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Characterization of Individual Cotton Fibers via Light-Scattering Experiments

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A detailed experimental/theoretical study is conducted to explore the fundamental nature of individual cotton fibers via light-scattering experiments. For this purpose, a new precision nephelometer is built and calibrated with quartz fibers. In the experiments, iris opening (viewing angle) and scanning range and rate were determined to be the key parameters for precision measurements. The experimental results are compared against the theoretical predictions based on a finite element model. It is shown that the scattered intensity profiles as a function of scattering angle (θ) can be related to the quality (fineness) of cotton. At small scattering angles of $\theta < 10$ deg, these profiles can be used to infer the shape (cross section) of cotton fibers. On the other hand, within the range of 30 deg $< \theta <$ 50 deg they may be used to evaluate single-fiber cotton quality (fineness).

Nomenclature

$A_{//}, A_{\perp}$	=	amplitudes of the electric field vector
b	=	thickness of cotton fiber, μm
d_i	=	incident light beam diameter, mm
d_s	=	iris opening front of the photomultiplier tube, mm
$E_{//}, E_{\perp}$	=	components of the electric field vector
$\boldsymbol{I}$	=	Stokes vector
I, Q, U, V	=	components of Stokes vector
$I_s(\boldsymbol{r})$	=	scattered light intensity at observing point, $\boldsymbol{r}$ in a far field
k	=	the complex wave number
l_1, l_2, l_3	=	characteristic dimensions of fiber, μm
m	=	complex refractive index
α	=	orientation angle of cotton cross section, deg
δ	=	phase shift
$\varepsilon_{//}, \varepsilon_{\perp}$	=	phases of the electric field vector
θ	=	scattering angle, deg
λ	=	wavelength, μm

Introduction

KNOWLEDGE of cotton fiber properties, such as fineness, maturity, color, trash content, strength, length, and length uniformity, is needed to better identify possible uses of cotton for different applications.[1] Most of the previous work on cotton has focused on obtaining these properties from experiments conducted on bulk samples.[2–5] From a practical point of view, bulk measurements are cheaper and, therefore, desirable. However, the fundamental nature of fibers cannot be determined from such experiments. It is important to develop a more thorough understanding of cotton fiber, its nature and structure, for the development of more advanced and novel tools for measuring its properties. This can be achieved, at least in theory, if individual fiber experiments can be carried out, and the results are tied to bulk measurements. With the availability of more versatile light sources and with the increasing power of computers that can be used to model the complex light–matter interactions rigorously, more detailed studies on cotton fibers can be carried out.

Unlike many other fibrous materials whose radiative properties were studied and available in the literature, cotton fibers do not have circular cross sections.[1] In addition, cotton fibers are not homogeneous but display intricate patterns of convolutions along their axes (see Fig. 1). These ribbonlike convolutions occur during the drying process right after opening of the cotton boll.[5] Indeed, this property makes the cotton easily spinnable, and for that reason cotton fiber has been one of the most valuable agricultural products of all civilizations.[1]

Our objective in this paper is to present a rigorous, experimental/theoretical approach in determining the radiative properties of single cotton fibers and to correlate these results with cotton properties, particularly with fineness and maturity. For this purpose, a precision nephelometer was designed and built. Calibration of the nephelometer was carried out using quartz fibers. In the cotton-fiber experiments, first the optimum slit/iris opening was determined for detailed measurement of scattered light from the fibers. These experiments required careful scanning of fibers to avoid the anomalous scattering patterns due to off-axis deviations. After that, detailed polarized-light-scattering scanning experiments were carried out on six different samples. These results were compared against the predictions from a finite element model (FEM). Differences between the theoretical and experimental findings were outlined. Finally, the relationships between the light-scattering experiments and fineness of cotton fibers were discussed.

Cotton Fiber Quality

The cotton market today has become increasingly competitive, with the consumer sector becoming more quality conscious. Yet cotton fiber characteristics vary from bale to bale because of genetic and environmental factors such as growing, harvesting, and ginning conditions.[1] Given this, it is very important for textile mills to know, a priori, cotton-fiber quality for each and every bale to determine the yarn quality and also processing performance.

Cotton fiber quality involves many factors such as fineness, maturity, color, trash content, strength, length, and length uniformity.

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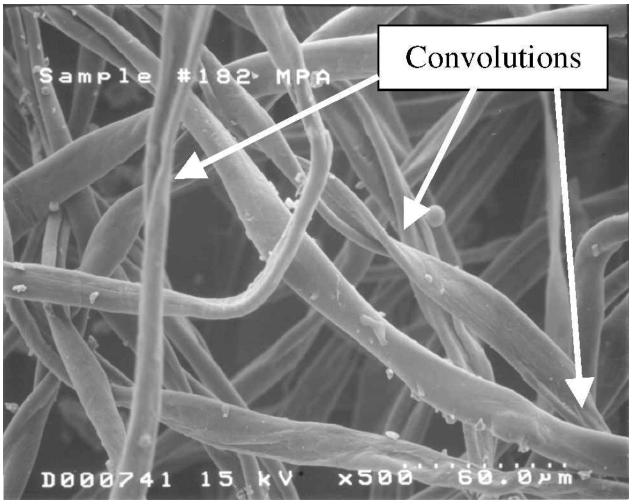


Fig. 1 SEM picture of typical cotton fibers.

In general, fibers exhibit a variety of shapes, which vary in cross-section along their length and definitely vary from fiber to fiber. Fineness can be considered a very important parameter in determining yarn quality characteristics.[1] This is because fineness influences the number of fibers in the cross section of yarn: the finer the fiber, the higher the number of fibers in the cross section. While the importance of fineness has generally been understood, accurate determination of this parameter has always been a problem.

Because mass is directly proportional to the area of cross section for a given length of fiber, fineness has traditionally been expressed as the mass of a given length of fiber. The most common among these expressions is the micronaire value, which is defined as the weight of 1 in. of fibers in micrograms (10^{-6} g).[1] Airflow instruments are widely used for the estimation of fiber fineness. These instruments are based on the principle that, for equal weights of fiber samples, the rate of airflow across the sample would be less for finer fibers than for the coarser fibers. This is due to the relatively greater surface area in the case of finer fibers, which offer larger drag on the flow of air.

In a more fundamental way, the fineness can be related to the effective diameter of a fiber. On the other hand, the maturity is understood as the degree to which the interior of a fiber is filled with cellulose. In light-scattering terms, the fineness is related to size and structure, whereas the maturity is tied to the structure and material characteristics. Therefore, one may expect that the light-scattering measurements would yield reasonable correlations with both fineness and maturity.

Even though methods (such as SEM imaging) are available for estimation of fiber quality including fineness, there is no established approach to fully characterize the quality of individual cotton fibers accurately. In addition, no known measurement technique is capable of revealing the fundamental structure of fibers, which defines fineness. In this study, we attempt to develop a light-scattering approach to predict the degree of fineness and maturity of individual cotton fibers.

Cotton-Fiber Samples

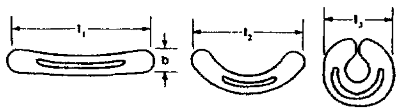
The Southern Regional Research Center, ARS-USDA, New Orleans, Louisiana, provided 14 well-characterized cotton-fiber samples for this experiment. Of these we randomly picked 6 for this research. Dimensions of individual cotton fibers were measured using an optical microscope and are listed in Table 1. The parameter b represents the thickness of the fiber in a linearly flattened condition, and l_1, l_2, and l_3 are the dimensions for different cross sections that occur along the fiber axis y. As mentioned earlier, fineness is known to be related to effective fiber diameter. Given this, we assume that the dimension l_1 in Table 1 is a reasonable measure of fineness of a cotton fiber.

Cotton is a hollow fiber whose wall is mainly cellulose. All cotton fibers have natural convolutions as shown in Fig. 1. Distances between these convolutions are rather arbitrary; therefore, the laser light is not necessarily incident on the entire fiber surface at the same angle of orientation. On the other hand, angular profiles of scattered light by noncircular fibers are a strong function of their orientation, in addition to their characteristic dimensions. A slight change in orientations of ribbonlike fibers is likely to change the scattered-light profiles significantly.[6] Given this, it is crucial to know the orientation of fibers in order to make unambiguous and reasonable comparisons against the numerical predictions.

Finding a location where the laser light would be incident on a fiber surface perpendicularly is difficult. To determine shape and structure of cotton fibers at the scattering measurement locations, an optical microscope was used and digital images of fibers were first recorded. Then, scattering experiments were conducted at these precise locations. This approach proved to be quite tedious, yet allowed us to make one-to-one comparisons between the scattering measurements and modeling attempts.

Table 1 Characteristic dimensions of cotton-fiber samples (based on optical microscope images)

Characteristic Dimensions (µm)



Sample	l_1	l_2	l_3	b	Fineness[a]	Maturity[b]
1	23	19.5	10	6.0	4	4
2	31	20.5	13	6.6	6	5
3	22	18	9	3.7	3	1
4	25	20	11	7.4	5	6
5	21	17.5	12	5.5	1	3
6B	22	18	11	4.3	2	2

[a] 1 indicates the highest fineness value. [b] 6 indicates the most mature fiber.

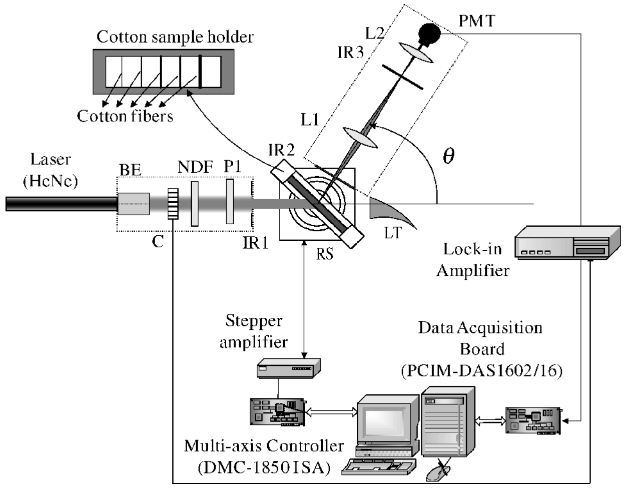


Fig. 2 Schematic of the experimental system: BE, beam expander; C, optical chopper; IR1, IR2, IR3, irises; L1, L2, lenses; LT, light trap; NDF, neutral density filter; P1, polarizer; RS, rotationary stage; θ, scattering angle.

Experimental Setup

The experimental setup built to measure the scattering elements of the cotton fibers is shown in Fig. 2. The setup is an improved and revised version of the nephelometer developed earlier in the Radiation Transfer Laboratory.[7,8] As the light source, a 20-mW HeNe laser ($\lambda = 632$ nm) is employed. The incident-light-beam path consists of a beam expander, a neutral density filter (NDF), an optical modulator (chopper), a polarizer (P1), and an iris (IR1). The polarizer (P1) is used in front of the laser to make sure that the laser beam is vertically polarized [transverse magnetic (TM) mode]. Power of the incident beam is adjusted with the NDF in order to avoid any damage to the detector.

A specimen holder is designed to hold different cotton fibers in a vertical position. The orientations of the fibers need to be monitored very precisely to make sure that the scattered-light cone of the cotton fibers is in a horizontal (detection) plane. For that reason, the sample holder is mounted on a tilt stage, which is mounted on an x–y–z stage.

The scattered-light-beam path consists of an iris/slit (IR2) and two biconvex lenses, L1 (Newport, KBX067, with focal length of 125 mm) and L2 (Newport, KBX049, with focal length of 38.1 mm). Scattered-light-beam-path optics were mounted on a rail attached to a rotational stage and controlled by a personal computer. Scattered light was detected by a photomultiplier tube (PMT; Hamamatsu R446). The field of view of the detector was restricted by placing an iris/slit (IR3) with a 100-μm to 2-mm opening. Signals received by the PMT were first amplified with a lock-in amplifier, then collected by a data acquisition card and finally stored in a personal computer.

Modeling Light Scattering by Fibers

Scattering of electromagnetic radiation by particles and fibers is outlined in detail by Bohren and Huffman.[9] Recently, different approaches used for modeling cylindrical particles were reviewed.[10–12] The model used here starts with the one discussed by Manickavasagam and Mengüç[10] for infinite cylinders. However, to account for the shape and structures of fibers, the finite volume approach of Yamada[12] is adapted for numerical analysis.

Assume a coherent light beam of circular frequency ω traveling in the z direction is incident on a fiber. The electric field vector of the incident light can be divided into two orthogonal components, such as parallel and perpendicular, as shown in Fig. 3. These components can be written in terms of the corresponding amplitudes ($A_{//}$ and $A_{\perp}$) and phase shifts ($\varepsilon_{//}$ and $\varepsilon_{\perp}$):

$$E_{//} = A_{//} \exp[i(\omega t - k_o z - \varepsilon_{//})]$$
$$E_{\perp} = A_{\perp} \exp[i(\omega t - k_o z - \varepsilon_{\perp})] \tag{1}$$

where t is time and $k_o = 2\pi/\lambda_o$ is the wave number in space. The Stokes parameters of scattered/incident light are time averages of these two components of the electric field vector:

$$[\boldsymbol{I}] = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_{//}E_{//}^* + E_{\perp}E_{\perp}^* \rangle \\ \langle E_{//}E_{//}^* - E_{\perp}E_{\perp}^* \rangle \\ \langle E_{//}E_{\perp}^* + E_{\perp}E_{//}^* \rangle \\ \langle E_{//}E_{\perp}^* - E_{\perp}E_{//}^* \rangle \end{bmatrix} = \begin{bmatrix} \langle A_{//}^2 + A_{\perp}^2 \rangle \\ \langle A_{//}^2 - A_{\perp}^2 \rangle \\ 2\langle A_{//}A_{\perp}\cos\delta \rangle \\ 2\langle A_{//}A_{\perp}\sin\delta \rangle \end{bmatrix} \tag{2}$$

where $\delta = \varepsilon_{//} - \varepsilon_{\perp}$. In the experiments, only the vertical polarization direction is used. If the polarizer (P1) is set in vertical orientation,

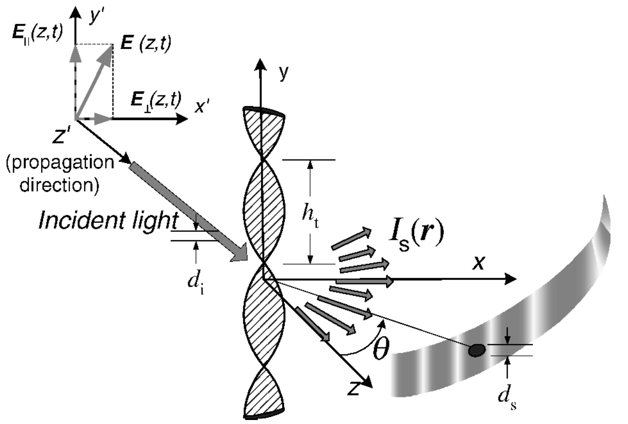


Fig. 3 Schematic and nomenclature for light scattering from a cotton fiber.

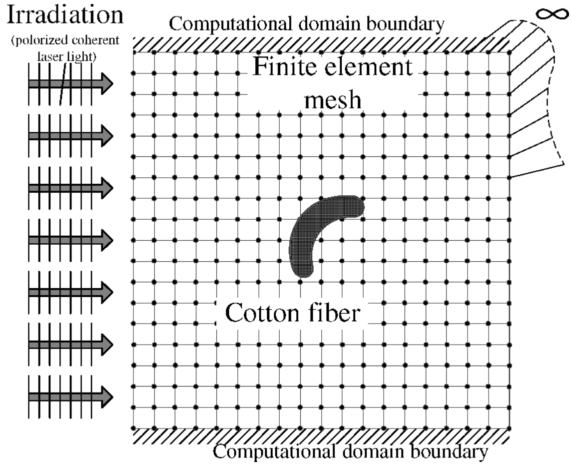


Fig. 4 Computational domain for the FEM of carbon fiber.

the Stokes vector of incident light becomes

$$[\boldsymbol{I}] = \begin{bmatrix} \langle A_{//}^2 \rangle \\ \langle A_{//}^2 \rangle \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

The intensity profile of the light scattered by irregular-shaped cotton fibers can be estimated by solving the Maxwell equations. Here, a brief outline of the model based on Ref. 12 is given.

Figure 4 shows the numerical model for estimating a two-dimensional electric field induced by scattering of a single fiber. In this analysis, first the electric field within the computation domain is estimated. And then, using this field, the intensity profile of the scattered light in the far-field region is derived. The fiber is assumed to be in the center of the computation domain, as shown in Fig. 4. The area is divided into square elements each having the edge size of $\lambda/24$, and the fiber shape is represented by more than 150,000 elements.

The governing equation for the electric field E is the Helmholtz equation, which is derived from the Maxwell equations as

$$\nabla^2\boldsymbol{E} + k^2\boldsymbol{E} = 0 \tag{4}$$

where k is the complex wave number, defined as before ($k = 2\pi m/\lambda$), where m is the complex index of refraction of fiber. Note that k varies spatially because the elements representing the fiber have a different index from that of the surroundings.

The electric field vector of the incident radiation is assumed to be in the y direction (vertically polarized, i.e., the TM mode). Therefore, only the y component of the electric field vector of the scattered light is nonzero, and only the scalar Helmholtz equation for the y components needs to be solved. Note that either the TM (perpendicularly polarized) or TE (parallel polarized) can be used in the experiments. In general, the TM mode yields detailed information, and no additional information may be obtained by performing additional TE-mode experiments. For that reason, we perform experiments at the TM mode and outline the numerical formulation only for the perpendicularly polarized light.

The intensity profile of scattered light in the far field is derived by using the integral representation[13] given as

$$I_s(\boldsymbol{r}) = 2\big/\left(\pi k_o r\sqrt{\mu/\varepsilon}\right)|F(\boldsymbol{r})|^2 \tag{5}$$

where ε and μ are the electrical permittivity and the magnetic permeability of free space, respectively, and

$$F(\boldsymbol{r}) = \frac{i}{4}\oint_C \left[\frac{\partial E_y^s}{\partial n'} - ik_o(\boldsymbol{i}_n' \cdot \boldsymbol{i}_r)E_y^s\right] e^{ikr'\cdot i_r}\,\mathrm{d}l' \tag{6}$$

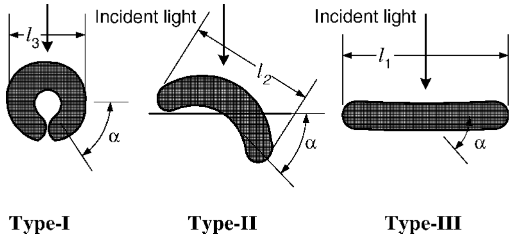


Fig. 5 Cross sections of cotton fibers considered in the FEMs. The angle α is the orientation angle.

The integral in Eq. (6) is a line integral, and it is evaluated over a closed contour C, which is arbitrarily defined around the fiber; l' is a coordinate along the closed contour; $\boldsymbol{r}$ is a vector from the fiber to an observation point and $\boldsymbol{r}'$ to a point on the closed contour l'. The direction normal to the closed contour at l' is n'; i is the unit vector of the direction specified by the corresponding subscript.

Numerical simulations were carried out for three types of fibers with different cross sections, which were chosen based on the observations made via an optical microscope, as shown in Table 1. The complex refractive index of cotton fibers is assumed $m = 1.4 - i0.1$. All fibers modeled in this study were assumed to have a thickness of 5 μm and a dimension of 21 μm as measured along the centerline. The apparent dimension of a fiber depends on how much curvature the fiber has. For example, type I, type II, and type III have dimensions of 11, 17, and 21 μm, respectively. The numerical predictions represent cotton sample 5. Because the fibers have asymmetrical cross-sectional shapes (Fig. 5), the scattering profiles may vary as a function of the angle of the irradiation. The numerical calculations were repeated for several incident angles in 30-deg increments and were carried out on the parallel computer (VPP800/63 of Kyoto University in Japan). The computer has 63 processing elements, and a single element has the maximum processing capability of 8 GFlops. The CPU time to obtain an electric field induced by the scattering was about 20 min without parallel processing. The numerical results are compared against the experimental ones in the following section.

Calibration Experiments

Calibration of a nephelometer can be carried out only if the fibers are well defined. For this purpose, we employed pure fine quartz (SiO_2) fibers from Nippon Sheet Glass Co., Japan. During the experiments, it was found important that the optical components along the scattered-light path were aligned precisely and the cotton fibers were oriented perpendicularly to this plane. To check the alignment and the orientation of fibers, scattered-light intensity profiles were scanned in both clockwise and counterclockwise scattering angles, over the range of 3–35 deg. These results are compared in Fig. 6a, where the normalization was performed with the 3-deg intensity value. The agreement between these two sets of results suggests that the optical alignment is correct.

Next we checked the accuracy of the measurements. For this purpose, results from the quartz-fiber scattering experiments were compared against the theoretical predictions obtained from the Mie cylinder model. The diameters of the circular fibers were obtained from the best-fit numerical predictions of the scattering experiments; the numerical results reported were for a diameter of 4.005 μm and the quartz index of refraction of $m = 1.457 - i0$. Figure 6b depicts these comparisons within the angular range of 10 to 35 deg. In this case, the normalization was performed with the 10-deg intensity value. The fact that the experimental and theoretical results displayed the same repeatable patterns with the same angular frequencies indicates the reliability of the experiments.

Cotton Experiments

Cotton experiments were conducted after establishing the accuracy and reliability of the nephelometer. Cotton fibers were mounted vertically on aluminum fiber holders. A fiber holder was attached to the stage that allows four-dimensional freedom in order to align

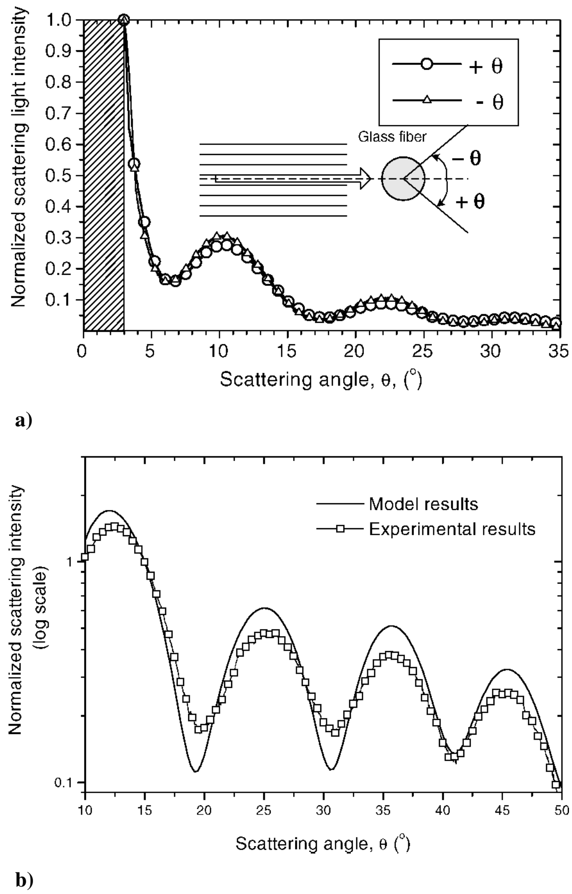


Fig. 6 Results of calibration experiments: a) symmetry experiments with quartz fibers and b) comparisons with the Mie cylinder code predictions.

fibers vertically. After a series of initial experiments, we determined that additional measures needed to be taken before carrying out the final data analysis. These issues are discussed in the following sections.

Optimum Iris Opening

Cotton fibers were not straight along the fiber axis and the off-axis deviations affected the scattered-light intensity distribution strongly. In addition, the convolutions of cotton fibers displayed an arbitrary sequence of repetitions along the fiber axis. If the optical system was not fine-tuned, the recorded scattered intensity profiles would be the average of light scattered by different parts of the fiber. For that reason, we added an iris (IR2) into the optical system, which determined what fraction of fiber was to be "seen" by the detector. For axially homogeneous fibers, such as quartz fibers, the value of this iris was not critical. However, in cotton experiments, if a large iris was used, the results would represent the average over several convolutions on a cotton-fiber axis. Such measurements would yield ambiguous interpretation of trends. Therefore, the impact of the iris opening on the accuracy of the results should be investigated carefully.

A series of experiments was conducted to find the optimum opening for IR2 to locate positions of convolutions; these results are depicted in Fig. 7. While the IR2 opening was set to 2 mm, cotton sample 5 was scanned from $\theta = 3$ to 10 deg. These experiments were repeated with 1-mm scanning steps along the fiber axis for 5 mm of length (Fig. 7a). Then scanning steps were reduced by half and experiments were repeated with the same iris opening (Fig. 7b). The iris opening was decreased to 1 mm, and experiments were repeated with scanning steps of 0.5 and 0.25 mm (Figs. 7c and 7d). These four figures are, in general, very similar. However, Fig. 7d, which is for an iris opening of 1 mm and scanning steps of 0.25 mm, depicts more details.

These results show fluctuations of intensity along the long axis of the fibers. These fluctuations are mainly due to two effects: either

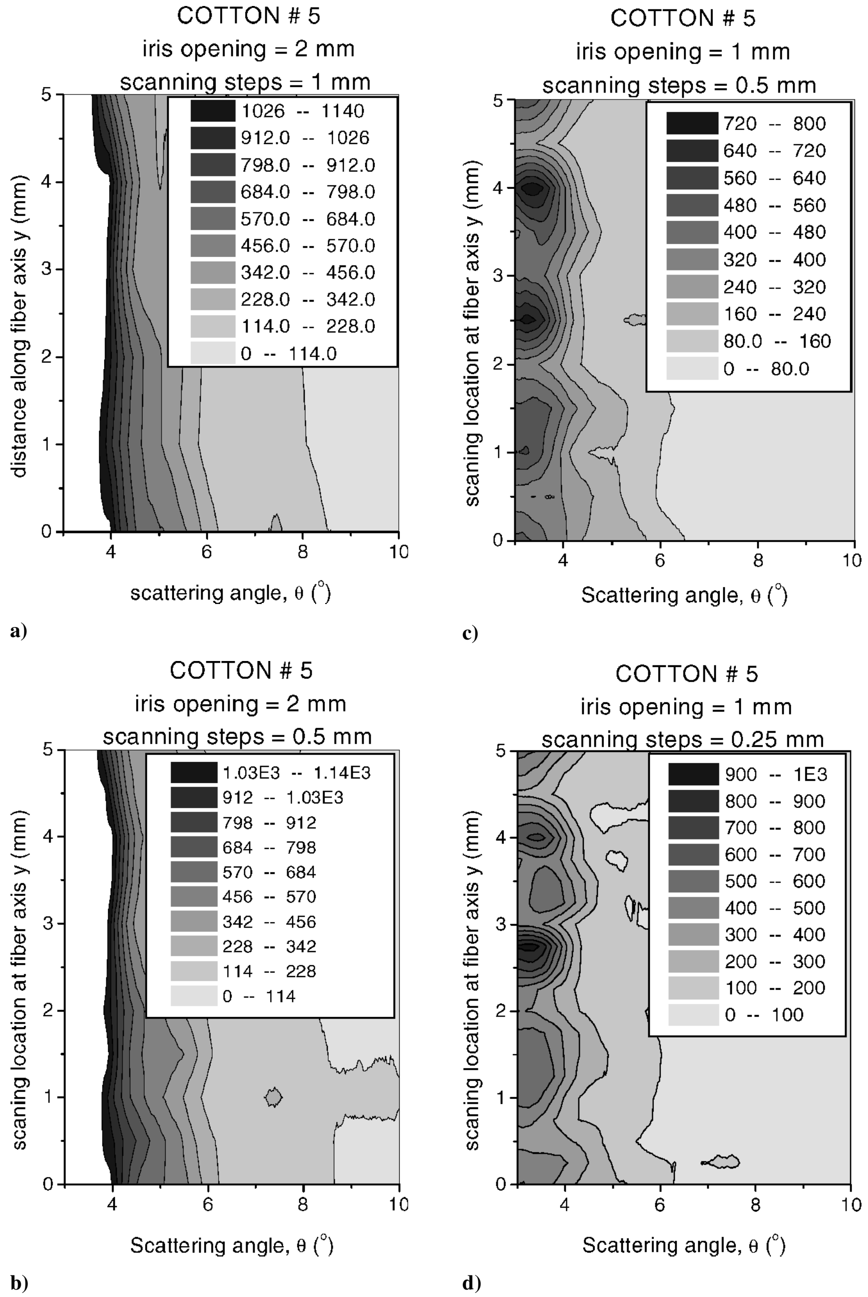


Fig. 7 Effect of iris opening and scanning steps on scattered-light intensity.

the fiber shape changes along the axis due to convolutions, or the fibers are not straight and may move out of the focus of the beam. Because lock-in amplifier and PMT settings were retained during the experiments, the PMT was saturated when the iris opening was large. To overcome this problem, the settings needed to be changed. By decreasing the iris opening and having finer scanning rates, we were able to detect the changes in scattered intensity signals along the fiber.

Off-Axis Deviations of Cotton Fibers

If cotton fibers were not straight and deviated from the desired vertical orientation, their scattered intensity profiles varied significantly. Figure 8 depicts optical microscope images of the off-axis part of cotton sample 1 and their effects on scattered-light intensity distribution. Note that Figs. 7 and 8 display "white" regions at small scattering angle regimes. These regions correspond to "overexposed" detector readings. Because the experimental readings were taken without any changes in lock-in amplifier sensitivity settings, the overexposure could not be avoided. It is noted that if a cotton fiber is convoluted away from the axis of detection, the overexposure problem was more frequent. To have reliable data, the experiments were conducted far away from those off-axis locations along the y axis of fibers. To identify the problem with off-axis locations, the cotton samples were imaged using an optical microscope and their structures as well as locations of convolutions were determined. This information was also used in scattering experiments to make sure the overexposure problem did not affect the accuracy and reliability of data.

Cotton-Fiber Experiments

After all the corrections were introduced to the optical system, several sets of measurements were conducted using different cotton fibers. Only the results from the cotton samples 1, 2, 5, and 6B are reported here, because only in these samples were there 1-mm zones along the fiber axes where scanning could be made without any off-axis deviations. Cotton fibers were scanned from 10 to 50 deg along a 1-mm span of the fibers with 100-μm steps. The second iris (IR2)

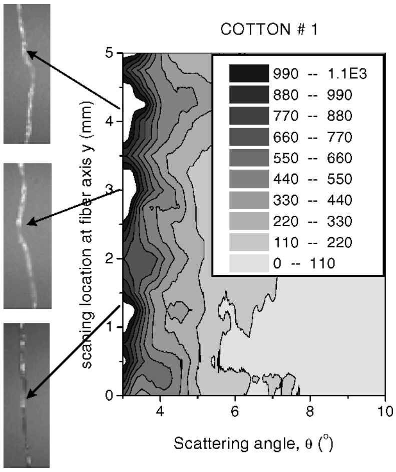


Fig. 8 Effect of off-axis orientation of fibers on scattered-light intensity; iris opening is 1 mm.

opening was set to 100 μm during these experiments. Experiments were repeated for a number of fibers several times to establish the repeatability, which was found to be consistently high.

Figure 9 depicts the results, normalized with the largest scattered intensity value measured at about 10 deg. The results for sample 6B yield the highest scattered intensity values compared to all others, whereas the results for sample 2 are the lowest; the results for samples 1 and 5 look similar and fall between the other two. Figure 10 depicts the smoothed (curve-fit) average of all scattered intensity values for these four samples. The normalization was carried out with respect to the highest intensity reading between 3 and 10 deg. These averages support the earlier observations from Fig. 9 that the cotton sample 6B yields the highest intensity values and sample 2 the lowest. Interestingly, these results correlate with the fineness and maturity values given in Table 1. The l_1 dimension of sample 2 is the largest, indicating that its fineness is not good compared to others. On the other hand, the b dimension of sample 6B is the lowest of all four samples (about 25% smaller than the b dimension of samples 1, 2, and 5), and 6B is considered the least mature of all. Note that samples 1, 5, and 6B have comparable l_1 values.

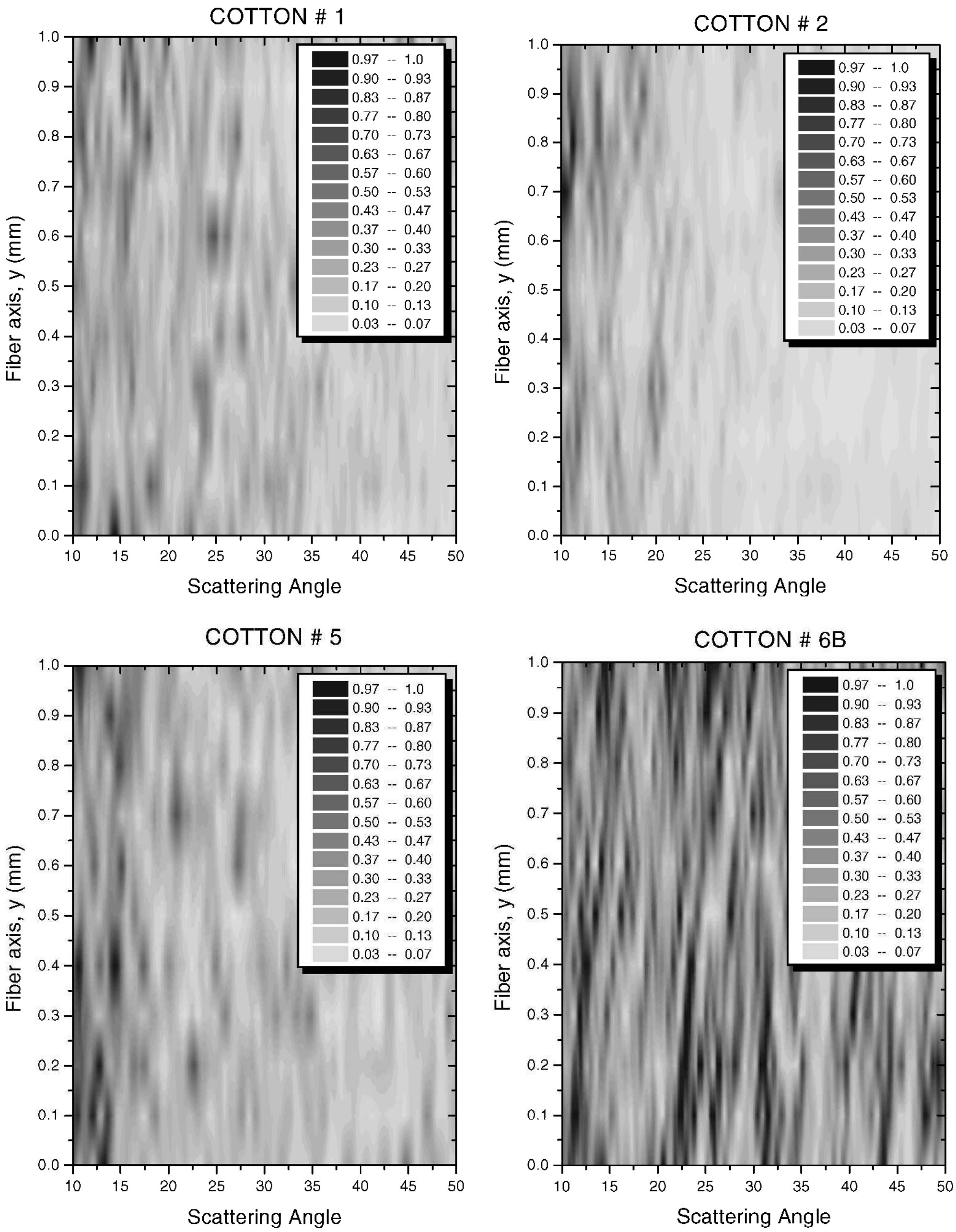


Fig. 9 Light-scattering maps of cotton samples 1, 2, 5, and 6B (10 deg $\leq \theta$ (scattering angle) $\leq$ 50 deg); iris opening is 1 mm.

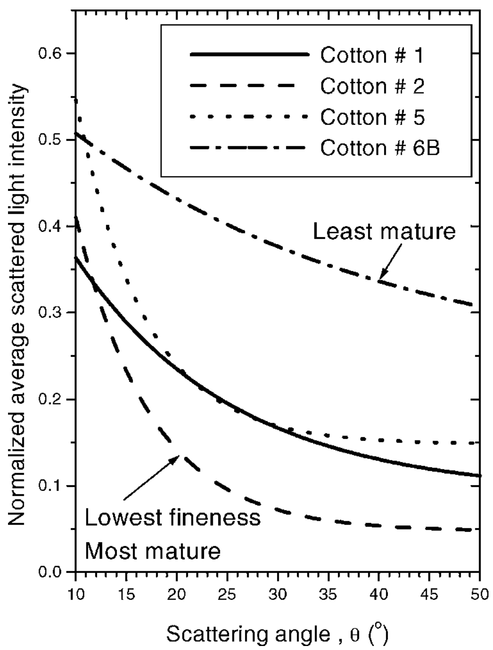


Fig. 10 Comparisons of experimental results for cotton samples 1, 2, 5, and 6B. Lines show the curve fits to average experimental values over the angular range of 10–50 deg.

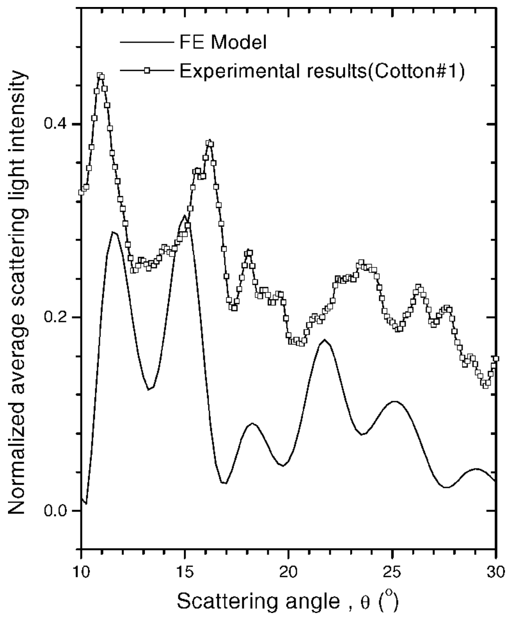


Fig. 11 Comparison of experimental data and numerical predictions for cotton fiber (sample 1) over the angular range of 10–30 deg.

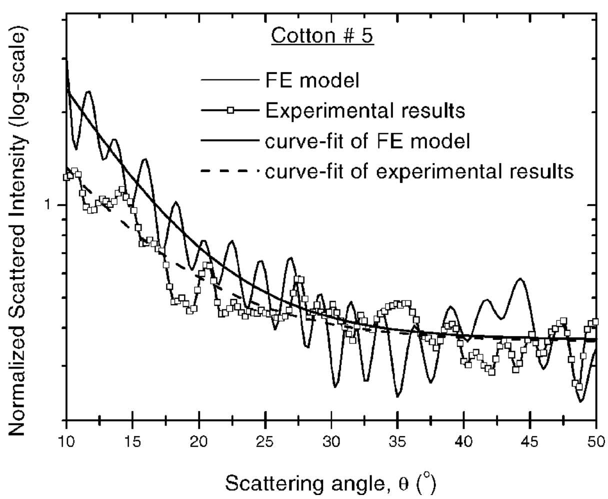


Fig. 12 Average results of type II cross section and average of experimental scanning results over 1 mm for cotton sample 5.

The light-scattering experiments indicate that the fibers with the least fineness would scatter the light the least amount in forward angles between 10 and 50 deg. If their fineness values are comparable, fibers with the smallest thickness (lower maturity) scatter the most light. This observation is very important because it may allow possible identification of cotton quality from light-scattering measurements. As discussed before, the fineness is related to the effective diameter of a fiber, and the maturity involves how the interior of a fiber is filled with cellulose. It is obvious that the fineness is related to size and structure, whereas the maturity is tied to the structure and material characteristics, and these two parameters can be characterized via light-scattering measurements. Note that more detailed quantitative and statistical analyses of results given in Figs. 7–9 can be carried out; however, for our current objectives, there is no need to obtain more details than what we present here.

Comparison with the FEM

Next, the experimental results were compared qualitatively against the numerical results. As discussed before, experimental results were obtained with 100-μm axial resolution on cotton fibers. This means that scattered intensity profiles corresponded to the average scattering profiles over 100 μm of samples. Although we observed uniform profiles of fibers over such small distances, a slight change in fiber thickness or orientation would yield different results.

In most cases, a 100-μm span of the fibers corresponds to one convolution. Because of this, the orientation of a cross section of fiber may change from $\alpha = 0$ to 360 deg (see Fig. 5) in one scanning step of 100 μm. For these cases, numerical results can be compared against the experimental results only if they are orientationally averaged. It is possible that some fibers may not have many convolutions or they may be straight. In such cases, comparisons between the experimental results should be made against the numerical predictions for a single orientation of fibers. Figure 11 depicts such a comparison: the scattered-light pattern obtained for cotton sample 1 and model type II at an orientation angle of $\alpha = 120$ deg. The normalization was again carried out with respect to highest-intensity reading between 3 and 10 deg. The similarities between these results are very encouraging, suggesting that the theoretical model is able to predict orientations of fibers accurately.

Figure 12 shows the results for cotton sample 1 averaged over all orientations as predicted by the FEM. Also plotted on this figure are the average results for the entire scan range of experiments over the fiber length. Again, the comparisons are very good, particularly between $\theta = 30$ and 50 deg.

Conclusions

Light-scattering patterns of individual cotton fibers were measured using a new precision nephelometer and were correlated against cotton fineness and maturity. Scattered-light intensity profiles at small forward-scattering angles revealed information about straightness of the fiber and location of convolutions. Measurements between 10 and 50 deg, on the other hand, were related to cotton fineness and maturity. It was observed that fibers with the least fineness and the most maturity (sample 2) scatter less within this angular range, whereas the least mature ones (sample 6B) scatter the most.

To carry out more precise experiments, a new iris was added in front of the scattered-light optic path. It was shown that the resolution of the optical nephelometer can be improved drastically with carefully selected iris openings.

The experimental results were compared against numerical predictions based on a finite element method formulation. Very good agreement was observed between the experiments and the numerical results, particularly for the fibers whose orientations are relatively well identified. This suggests that the FEM was capable of predicting the behavior of complex shapes of cotton fibers.

The experimental study can be expanded to perform polarized-light-scattering measurements on cotton fibers. Such measurements would allow us to determine the scattering matrix elements, which are expected to reveal more information about the nature and structure of cotton fibers. In addition, polarized-light-scattering experiments from bulk samples should be carried out to correlate individual fiber experiments with the relatively less complicated bulk measurements.

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