THEORETICAL ANALYSIS FOR SHORT FIBER CONTENTS IN DUAL-BEARD COTTON SAMPLES

J. Jin
M. Wu
F. Wang
Donghua University
Shanghai, China
B. Xu
University of North Texas
Denton, TX

Abstract

Dual-beard is a novel type of sample for cotton fiber length measurement, which can be made via clamping a cotton sliver and combing it in the two opposite ends. Compared with HVI® beard, dual-beard can be wholly scanned to generate a grayscale image for measurement, which gives it the ability to provide more detailed length information, especially on the content of short fibers. This study introduced a theory on how to iteratively divide the dual-beard cotton sample into sub-beards to filter out short fibers from the dual-beard. Based on this theory, *Short Fiber Content* (SFC) formulae were deduced to calculate the number-based SFC in dual-beard, which is equal to the weight-based SFC in cotton bale. The results of multiple measurements on a total of eighteen cotton samples showed that the measurements by these SFC formulae had analogous, sometimes even better robustness compared with those from the Advanced Fiber Information System® (AFIS®). The measurement bias between these two methods was also proved statistically indistinctive. In contrast to costly dedicated devices, dual-beard method with these formulae can be capable of providing stable and accurate measurements of *Short Fiber Content* in an economical way.

Introduction

As a vital cause leading to obvious increases of breakage rates, yarn unevenness and yarn hairiness, short fibers are acknowledged as having a negative role in high-quality yarns manufacture and production cost reduction. Thus, measuring and controlling short fiber contents in raw cotton and semi-finished cotton sliver continues to be a big concern for the textile manufacturing industry [Cui, et al. 2011; Thibodeaux, et al. 2008]. *Short Fiber Content* (SFC) is a common parameter for quantifying the weight-based or number-based proportion of fibers shorter than a certain threshold; that is 12.7mm (0.5 inch) in the USA and 16mm in China.

Methods for testing SFC are usually applied to measure other length parameters simultaneously. A traditionally approach is the array method where fibers are manually aligned to form a baseline and divided into a range of length groups for weighting. A length-weight histogram is plotted for figuring out length parameters including weight-based SFC. During the time-consuming operation of array method, short fibers tend to bear a bigger risk to be lost than long fibers do. The High Volume Instrument® (HVI®) is an efficient device for evaluating the integrated quality of raw cotton. In HVI®, fibers are randomly grabbed by a row of needles and combed to form a tapered beard which can be scanned by a light slit to generate a fibrogram. Parameters are extracted from the fibrogram except SFC, because the fiber segments nearby the needles are too tangled to be meaningfully measured. Instead, HVI® provides Short Fiber Index (SFI) which is calculated by a prediction algorithm on the basis of some other available HVI parameters [Gibson, 1999; Knowlton, 2001]. The Advanced Fiber Information System® (AFIS®) is another widely employed instrument which separates cotton sliver into individual fibers by a built-in opener, and measures them by a photoelectric sensor, fiber by fiber. AFIS® outputs length histogram and parameters on the basis of a mass of directly measured data, which makes it becoming a prevalent SFC measuring instrument. However, many studies have testified that possible fiber breakages in the opening process may bring a bias into the measurement [Cui, et al. 2009; Krifa, M. 2008]. It is obvious that, the shorter an individual fiber is, the more difficult it can be easily felicitously controlled, arranged and identified, hence, the accurate and practical determination of SFC remains a challenge to be beaten.

As a new type of sample, dual-beard has two tapered ends in the opposite directions, and has an inherent potential for accurately testing short fibers because it effectively eliminates the fiber entanglements that severely harm the SFC measurement [Wu and Wang, 2014]. However, no usable method for calculating SFCs in dual-beard samples has been reported so far. In this paper, we present a novel theory work on how to separate short fibers from dual-beard sample and how to calculate their contents. Based on our theory, the device needed for SFC measurement is just an off-the-shelf scanner, which could be a more economical way than the aforesaid commercialized instruments.

Methods

Dual-beard Preparation

As shown in Figure 1, 0.65±0.15g raw cotton or semi-finished sliver from carding process is drawn to form a 20cm ×5cm sliver sample by a fiber drafting device which can straighten tangled fibers without breaking them. Then, the silver sample is randomly clamped by a clamp with extra narrow jaw, and the clamping line should be perpendicular to the axial direction of the sliver. After the unclamped fibers are gently combed away, an eligible dual-beard sample is ready. As there are not any coverings, no fiber is covered when tested, the dual-beard can be completely measured, which is crucial for measuring short fibers. Besides, the probability of fibers to be clamped is only concerned with their lengths, so dual-beard is perfect length-bias sample which is closer to Hertel's sampling theory than Fibrograph beard. It has been proven that the number-based length probability density function of the dual-beard sample is equal to the weight-based length probability density function of sliver sample, therefore, we can get weight-based SFC in raw cotton by calculating number-based SFC in dual-beard sample.

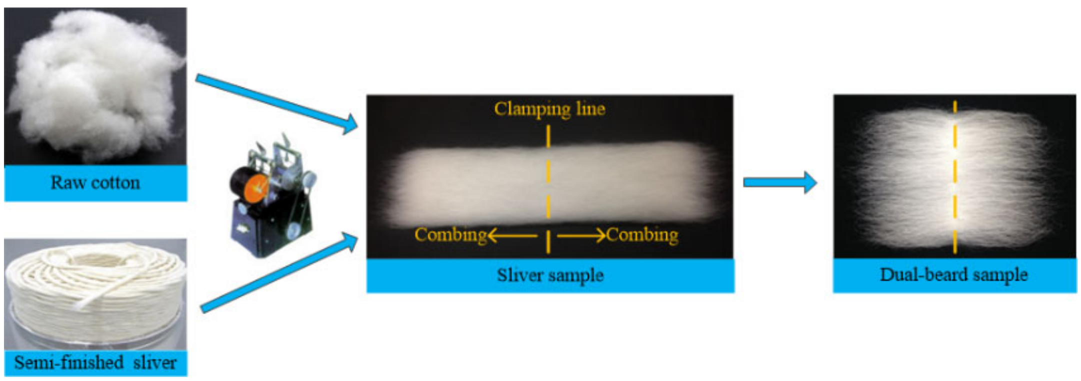


Figure 1. Dual-beard sample preparation

Image Processing

The dual-beard sample is scanned to generate a transmission grayscale image with 256 shades in a resolution of 1000ppi, as shown in Figure 2. The gray values of pixels, from 0 to 255, reflect the relative intensity of transmission light, and can be transformed into the dual-beard's areal density at each pixel by using an optical algorithm introduced in a previous paper [Wu and Wang, 2016]. Summing the areal densities of pixels in one column gives the dual-beard's linear density at the corresponding infinitesimal fragment. Normalizing the linear densities of every infinitesimal fragments as ordinate values, multiplying the columns' sequence number by 0.0254mm as abscissa values (1000 points per inch), it will yield a relative linear density (R.L.D.) curve. Further, under an assumption that individual fibers in a same sample have constant linear density, the R.L.D. curve is equivalent to the relative fiber number (R.F.N.) curve.

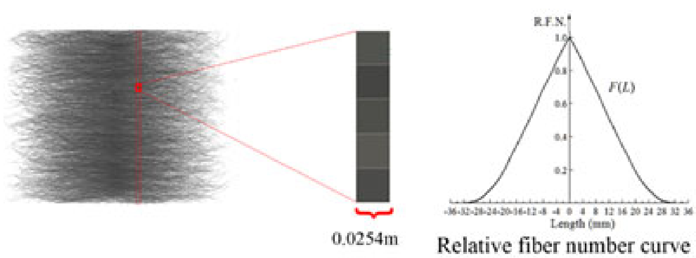


Figure 2. Principle of image processing

Separating Short Fibers

When measuring the number proportion of short fibers (SFN), the key problem is how to distinguish short fibers from others, thus we presented a method consisting of a set of fictitious operations which are extremely critical for explaining the calculation principle.

The first step of operation is shown by Figure 3(a), where α is the length threshold of short fibers. Imaginarily, clamping the original dual-beard at $L=\frac{1}{2}\alpha$, moving the hold fibers (Beard 1) away without influencing others, then clamping the remainder dual-beard at $L=-\frac{1}{2}\alpha$, moving the hold fibers (Beard 2) again. Now the fibers left (Beard 3) are definitely shorter than α, however, Beards 1 and 2 still include short fibers and need further separations.

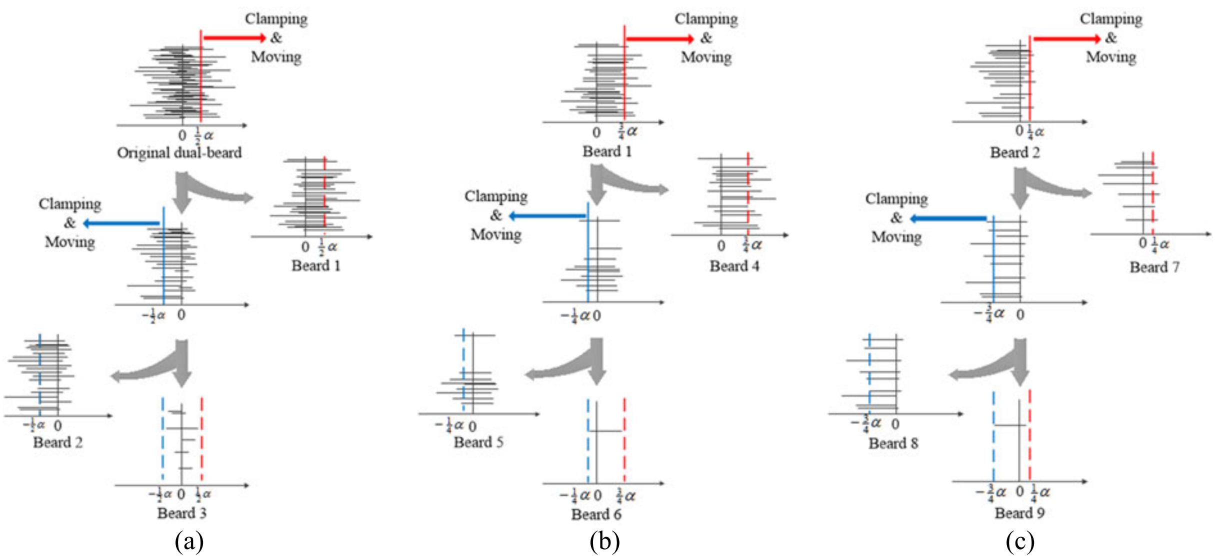


Figure 3. Diagram of separating short fibers

In the second step, as shown in Figures 3(b) and 3(c), imaginarily clamping Beard 1 at $L=\frac{3}{4}\alpha$ and $L=-\frac{1}{4}\alpha$ successively, moving away the clamped fibers to generate Beards 4 and 5 with Beard 6 left. Beard 2 is successively clamped at $L=\frac{1}{4}\alpha$ and $L=-\frac{3}{4}\alpha$, divided into three parts including one completely consisting of short fibers (Beard 9). Fibers in Beards 4, 5, 7 and 8 are all longer than $\frac{3}{4}\alpha$, so there is still a need for separating the fibers shorter than α. Note that the distance between the two virtual clamping lines when dividing beards should be α, to ensure the remainder fibers are all short fibers.

The tree diagram of Figure 4 describes the iterative separation process, during which the aggregate number of fibers in Beards 3, 6, 9, $\cdots$ gets closer and closer to the real number of short fibers in the original dual-beard, until the difference can be ignored. In this paper, SFN is the summation of relative fiber numbers of Beards 3, 6, 9, $\cdots$.

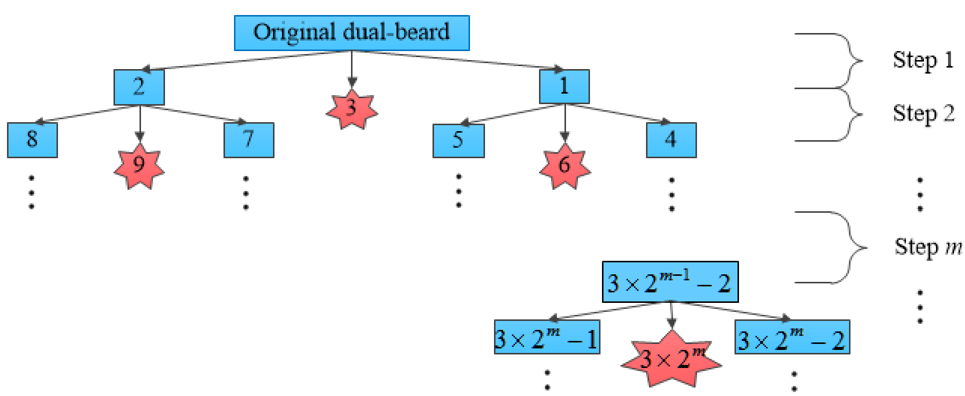


Figure 4. Tree diagram of fictitious separation

Generating Calculation Formula

To calculate the number of fibers in Beard 3, we can subtract the fiber number of Beards 1 and 2 from that of the original dual-beard. Figure 5 shows the relative fiber number (R.F.N.) curves corresponding to the first separation step. It's obvious that the R.F.N. of the original dual-beard is $F(0)$, and that of Beard 1 (red curve) is $F(\frac{1}{2}\alpha)$. The R.F.N. of Beard 2 is $F(-\frac{1}{2}\alpha)-F_1(-\frac{1}{2}\alpha)$, where $F_1(-\frac{1}{2}\alpha)$ is the R.F.N. of fibers extending beyond both $L=\frac{1}{2}\alpha$ and $L=-\frac{1}{2}\alpha$, which will be clamped at $L=\frac{1}{2}\alpha$ first to constitute Beard 1 and can't be hold into Beard 2. These fibers are represented by shadow area in Figure 5.

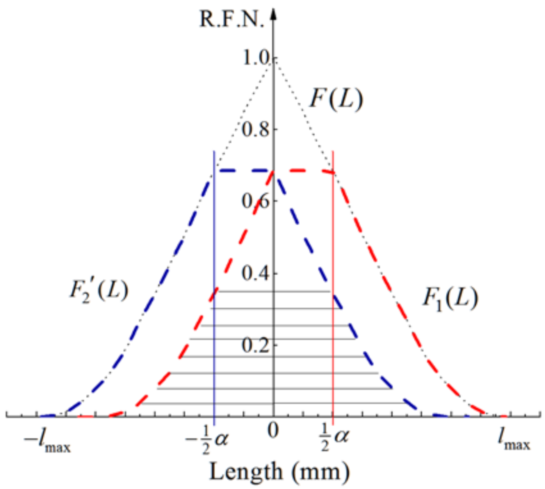


Figure 5. R.F.N. curves in separating dual-beard

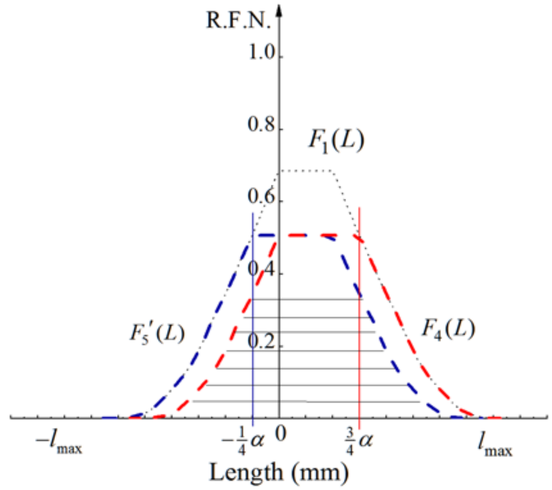


Figure 6. R.F.N. curves in separating Beard 1

Plotted by dash red curve of Figure 5, the R.F.N. function of Beard 1 can be written as:

$$F_1(L)=\begin{cases} F(L-\frac{1}{2}\alpha) & L\in[-l_{max}+\frac{1}{2}\alpha,0) \\ F(\frac{1}{2}\alpha) & L\in[0,\frac{1}{2}\alpha] \\ F(L) & L\in(\frac{1}{2}\alpha,l_{max}] \end{cases} \quad (1)$$

Combined with $F(-L)=F(L)$ and Equation 1, the relative number of fibers in Beard 3 can be figured out by

$$SFN_3=F(0)-F(\tfrac{1}{2}\alpha)-[F(-\tfrac{1}{2}\alpha)-F_1(-\tfrac{1}{2}\alpha)]=F(0)-2F(\tfrac{1}{2}\alpha)+F(\alpha) \quad (2)$$

Note that the difference between Beards 1 and 2 only involves the fibers extending beyond $L=\frac{1}{2}\alpha$ and $L=-\frac{1}{2}\alpha$ which are definitely longer than α, in other words, they have the same amount of short fibers, i.e. $SFN_1=SFN_2$. Thus, the calculation formula of SFN could be

$$SFN=SFN_1+SFN_2+SFN_3=2SFN_1+SFN_3 \quad (3)$$

Now the focus turns to how to calculate SFN_1.

The calculation of SFN_1 is analogous to the aforementioned analysis on SFN. The corresponding R.F.N. curves are plotted in Figure 6, and equations can be deduced as

$$SFN_1=SFN_4+SFN_5+SFN_6=2SFN_4+SFN_6 \quad (4)$$

$$SFN_6=F_1(\tfrac{1}{2}\alpha)-F_4(\tfrac{3}{4}\alpha)-[F_1(-\tfrac{1}{4}\alpha)-F_4(-\tfrac{1}{4}\alpha)]=F(\tfrac{1}{2}\alpha)-2F(\tfrac{3}{4}\alpha)+F(\alpha) \quad (5)$$

According to the tree diagram of Figure 4, the relative numbers of short fibers in sub-beards of the iterative separation have relations of Equations 6 and 7, where m is the sequence number of the separation step.

$$\begin{cases} SFN = 2SFN_1 + SFN_3 \\ SFN_1 = 2SFN_4 + SFN_6 \\ SFN_4 = 2SFN_{10} + SFN_{12} \\ SFN_{10} = 2SFN_{22} + SFN_{24} \\ \cdots \\ SFN_{3\times2^{m-1}-2} = 2SFN_{3\times2^m-2} + SFN_{3\times2^m} \end{cases} \quad (6)$$

$$\begin{cases} SFN_3 = F(0) - 2F(\tfrac{1}{2}\alpha) + F(\alpha) \\ SFN_6 = F(\tfrac{1}{2}\alpha) - 2F(\tfrac{3}{4}\alpha) + F(\alpha) \\ SFN_{12} = F(\tfrac{3}{4}\alpha) - 2F(\tfrac{7}{8}\alpha) + F(\alpha) \\ SFN_{24} = F(\tfrac{7}{8}\alpha) - 2F(\tfrac{15}{16}\alpha) + F(\alpha) \\ \cdots \\ SFN_{3\times2^m} = F(\tfrac{2^m-1}{2^m}\alpha) - 2F(\tfrac{2^{m+1}-1}{2^{m+1}}\alpha) + F(\alpha) \end{cases} \quad (7)$$

Merging Equations 6 and 7, it becomes

$$SFN = F(0) + (2^{m+1}-1)F(\alpha) - 2^{m+1}F(\tfrac{2^{m+1}-1}{2^{m+1}}\alpha) + 2^{m+1}SFN_{3\times2^m-2} \quad (8)$$

Actually the last term of Equation 8 represents the short fibers that have not been filtered out after the step of $m+1$, which is so little when $m \to +\infty$ that it can be ignored. If m is large enough, Equation 8 can be simplified to

$$SFN = F(0) + (2^{m+1}-1)F(\alpha) - 2^{m+1}F(\tfrac{2^{m+1}-1}{2^{m+1}}\alpha) \quad (9)$$

In the practical application, however, the factor 2^{m+1} will sharply increase when the value of m gets bigger, and the last two items of Equation 9 will become unstable because of the existence of measurement errors in R.F.N. curve. In this paper, we set $m=4$ and transform Equation 9 into

$$SFN = F(0) + 31F(\alpha) - 32F(\tfrac{31}{32}\alpha) \quad (10)$$

As the R.F.N. curve of dual-beard is theoretically symmetrical, we can apply

$$SFN = F(0) + 31F(-\alpha) - 32F(-\tfrac{31}{32}\alpha) \quad (11)$$

to provide the other SFN estimate based on the left side data of the curve, and consider the average result of Equations 10 and 11 as the final SFN, which is

$$SFN = F(0) + 15.5[F(\alpha) + F(-\alpha)] - 16[F(\tfrac{31}{32}\alpha) + F(-\tfrac{31}{32}\alpha)] \quad (12)$$

As mentioned above, the number proportion of short fibers in dual-beard sample is equal to the weight proportion of them in raw cotton, the weight-based SFCs in cotton bales or semi-finished slivers can be calculated by

$$SFC_{w12.7} = F(0) + 15.5[F(12.7) + F(-12.7)] - 16[F(12.3) + F(-12.3)] \quad (13)$$

and

$$SFC_{w16} = F(0) + 15.5[F(16) + F(-16)] - 16[F(15.5) + F(-15.5)] \quad (14)$$

respectively according to the American and the Chinese standard.

Experimental Results and Discussion

Eighteen types of cotton samples, marked as $1^\#$~$18^\#$, were tested according to the described preparation and image processing procedures, and the proportions of short fibers were calculated using Equations 13 and 14.

Repeatability of Multiple Measurements

Samples $5^\#$ and $15^\#$ were elected to test the repeatability of multiple measurements. Five results of $SFC_{w12.7}$ and SFC_{w16} were made from each sample by using our SFC formulae. Also, five tests by AFIS were conducted to be reference.

In Table 1, the difference ratio is the difference between the maximum and minimum measurements divided by the average of the five. It can be seen that the difference ratios from dual-beards are lower than those from AFIS, which means that dual-beard method using our formulae has analogous or even better robustness when measuring weight-based SFCs, compared with AFIS. The scatter of measurements is primarily contributed to the short fibers' naturally uneven distribution from one cotton boll to another and from one plant to another. That is why AFIS always uses the mean of three or five measurements as final output, moreover, it suggests the necessity of adopting the same practice in dual-beard method.

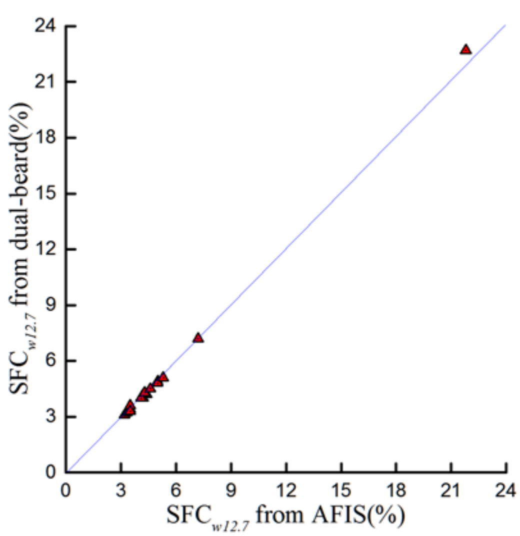
Consistency with AFIS values

Figure 7 displays the comparisons of SFC measurements by our dual-beard formulae and those by AFIS. Each data is the mean of five measurements. It can be seen that spots locate closely near the 45° lines, showing that measurement results from dual-beard formulae are almost equal to the AFIS data. For samples with unusual high SFC, the risk of determination bias increases, which reveals that more tests may be needed.

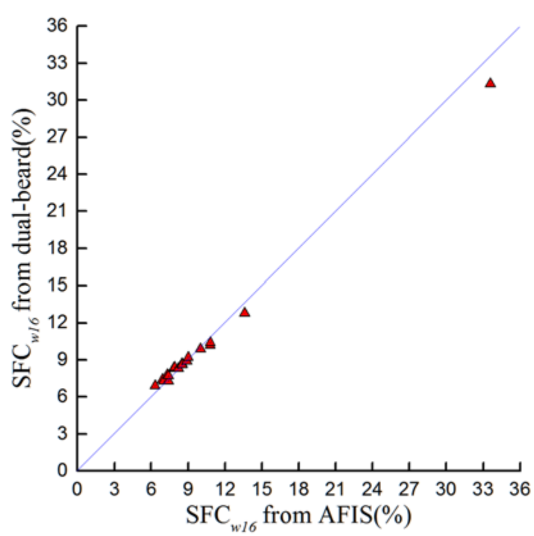
Table 1. Repeatability of multiple measurements by dual-beard method and AFIS

	$SFC_{w12.7}$ (%)				SFC_{w16} (%)			
	Sample 5#		Sample 15#		Sample 5#		Sample 15#	
	AFIS	Dual-beard	AFIS	Dual-beard	AFIS	Dual-beard	AFIS	Dual-beard
Five test values	3.7	3.8	4.8	4.7	7.5	7.6	10.6	10.4
	3.7	3.6	4.8	4.8	7.7	7.4	11.0	10.4
	3.4	3.5	5.4	4.8	7.7	7.2	10.0	10.7
	3.4	3.6	5.1	5.1	7.0	7.5	11.4	9.7
	3.5	3.5	5.0	4.7	6.9	7.0	11.2	10.0
Mean	3.5	3.6	5.0	4.8	7.4	7.3	10.8	10.2
Standard deviation	0.2	0.1	0.2	0.2	0.4	0.2	0.6	0.4
Difference ratio (%)	8.5	8.3	12	8.3	10.9	8.2	12.9	9.8

T-test was applied to test the significance of differences between SFC measurements from the two methods. When the confidence degree is 95% and the sample number is 18, $t_{1-0.05/2}(18-1)=t_{0.975}(17)=2.1098$. The T-test statistics of $SFC_{w12.7}$ and SFC_{w16} are 0.816 and 0.166, obviously smaller than 2.1098. Thus, the differences are deemed to be not significant, and it can be considered that weight-based *Short Fiber Content* measurements by our dual-beard formulae have a good agreement with those from AFIS.



(a)



(b)

Figure 7. Relationships between SFC measurements from dual-beards and AFIS

Summary

The theory on how to separate short fibers from dual-beard cotton sample and how to quantify them is the basis of the SFC calculation formulae of dual-beard method. Although this theory was presented with an aim of settling the dual-beard's SFC issue, the theoretical formulae can be applied to any number-based fibrogram conforming to Hertel's sampling principle. In this study, eighteen cotton samples were tested to examine the repeatability and trueness of SFC measurements from dual-beard method with our formulae. The measurements appeared some scatter due to the natively uneven distribution of short fibers, however, it was found that dual-beard method's SFC data were at least as repeatable as AFIS'. When averaging five measurements to be the final result, there was statistically no difference between the results from these two methods. As only a set of imaging device are needed, dual-beard method with the use of our formulae could be a cheap approach for accurately determining the *Short Fiber Content* of cotton fibers.

References

Cai, Y., X. Cui, J. Rodgers, D. Thibodeaux, V. Martin, M. Watson, and S. Pang. 2011. An investigation on different parameters used for characterizing short cotton fibers. Text. Res. J. 81: 239-246.

Cui, X., Y. Cai, J. Rodgers, D. Thibodeaux, V. Martin, and M. Watson. 2009. The advantage of lower half mean length in characterizing short fibers. Proceedings of the 2009 Beltwide Cotton Conference. pp: 1227-1228.

Gibson, L. 1999. HVI Short Fiber Content measurement. Proceedings of the 1999 Beltwide Cotton Conference. pp: 1406-1407.

Knowlton, J. L. 2001. HVI short fiber measurements. Proceedings of the 2001 Beltwide Cotton Conference. pp: 1372-1374.

Krifa, M. 2008. Fiber length distribution in cotton processing: a finite mixture distribution model. Text. Res. J. 81: 688-698.

Thibodeaux, D., H. Senter, J. Knowlton, D. McAlister, and X. Cui. 2008. A comparison of methods for measuring the Short Fiber Content of cotton. Journal of Cotton Science 12: 298–305.

Wu, H., and F. Wang. 2014. Dual-beard sampling method for fiber length measurements. Indian J. Fiber Text. 39: 72-78.

Wu, M., and F. Wang. 2016. Optical algorithm for calculating the quantity distribution of fiber assembly. Appl. Opt. 55: 7157-7162.