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Report No.14

The Effect of Between Fibre Coefficient of Variation on the Fibre Fineness Measured by the Airflow

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SUMMARY

The theory of the Airflow instrument is based on the theory of fluid flow through porous beds. This theory predicts that in conditions where the mean hydraulic radius of the pore space within the bed is constant, but the distribution in the mean hydraulic radii of individual pores varies, then the fluid flow will also vary, all else remaining equal. In developing the Airflow instrument for the estimation of the mean fibre diameter of wool, Anderson and Warburton, demonstrated that theoretically the Airflow instrument is sensitive to variation in estimated diameter for samples that had the same projection microscope mean diameter, but different coefficients of variation in diameter. This theory is widely accepted, and is widely cited by various researchers. However there are no reports of experimental verification of this effect for the Airflow instrument. The development of the theory is described and an experiment has been conducted that confirms the theoretical predictions of the effect of Coefficient of Variation on the estimates of fineness obtained by the Airflow instrument.

INTRODUCTION

The following review of the theoretical principles behind measurement of mean fibre diameter by the Airflow method provides the basis for the belief that the Coefficient of Variation of fibre diameter influences the Airflow.

The theory underlying the physics of the flow of air through porous beds of fibres is founded on the work of a French Mathematician in 1840. Poiseuille's Law describes the relationships governing the flow of fluids though capillaries.

$$u = \frac{d_e^2}{32h} \cdot \frac{\Delta P g}{L_c} \tag{1}$$

where

$u =$ the face velocity
$d_e =$ the diameter of a circular capillary
$h =$ the viscosity of the fluid
$\Delta P =$ the pressure difference along the capillary
$g =$ acceleration due to gravity
$L_c =$ the length of the capillary.

Much of the later developments have rested on the assumption that the flow of fluid through porous beds is analogous to the flow of fluid through a network of capillaries.

Darcy[1] (1856) derived an empirical relationship to describe the flow of water through sand filter beds.

$$u = K\frac{\Delta P}{L_c} \quad (2)$$

where in this case $K =$ a constant

$L_c =$ the depth of the bed,

$u =$ the face velocity

$\Delta P =$ the pressure difference across the bed

The first extension of Darcy's relatively simple model was by Dupuit (1863). Dupuit realised that the face velocity, u, must be less than the actual velocity in the pores. If the pore space in the bed is evenly distributed, then the porosity of a layer of infinitesimal thickness normal to the direction of flow must be equal to the porosity e of the bed as a whole. For such a layer, the fractional free volume must be equal to the fraction free area, and the pore velocity must therefore be u/e. He expressed this mathematically as follows:

$$u = e \cdot K_1 \cdot \frac{\Delta P}{L_c} \quad (3)$$

where

$$e = \frac{V_c - V_m}{V_c} \quad (4)$$

$V_c =$ the volume of the bed

$V_m =$ the volume of the bed material

Greenhill[2] (1881), developed a theorem that described the flow of viscous fluids through pipes or channels. He demonstrated that the flow of fluid through a linear channel of defined length and cross-section can be described by complex hydrodynamic equations. The essence of his theorem is the conclusion that the solutions to these complex equations, when expressed as a ratio of the volume of the channel to the area exposed to the fluid **do not depend critically on the shape of the channel**. He demonstrated that:

$$u = \frac{f}{h} \cdot \left(-\frac{dP}{dr}\right) \cdot \left(\frac{V}{S}\right)^2 \quad (5)$$

where $f =$ a surface shape factor

$\frac{dP}{dr} =$ rate of change of pressure with the direction of flow

$V =$ volume of the channel

$S =$ surface area of the channel per unit volume of fluid.

Blake[3] (1922) and Kozeny[4] (1927) used Darcy's law and Greenhill's Theorem. They expanded on the concept of porosity introduced by Dupuit, and developed a generalised equation describing the flow of fluids through porous beds. Kozeny, in particular, assumed that a granular bed is equivalent to a group of parallel, similar channels, such that the total internal surface and the total internal volume are equal to the particle surface and the pore volume respectively. Kozeny assumed:

$$m = \frac{\text{area normal to flow}}{\text{perimeter presented to fluid}} = \frac{e}{S} \quad (6)$$

where $m =$ the mean hydraulic radius*

* For a circular pipe, $m = diameter/4$

The general equation that Kozeny formulated takes the form:

$$u = \frac{e^3}{khS^2} \cdot \frac{\Delta Pg}{L_c} \tag{7}$$

where

$$S = \frac{6(1-e)}{fd_e} \tag{8}$$

$k =$ the Kozeny Constant

$d_e =$ the effective diameter of the particles.

All the other terms in equation 7 have been previously defined. For a bed of spheres, equation 8 takes the form:

$$S = \frac{6(1-e)}{d_e} \tag{9}$$

The shape factor, f, is a correction for particles that are non-spherical, and is usually experimentally determined. This term is a surface related factor, which is unity for spherical particles, and since a sphere has a minimum specific surface, the value of f must be less than unity for all other non-spherical particles. The effective diameter, d_e, is the diameter of a sphere with the same surface area.

The extension Kozeny made to Greenhill's theorem was to recognise the equivalence between the surface area of the channel per unit volume of fluid and the surface area of the particles in a porous bed to the volume of the bed. The term S is equal to the surface area of the particles per unit volume of the bed.

Carmen[5] (1937) also recognised that the effective bed depth is greater than the actual depth. Carmen theorised, and demonstrated experimentally, that the Kozeny Constant could be replaced by a more exact expression such that the Kozeny Equation becomes

$$u = \frac{e^3}{k_0 hS^2} \cdot \frac{\Delta Pg}{L_c} \tag{10}$$

where

$$k_o = k \cdot \left(\frac{L_c}{L_e} \right)^2 \tag{11}$$

$L_e =$ the effective path length.

He observed that in packed beds of glass spheres the fluid tended to flow diagonally across the bed and suggested that as an approximation:

$$L_e = L_c \sqrt{2} \tag{12}$$

The literature on the study of beds of particles and powders report values for the Kozeny constant (k) in the range 5.0 - 6.5. However experiments where the effective path length is taken into account report values of approximately 2.5 for the modified constant k_o.

Carmen[6] (1938), while applying the Kozeny equation to the study of the surface area of very fine powders, recognised that the value of S, the surface area per unit volume of the bed, is very difficult to determine experimentally. It requires knowledge of the size, shape, volume and packing of the particles. If the size and shape of the particles are constant, then:

$$S = (1-e)S_0 \tag{13}$$

where the **Specific Surface**[†]

$$S_o = \frac{A_m}{V_m} \tag{14}$$

$A_m =$ surface area of the particles

$V_m =$ volume of the particles

[†] This is a different definition to that commonly used in the textile industry, where specific surface is defined as area per unit mass

By assuming specific dimensional characteristics of a porous bed, it is relatively straight forward to derive the more familiar general expression of the Kozeny equation from equation 7 or equation 10.

The flow of fluid through a porous bed is a function of the face velocity and the cross-sectional area of the bed. Therefore

$$Q = uA_c \tag{15}$$

Substituting equations 13, 14 and 15 into equation 7 gives the following general expression.

$$Q = \frac{1}{k} \cdot \frac{\Delta PgA_c}{hL_c} \cdot \frac{e^3}{(1-e)^2} \cdot \left(\frac{V_m}{A_m}\right)^2 \tag{16}$$

Cassie[7] (1942) was the first to investigate the application of the Kozeny equation to the determination of the mean fibre diameter of wool, and it is from his original work that the Airflow system has developed into an IWTO Standard Test Method. The principle of the Airflow instrument is based on the observation that plugs of wool fibres behave in much the same way as porous beds of powders, and that the flow of air through a plug of wool can be described by equation 16.

Cassie assumed that the fibres in the plug were circular in cross-section, and hence the surface area per unit mass could then be defined in terms of the mean diameter. Neglecting the areas at the end of the fibres the surface area then becomes $pd\ell$ where ℓ is the length, and the volume is $pd^2\ell/4$; or

$$S = \frac{4p}{p} \cdot \frac{d\ell}{d^2\ell} = \frac{4}{d} \tag{17}$$

Hence it follows that

$$Q = K_b \cdot \frac{A_c}{L_c} \cdot \frac{e^3}{(1-e)^2} \cdot \Delta P \cdot d^2 \tag{18}$$

Anderson and Warburton[8] (1949) examined the relationship between fineness estimates derived from projection microscope measurements and fineness determined by the Airflow technique. They pointed out that the fibre fineness of wool is variable between fibres and along fibres, and accordingly the approximation of **uniform** circularity implied by equation 20, is too simplistic. More rigorously:

$$S = \frac{\int 4pd \, \P\ell}{\int pd^2 \, \P\ell} \tag{19}$$

where the integrals are then over the total length of the fibre in the plug. It can be shown that

$$S = 4 \cdot \frac{\bar{d}}{\overline{d^2}}$$

where $\bar{d}$ is the length proportioned mean diameter as determined by the projection microscope (note that this still assumes circularity of cross-section) and $\overline{d^2}$ is the similarly proportioned mean square diameter. Anderson and Warburton then demonstrated the familiar relationship:

$$d = \bar{d}\left(1 + C^2\right) \tag{20}$$

where $C =$ the fractional Coefficient of Variation in $\bar{d}$

Roberts[9] (1959) proposed that a correction for the effects of Coefficient of Variation on fineness measurements by Airflow should be made. Assume a calibration top has a mean diameter d_o and a Coefficient of Variation C_o, determined by the projection microscope. From equation 20 the Airflow diameter, d_a, of this top will be:

$$d_a = \bar{d}_o \cdot \left(1 + C_o^2\right)$$

If another top is measured which has a projection microscope value of $\bar{d}_1$, a Coefficient of Variation C_1 and the same Airflow diameter d_a, then, according to Roberts, the equivalent projection microscope value of this second top will be obtained as follows:

$$\bar{d}_1 = \bar{d}_o \cdot \frac{1+C_o^2}{1+C_1^2} \tag{21}$$

In simple terms, if the mean Airflow fibre diameter of the two tops are the same and their Coefficients of Variation are different, then the mean fibre diameter as measured by the Projection Microscope may be different.

The mechanism for the effect of Coefficient of Variation can only be an increase in the effective porosity of the fibre plug. Carmen (1937) produced a mathematical proof of the following proposition:

> ***"Flow is greater through parallel channels unequal in size than through channels of even size, with the same internal volume and internal surface, that is, with the same average mean hydraulic radius".***

Consider one large circular pipe, diameter, d, and n smaller pipes, diameter rd with $r<1$. Then Poiseuille's law gives the total flow through the pipes, at constant pressure drop,

$$Q = K\left(d^4 + nr^4 d^4\right) = Kd^2\left(1+nr^4\right)$$

where $K =$ a constant.

Consider a series of circular pipes, all of the same diameter, d_1, and with the same aggregate values for the internal volume and the internal surface.

Then $$d_1 = \frac{d^2 + nr^2 d^2}{d + nrd} = d\left(\frac{1+nr^2}{1+nr}\right)$$

and the number of tubes, $m = \dfrac{d+nrd}{d_1} = \dfrac{(1+nr)^2}{1+nr^2}$

whence the total flow through the tubes, Q_1 is given by:

$$Q_1 = Kmd_1^2 = Kd^4 \cdot \frac{\left(1+nr^2\right)^3}{(1+nr)^2}$$

It follows that in the ratio $$\frac{Q_1}{Q} = \frac{\left(1+nr^2\right)^3}{(1+nr)^2\left(1+nr^4\right)}$$

Q_1 is greater than Q if $$\left(1+nr^2\right)^3 > (1+nr)^2\left(1+nr^4\right)$$

that is, $$3r + 3nr^2 > 2 + nr + r^3 + 2nr^4$$

that is, $$n\left(3r^3 - r - 2r^4\right) > \left(2 + r^3 - 3r\right)$$

But this is impossible because n is positive and $0<r<1$, so the right hand side of the inequality is always positive and the left hand always negative. It may be concluded, therefore, that Q_1 is always less than Q

Andrews and Irvine[10] (1972), in a report on the relationship between projection microscope and Airflow, observed "*for some tops the degree of agreement is surprising, in view of the atypical values obtained for their coefficients of variation in diameter*". Baird, Barry and Marler[11] (1993) reported contradictory effects when they attempted to explain consistent small differences between Laserscan and Airflow measurements by correcting the Airflow measurement for Coefficient of Variation as proposed by Roberts (1959). Again Baird, Marler and Barry[12] (1994), after an extensive investigation of these differences concluded "*the standard deviation of the test specimen relative to the standard deviation of the calibrating material might give rise to the observed discrepancies between Laserscan and Airflow.*" Edmunds[13] (1993), suggested on the basis of the theory, that "*significant uncertainty arises in deriving the true value of the mean fibre diameter from Airflow measurements. This has important consequences for the new measurement methods such as LASERSCAN and OFDA with regard to their calibration and* *comparison against Airflow values.*[‡]"

Although a seemingly trivial exercise, it was considered that it is timely that the theoretical predictions of the effect of Coefficient of Variation on the mean fibre fineness of wool determined by Airflow should be verified experimentally.

METHODS AND MATERIALS

By assuming a circular cross section for the wool fibre, constant density and by defining the mean diameter of a lot of wool as a length proportioned mean, Fell, Andrews and James[14] (1972) developed the mathematical formulae that are used today to combine measurements on individual lots. These formulae are defined in IWTO-31.

The formula for the mean diameter of a consignment where the diameter is estimated by Airflow is as follows:

$$D = \frac{MB}{\sum_{i=1}^{q} \frac{M_i B_i}{D_i}} \qquad (22)$$

For consignments where the Coefficient of Variation of the mean diameter of the individual lots is known then:

$$D = \frac{\sum_{i=1}^{q} \left(\frac{M_i B_i}{D_i (1 + C_i^2)} \right)}{\sum_{i=1}^{q} \frac{M_i B_i}{D_i^2 \left(1 + C_i^2\right)}} \qquad (23)$$

The Coefficient of Variation for the consignment can be calculated from:

$$C = \left[\frac{\sum_{i=1}^{q} M_i B_i}{D^2 \sum_{i=1}^{q} \left(\frac{M_i B_i}{D_i^2 \left(1 + C_i^2\right)} \right)} - 1 \right]^{1/2} \qquad (24)$$

In these equations:

D	= mean diameter
B	= wool base
M	= nett mass
C	= Coefficient of Variation in diameter
i	= a subscript to identify each component lot
q	= the total number of lots to be combined

Fell, Andrews and James actually derived equation 23. Equation 22 is a special case, where it is assumed that the difference in mean diameter of the components is small and the coefficients of variation are similar.

[‡] Edmunds did not provide a definition of the "true" diameter of wool. This is subject in its own right.

For two components, of constant wool base, it is a simple task to show from equation 23 that:

$$\frac{M_1}{M_2} = -\left(\frac{D-D_2}{D-D_1}\right)\cdot\left(\frac{1+C_1^2}{1+C_2^2}\right)\cdot\frac{D_1^2}{D_2^2} \tag{25}$$

From equation 25 it is possible to construct blends of two samples of wool, which will have the same mean diameter as determined by the projection microscope, but distinctly different coefficients of variation.

In this experiment the mean diameter selected was 25 micrometres. The range in diameter in the Interwoollab tops primarily determined this selection. To construct sufficient blends with a sufficiently wide range of Coefficient of Variation, a diameter towards the centre of the range was required.

The value of the left hand term in equation 25 was calculated for a number of combinations of the tops. A set of seven combinations, which gave a Coefficient of Variation ranging from 27% to 47%, was selected. Duplicate blends of 25 grams samples were then prepared for each of the selected combinations, by first conditioning the tops in a standard atmosphere, and then weighing the calculated proportions very precisely.

The blends were then passed 6 times through a Shirley analyser to blend the components as completely as possible. The reject from the analyser was repassed each time with the sample bulk. The blending proved to be quite difficult, particularly where the diameters of the components were markedly different.

The duplicates of each blended sample were split into two subsamples. From these subsamples four 2.500 gram plugs were prepared. The four plugs from one subsample were measured twice on one Airflow, and the four from the other subsample were measured twice on another Airflow, giving a total of 32 readings for the 16 plugs obtained for each blend. The plugs were retained and each plug was mini-cored and measured on Laserscan and OFDA, giving 16 measurements for each blend by each instrument.

The composition of the selected blends is shown in Table 1 and the specifications for the Interwoollab tops used to construct these blends are shown in Table 2.

TABLE 1: Composition of the Blends

	Blend 1	Blend2	Blend 3	Blend 4	Blend 5	Blend 6	Blend 7
Diameter of Component 1 (*mm*)	19.23	20.61	19.23	20.61	19.23	19.23	17.05
Mass of Component 1 (g)	3.7888	8.2134	6.0337	10.6509	8.1379	8.9359	6.0649
Diameter of Component 2 (*mm*)	27.09	29.42	29.42	34.14	34.14	37.40	37.40
Mass of Component 2 (g)	21.2112	16.7866	18.9663	14.3491	16.8621	16.0641	18.9351

TABLE 2: Interwoollabs Top Specifications

Top Reference	**212**	**204**	**209**	**213**	**205**	**206**	**210**	**208**
Assigned Value (*mm*)	17.05	19.23	20.61	23.43	27.09	29.42	34.14	37.4
Standard Deviation (*mm*)	3.43	3.39	4.61	5.15	6.28	7.3	9.32	8.73
Coefficient of Variation (%)	20.2	17.7	22.5	21.8	23.2	24.7	27.2	23.1

RESULTS

The results for this experiment are shown in Table 3. Figures 1, 2 and 3 are plotted from these data.

TABLE 3 : Experimental Results

		Blend 1	Blend2	Blend 3	Blend 4	Blend 5	Blend 6	Blend 7
Calculated AF MFD (*mm*)		25.51	25.80	26.08	26.68	27.26	27.96	29.00
Calculated PM MFD (*mm*)		25.00	25.00	25.00	25.00	25.00	25.00	25.00
Calculated PM CV (%)		26.57	30.07	31.09	36.36	38.62	40.63	46.47
Measured AF MFD(*mm*)	Value	***25.72***	***26.11***	***26.41***	***26.83***	***27.73***	***28.48***	***29.12***
	95% CL	0.17	0.25	0.17	0.17	0.22	0.44	0.48
Measured Laserscan MFD(*mm*)	Value	***25.29***	***25.33***	***25.54***	***24.93***	***25.74***	***25.85***	***25.58***
	95% CL	0.21	0.42	0.26	0.21	0.47	0.77	0.66
Measured OFDA MFD(*mm*)	Value	***25.64***	***25.25***	***25.38***	***24.73***	***25.04***	***25.29***	***24.95***
	95% CL	0.20	0.38	0.21	0.32	0.27	0.68	0.66
Measured Laserscan CV (%)	Value	***26.47***	***29.87***	***30.73***	***36.63***	***38.15***	***40.39***	***45.52***
	95% CL	0.29	0.34	0.30	0.43	0.47	0.58	0.60
Measured OFDA CV (%)	Value	***27.53***	***31.21***	***32.31***	***37.58***	***39.61***	***42.36***	***49.09***
	95% CL	0.19	0.35	0.19	0.27	0.28	0.38	0.42
Difference from Calculated PM MFD (*mm*)	Airflow	0.72	1.11	1.41	1.83	2.73	3.48	4.12
	Laserscan	0.29	0.33	0.54	-0.07	0.74	0.85	0.96
	OFDA	0.64	0.24	0.38	-0.27	0.04	0.29	-0.05
Difference from Calculated PM CV (%)	Laserscan	-0.10	-0.20	-0.37	0.27	-0.46	-0.24	-0.95
	OFDA	0.96	1.14	1.21	1.21	0.99	1.73	2.62
Difference from Calculated Airflow MFD (*mm*)	Airflow	0.21	0.31	0.32	0.15	0.47	0.52	0.12

The values for the calculated Projection Microscope mean fibre diameter and Coefficient of Variation in Table 1 are calculated from equations 23 and 24.

Figure 1 plots the measured and calculated values for the Airflow means as a function of the Coefficient of Variation calculated from equation 24 (Calculated Projection Microscope Coefficient of Variation). The calculated Airflow mean diameters are based on equation 22. The measured Airflow mean diameters are consistently higher but the trend is the same and, given the nature of the blends, the agreement is good. A higher measured value is to be expected due to possible losses of fine fibre in the Shirley analyser.

FIGURE 1: Measured and Predicted Diameters for the Airflow

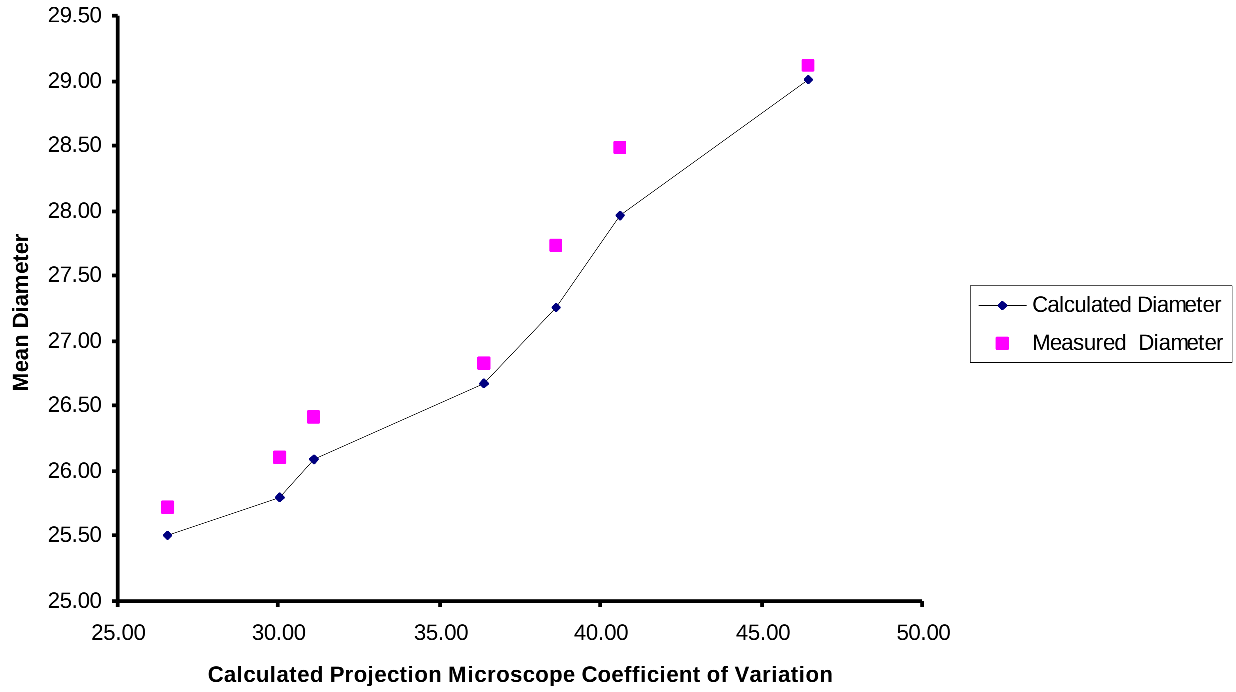


FIGURE 2: Comparison of Airflow, Laserscan and OFDA

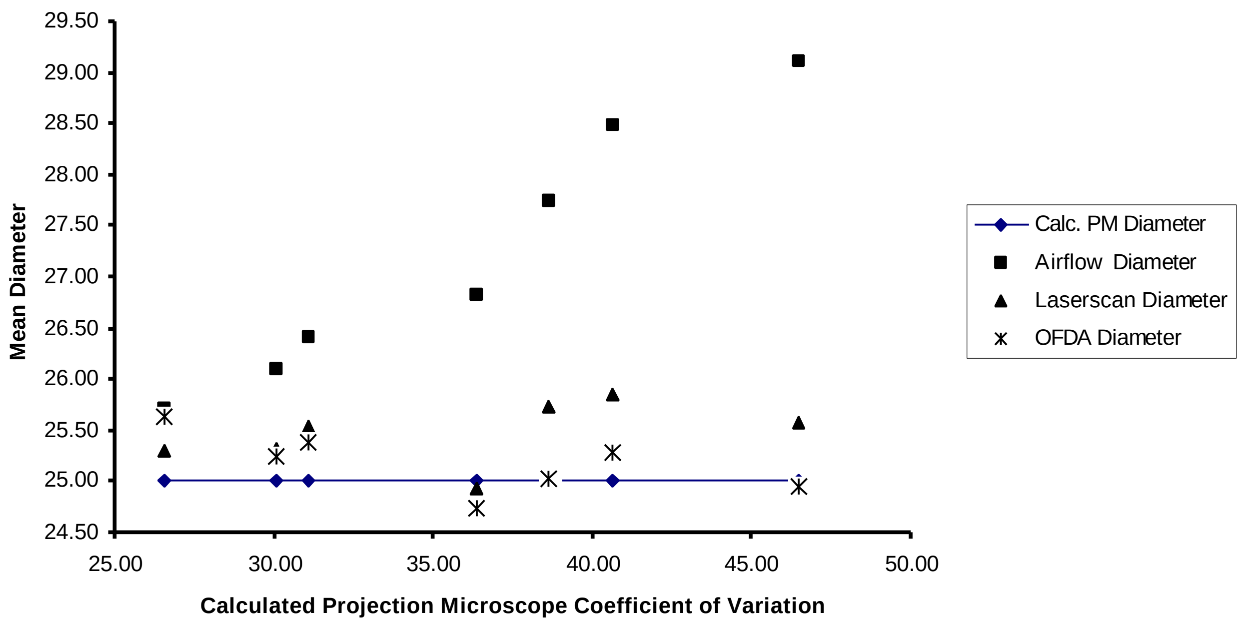


Figure 2 shows the measured mean fibre diameter for Airflow, Laserscan and OFDA as a function of predicted Coefficient of Variation. The OFDA and Laserscan results, as would be expected, are much closer to the PM result, with OFDA being closer to the PM mean than Laserscan.

Figure 3 shows the differences of the Laserscan and OFDA measured coefficients of variation from the predicted results. The OFDA results are higher that Laserscan and further from the predicted values.

FIGURE 3: Comparison of CV determined by Laserscan and OFDA

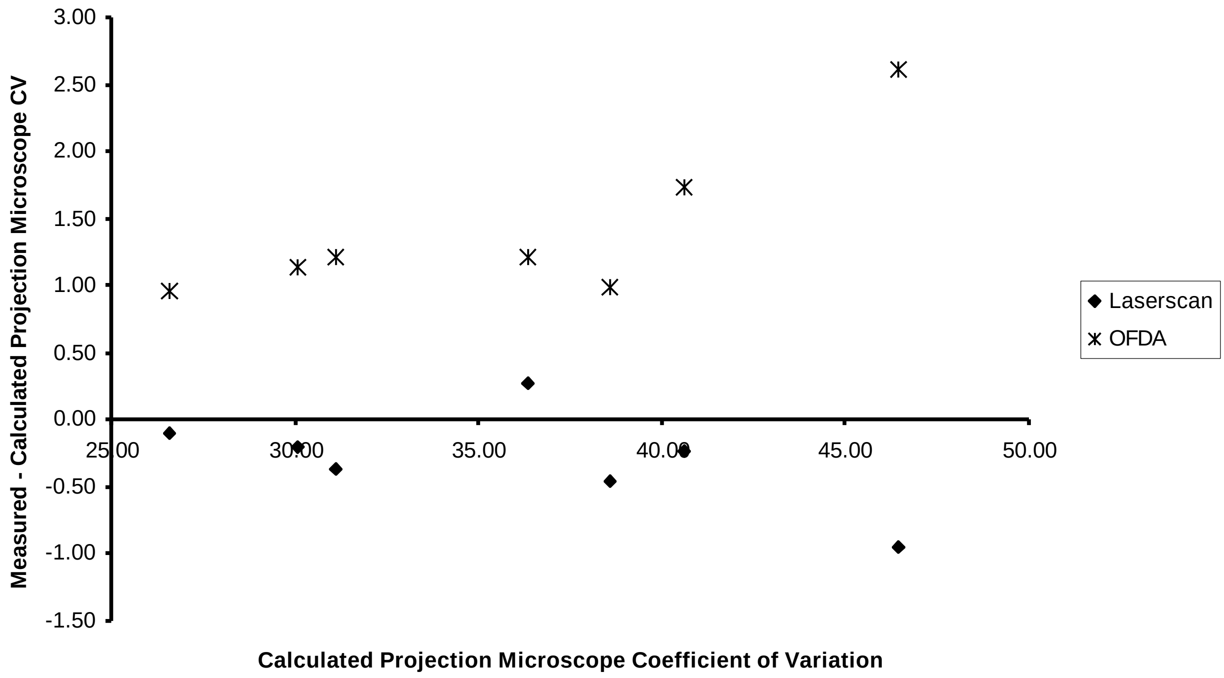
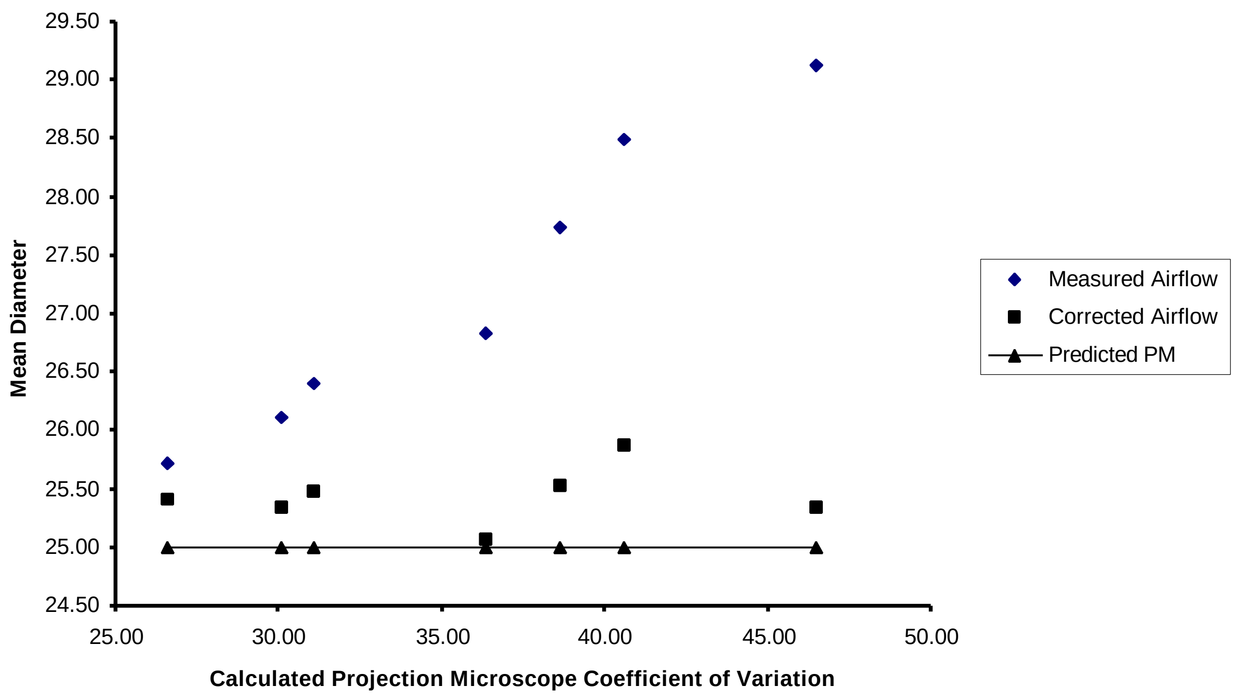


Table 4 shows the results of correcting the measured Airflow values using the predicted values for Coefficient of Variation as recommended by Roberts[9] (equation 21). The statistical regression provided by Baird, Barry and Marler[11] (1993) was used to estimate the Coefficient of Variation for a "theoretical" 25 micrometre Interwoollab Series 10 top (24%). These data are plotted in Figure 4, where Coefficient of Variation is again the independent variable. Although there is some variation, the correction reduces the Airflow mean fibre diameter values so they are much closer to the calculated Projection Microscope mean fibre diameter values.

TABLE 4 : Effect of Correcting the Airflow Measurements for CV effects

	Blend 1	Blend2	Blend 3	Blend 4	Blend 5	Blend 6	Blend 7
Measured Airflow MFD (mm)	25.72	26.11	26.41	26.83	27.73	28.48	29.12
Corrected Airflow MFD (mm)	25.41	25.32	25.47	25.06	25.53	25.85	25.33
Calculated PM MFD (mm)	25.00	25.00	25.00	25.00	25.00	25.00	25.00

FIGURE 4: Effect of Correcting the Measured Airflow diameters for CV Effects



DISCUSSION

The results of this experiment have produced effects consistent with the theory. The differences between the experimental data and the predicted values for these data are partly due to the difficulty in uniformly blending the mixtures (shown in Table 1). It has been reported that the Shirley actually separates the coarse and fine fibres, and a loss of some of the fine fibres was expected. Certainly the measurements on the individual plugs indicated that the two components in each blend were not uniformly mixed.

The possibility that loss of fine fibre had occurred during preparation was tested by assuming that the Laserscan measurement reflected the “true” Projection Microscope measurement for these blends. The same assumption was made for the Laserscan Coefficients of Variation. The uncorrected and the corrected Airflow measurements based on these assumptions are shown as differences from the Laserscan mean in Figure 5, where in this case the Laserscan Coefficient of Variation is used as the independent variable.

The same analysis was carried out using the OFDA measurements. The results are shown in Figure 6.

In both cases there is excellent agreement. Note that the corrected differences exhibit a little more scatter for the OFDA than for Laserscan but at the 95% level this is not significant.

These results may seem to be inconsistent, given the differences in mean fibre diameter obtained by both instruments, particularly for the high coefficients of variation (see Figure 2). However as shown in Figure 3 there are large differences in Coefficient of Variation between these instruments and in the calculations involved to produce Figures 5 and 6 these differences compensate each other.

FIGURE 5: Effect of Correcting Airflow for CV effects using Laserscan Means

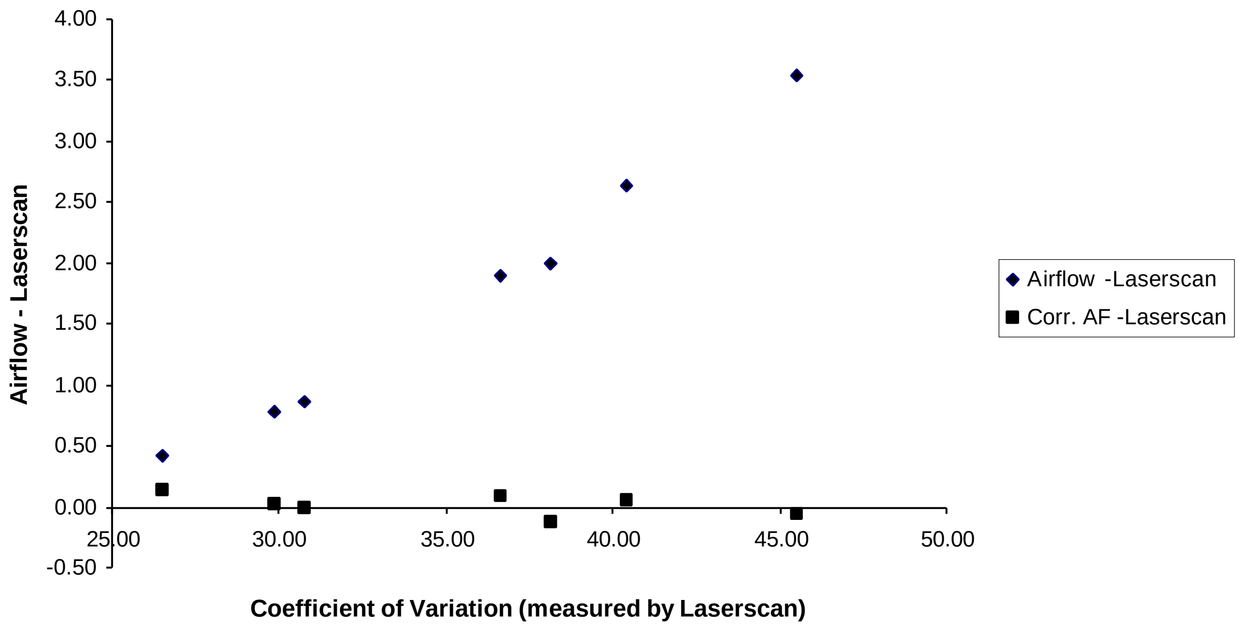
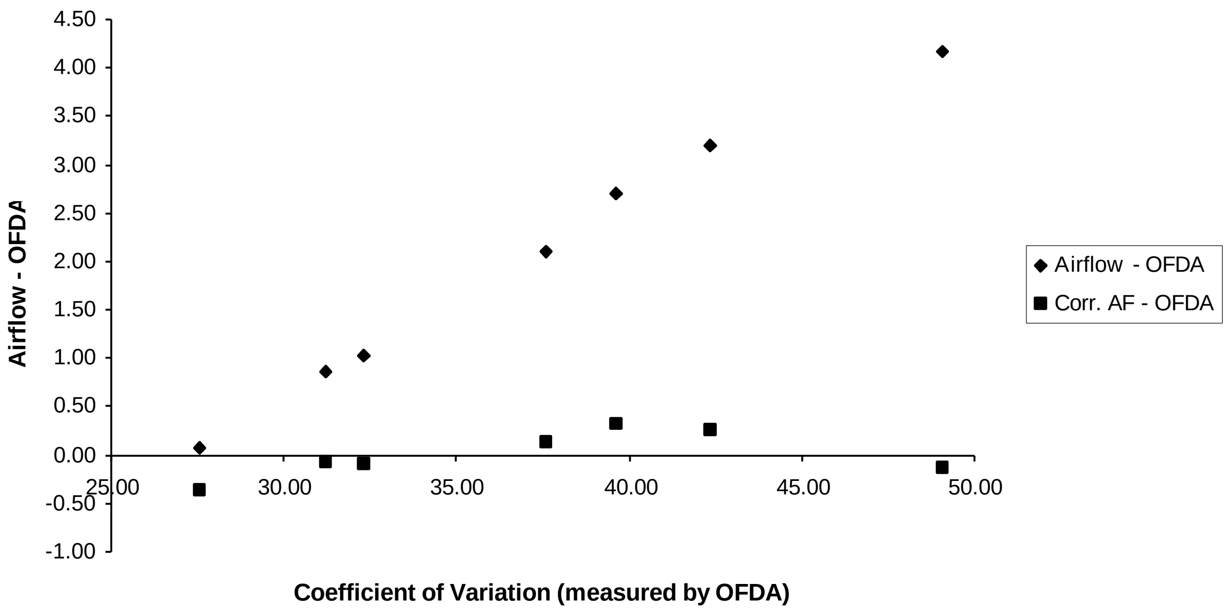


FIGURE 6: Effect of Correcting Airflow for CV effects using OFDA means



These data confirm that it is probable that a proportion of the fine fibres was lost during the blending of the samples, particularly when taken in conjunction with Figure 1. They also confirm the theory developed by Anderson and Warburton.

The data suggests that the combination formula for Airflow can be relied upon to accurately predict the diameter for blends of wools even though large differences in the Coefficient of Variation exist, provided the measurements for the combined material are also all obtained by Airflow. Comparison of Airflow and Projection Microscope measurements[§] will, in such cases, indicate differences.

[§] This applies to Laserscan and OFDA also

The range of Coefficient of Variation that was contrived in this experiment is most unlikely to occur in practice. As shown by the data, this degree of variation at a particular diameter can only be produced by mixing wools of very different diameter.

The Airflow system is probably less sensitive than predicted by the theory for small changes in Coefficient of Variation. The porosity of the compacted fibre in the instrument is relatively high (0.6 – 0.7) compared to the porosity of powders (< 0.5). There is some elasticity in the plug of wool compared to a powder. In this situation small differences in coefficient of diameter of the wool are not likely to produce the same effect that one would expect, and theory predicts, will occur in a powder.

CONCLUSION

The objective of this experiment was to validate the theoretical predictions first formulated by Anderson and Warburton (1949). The data obtained for samples with large differences in coefficient of diameter, but almost the same mean Projection Microscope diameter, is in close agreement with the predictions based on this theory. While the theory has been widely cited, it has never been experimentally verified. This experiment validates the theory.

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REFERENCES

[1] H.Darcy, Libraire des Corps Imperiaux des Ponts et Chaussees et des Mines, 1857, *Les Fontaines Publiques de la Ville de Dijon*

[2] A. G Greenhill, Proc. London Math. Soc., **13**, 43-46, 1881, *On the Flow of Viscous Liquid in a Pipe or Channel*

[3] , F. C Blake Trans. Amer. Soc. Chem. Engrs, **14**, 415-421, 1922, *The Resistance of Packing to Fluid Flow*

[4] J Kozeny, Sitzungsber. Akad. Wiss., Vienna, Abs. IIIa, **136**, 276-306, 1927, *Uber kapillare Leitung des Wassers im Boden,* Wasserkraft Wasserwirtschaft, **22**(5) , 67-70, 1927, *Uber Grundwasserbewegung*

[5] P. C. Carman, Trans. Inst. Chem. Eng., **15**, 150-166, 1937, *Fluid Flow through Granular Beds*

[6] P. C. Carman, J. Soc. Chem. Ind., **57**, 225-234, 1938, *The Determination of the Specific Surface of Powders.*

[7] A. B. D Cassie, J. Text. Inst. (Trans), 23, T195-T204, 1942, *The Porous Plug and Fibre Diameter Measurement. A Practical Method of Wool Fibre Diameter Measurement*

[8] S.L.Anderson & F. L. Warburton, J. Text. Inst. (Trans), **40**, T749-T758, 1949, *The Porous Plug and Fibre Diameter Measurement. Effect of Fibre Orientation and use of Plugs of Randomised Fibres*

[9] N. F.Roberts, IWTO Tech. Comm., Report No. 9, June, 1959, *Remarque sur l'influence du C.V. de diamètre dans l'étalonnage d'un appareil Airflow*

[10] M. W. Andrews, & P. A. Irvine, Tech. Comm. Int. Wool Text. Org., Report No 11, Paris, December , 1972, *The Relationship Between Airflow and Projection-microscope Diameters*

[11] K.Baird, R.G. Barry, & J. W.Marler, Tech. Comm. Int. Wool Text. Org., Report No. 8, Nice, 1993, *Mean Fibre Diameter Measurement Differences Using Airflow, Projection Microscope and Sirolan-Laserscan*

[12] K.Baird, R. G. Barry, & J. W. Marler, Tech. Comm. Int. Wool Text. Org., Report No. 7, Nice, December 1994, *Comparison of Mean Fibre Diameter Measurements by Airflow and laserscan for a Wide Range of Wool Types*

[13] A. R.Edmunds, Tech. Comm. Int. Wool Text. Org., Report No. 5, Nice, November 1993, *Effects of Standard Deviation on Airflow Measurements of Mean Fibre Diamete*

[14] K. T Fell, M. W.Andrews, and J. F. P.James, J. Text. Inst., **63**(2), 125-129, 1972, *Calculating Diameters of Blends of Wool from the Diameters of the Blend Components*