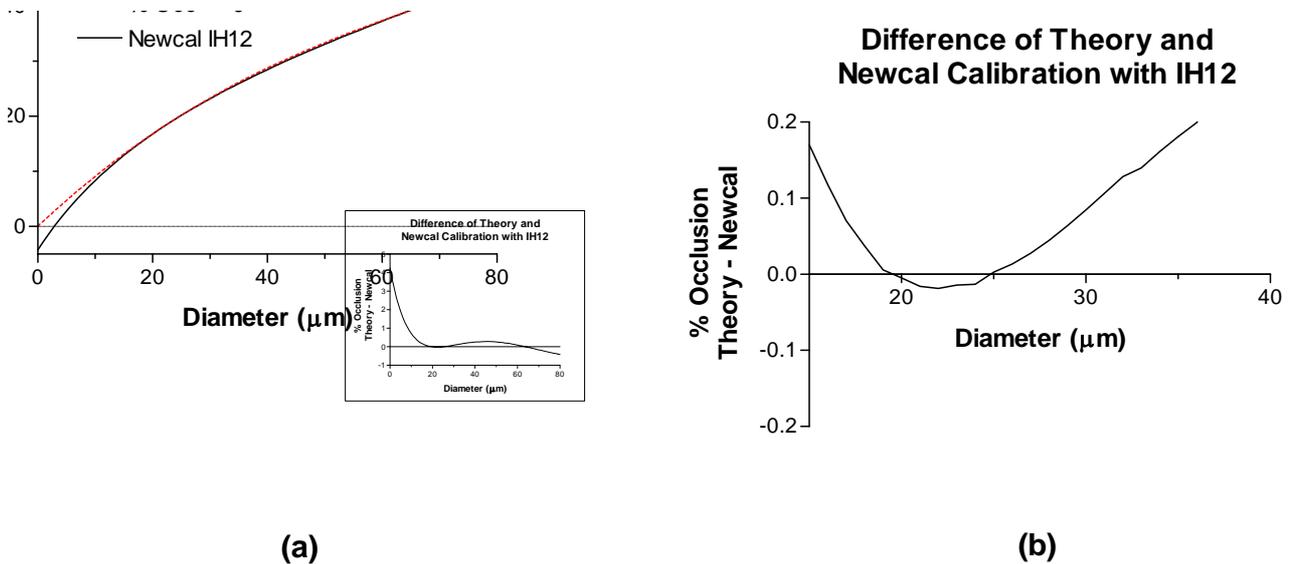


Figure 8. Comparison of standard Laserscan Newcal rational function calibration shape and theoretical response. (a) Direct curve comparison with full range inset of differences, and (b) differences over mean diameter range of IH tops.

Irvine and Barry⁷ have noted that Laserscan calibration models which cut the diameter axis at a few microns appear to give better agreement with assigned IH diameters than models that go through the origin. Although there may be a breakdown of Laserscan diffraction models as the fibre diameter approaches the wavelength of the laser ($0.633\mu\text{m}$) simple physical arguments suggest that the “true” calibration curve must intersect the origin. This discrepancy may be due to inaccuracies in assigned IH diameters at the fine end and is consistent with overestimation of snippet diameters because of projection microscope diffraction limits. This apparent paradox at the origin requires further investigation in an attempt to resolve the inconsistency.

CONCLUSIONS

The raw effect of wool fibre snippet position within the Laserscan measurement cell and also its effect on calibrated diameter distribution measurements has been investigated. Using Monte Carlo techniques in conjunction with a Fresnel diffraction model of the optical system raw effects are found to cause a downward shift on distribution mean fibre diameter while standard deviations are essentially unaffected. Although raw effects are found to be significant for mean fibre diameters greater than about 20 μm , calibration of the instrument reduces mean errors to an insignificant level. Calibrated SD errors are found to be slightly larger than for the means peaking at around $\pm 0.15\mu\text{m}$.

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