Measuring the particle-size distribution of residual ink in recycled paper

Byron D. Jordan, Nam G. Nguyen, and Roland J.R. Trépanier

ABSTRACT: If reflected illumination is used to measure residual ink particles in sheets of recycled paper, care must be taken to avoid artifacts from nonuniform surface reflectance. An image analysis instrument has been designed to measure these particles reliably and easily. The ink particles on one side of a sheet may be significantly larger or more numerous than on the other side, as demonstrated in some examples.

KEYWORDS: Diffuse reflection, image analysis, ink, measurement, paper, particle size distribution.

Cleanliness and shade are two appearance attributes influencing the marketability of recycled paper. Any specks of residual ink too small to be seen with the naked eye could still influence the shade of the sheet. In principle, one might want to control the deinking process completely from these two visible attributes; however, some may find greater insight from the direct measurement of changes in the particle-size histogram. Laboratories in the paper industry have been using a variety of image analysis procedures to measure the histogram of residual ink with no procedural consensus in sight *(1–9)*. Since there seems to be a need for an image analysis measurement of the residual ink histogram, we considered some of the problems and looked for ways around some of the predictable artifacts. We were looking for a configuration that could measure subvisible specks down to a diameter of 10 microns with high fidelity, reasonable speed and ease of use, and no hardware adjustments for the user.

The measurement of subvisible residual ink specks differs in several ways from the measurement of cleanliness with a standard dirt count. The standard dirt count needs some means to balance the visual impact of different colored specks, and this calls for a visual means or a close emulation of visual processes *(10)*. The physical size of the residual ink specks, rather than their psychophysical impact, is of interest. Secondly, dirt counting is performed at such a low magnification that the reflectance variations associated with the formation require accommodation in the detection scheme *(10)*. At the much higher magnification of ink speck measurement, the entire field of view will be smaller than most flocs. This calls for a different detection algorithm.

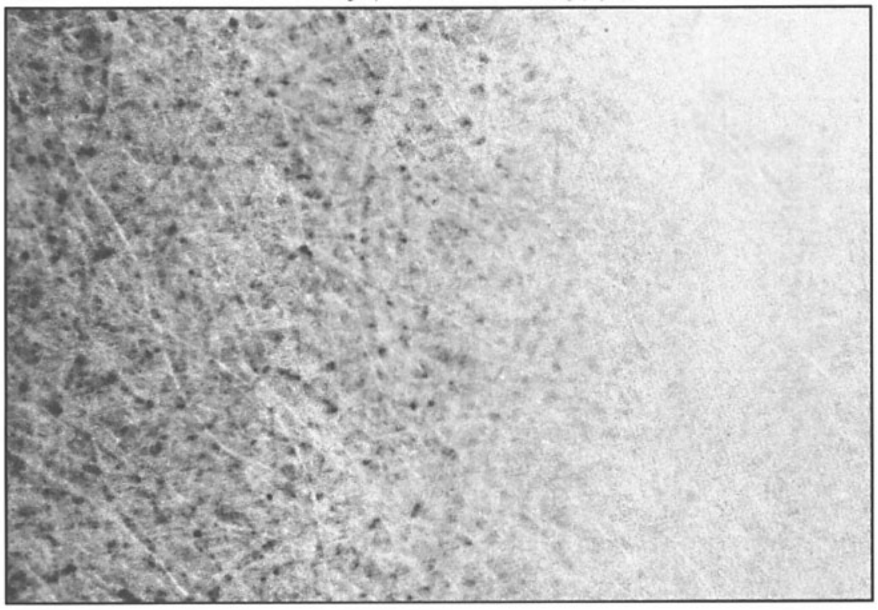
In spite of these differences, it would be helpful if dirt counting and residual ink measurement had enough in common that one histogram could be appended to the other. For this reason and others, we maintained the reflected light format of the standard dirt count. Wet and oil-impregnated samples can be messy to work with and may provide a random lens distortion to the image of internal specks. Reflected light can be used on a wide range of specimens, including some specimens for which light transmission through a dry sheet is complicated by formation effects. In spite of these relative advantages, ink measurement with reflected light is not free of complications and potential artifacts.

Potential artifacts with reflected-light imaging

The first step in the image analysis of residual ink specks is the automatic recognition of an ink speck as an image region of appropriate size or shape that is darker than its surroundings. Ideally, the background will be at a

Jordan is senior scientist and Nguyen is a research engineer at Paprican, 570 St. John's Blvd., Pointe Claire, PQ, Canada H9R 3J9. Trépanier is president of Noram Limited, 125 Hymus Blvd., Pointe Claire, PQ, Canada H9R 1E6.

1. "Windows" in a sheet with a dark backing (left) are the right size and contrast to be counted as residual ink, but on the side of the micrograph with a white backing (right), the black specks are gone.



single reflectance level and will be much lighter than the ink. If the background varies too much from point to point, the smaller ink specks will be detected only at advantageous locations. Furthermore, deep enough shadows of the right dimensions could be detected as spurious ink.

One form of artifact that is easily avoided is the "window." A window is a locally transparent region where the sheet is thin and the bonding is high. Windows show up as black spots unless the sheet has a light backing. Bonded areas between fibers do not scatter light. Because of their origin in bonding, windows are of comparable dimension to a fiber width and will be easily mistaken for ink specks in the 20-micron to 40-micron range. **Figure 1** shows a handsheet illuminated at 45° with a white backing behind part of the field of view. Windows are clearly visible where the backing is black.

A second easily eliminated form of artifact is the macrointerference that can be formed when a sheet surface is covered by a cover glass and illuminated at glancing angles *(11)*.

This can be reduced by the use of lower-angle illumination or eliminated by removing the cover glass.

Another artifact in the 20-micron to 70-micron range is shadowing at surface voids. **Figure 2** illustrates the formation of a shadow cast with glancing-angle collimated light. Such shadowing is the basis of some surface roughness testers *(12, 13)*. It is much less pronounced when the illumination is more vertical.

Contributions to a nonuniform image background

Higher magnification with reasonable fidelity usually requires that the lens move closer to the object than at lower magnification. As illustrated in **Fig. 3**, the lens itself can limit the available range of illumination angles. There are some hot spots or shadows at any single angle of collimated illumination, but the degree of complication increases at higher angles from the normal.

At low angles, near perpendicular illumination, the flat tops of fibers can return gloss peaks as illustrated in **Fig. 4**. At slightly higher angles, hot spots in the leading edges of some fibers show from another source of specular reflection. Above 45° a third kind of hot spot becomes important. We call this one fiber "light-up," because whole fiber segments become brightened by light that reflects around the inside of the fiber.

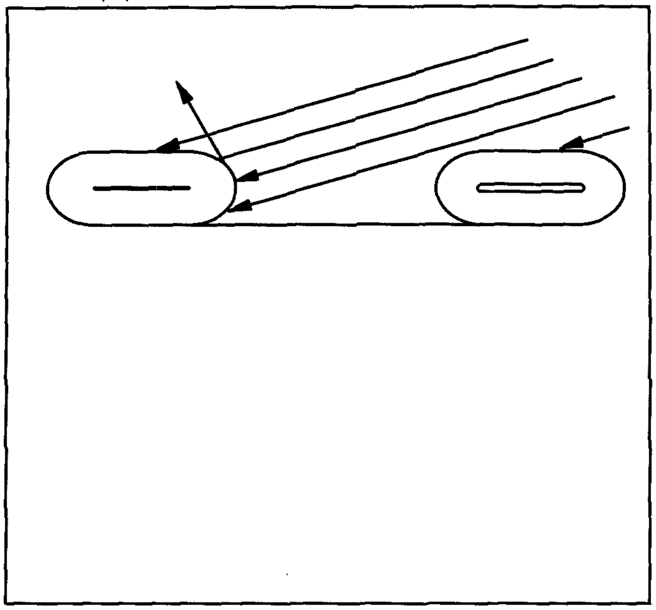
Using a Zeiss Tessovar lens and fiber-optic illumination as shown in **Fig. 5**, the same spot on a handsheet was photographed with different illumination. The handsheet was made from recycled fiber. **Figure 6a** was taken with the illumination at 40°, and the only significant background variation is in the bright spots from gloss. Figure 6b, taken at 45°, shows some leading-edge gloss spots and very few shadows. Figure 6c, taken at 50°, shows more shadows and the beginning of fiber light-up. Figure 6d, taken at 60°, shows pronounced shadowing and light-up. By an angle of 70° to 80° in Figs. 6e and 6f, the shadowing and light-up have become so pronounced that most of the ink specks have become obscured to our own vision!

To quantify the effect of illumination angle on background uniformity, the camera-back on the Tessovar was replaced with a digital CCD video camera, which fed the video image into an image analyzer working on a 512 x 512 pixel array of eight-bit intensity. The coefficient of variation (COV) of the pixel intensity was calculated for each image.

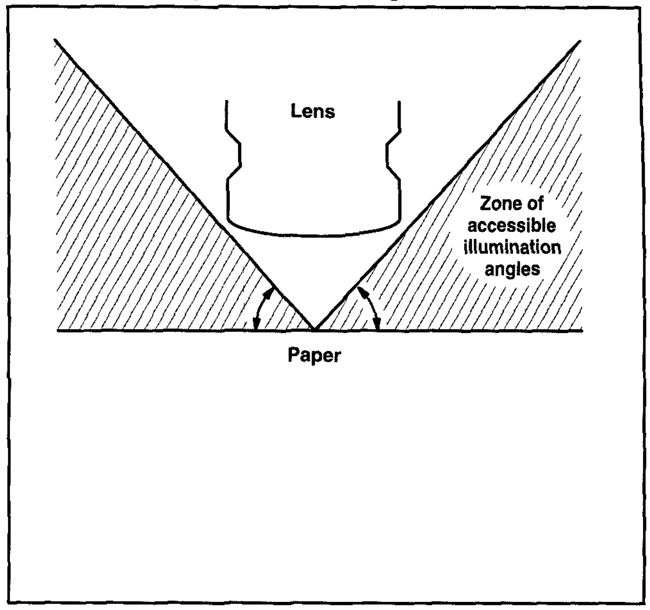
Surface roughness provides some variation at glancing angles. Except for some fiber roughening, coated paper provides relatively little opportunity for shadowing or light-up, as shown in **Fig. 7**. The coefficient of variation is about 5% at lower angles and rises gradually in the 70° region toward 10%. An uncoated fine paper was comparable to the coated paper at low angles, but its COV rose gradually above 45° to about 50% at 85°. The COV of newsprint begins at a minimum of 10% and also rises to a maximum of about 50%, as shown in **Fig. 8**. The glossy side of a handsheet produces an angular variation similar to newsprint, but the matte side of the handsheet diverges as high as 70% at 85°.

The coefficient of variation data quantify what is apparent in the micrographs of Fig. 6. Uncoated paper illuminated at a high angle can produce a very nonuniform background with variations of 20–70%, and these variations can obscure the detection of the residual ink. These problems, how-

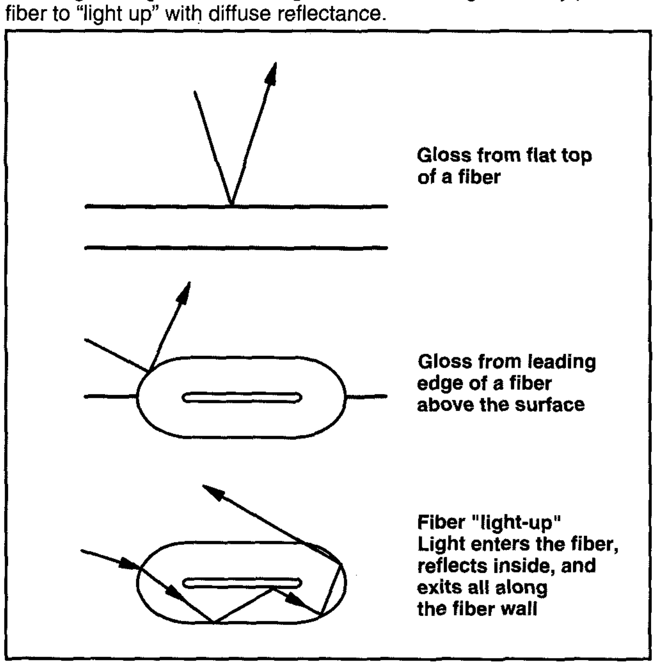
2. Oblique collimated light can cast dark shadows on the surface of uncoated paper.



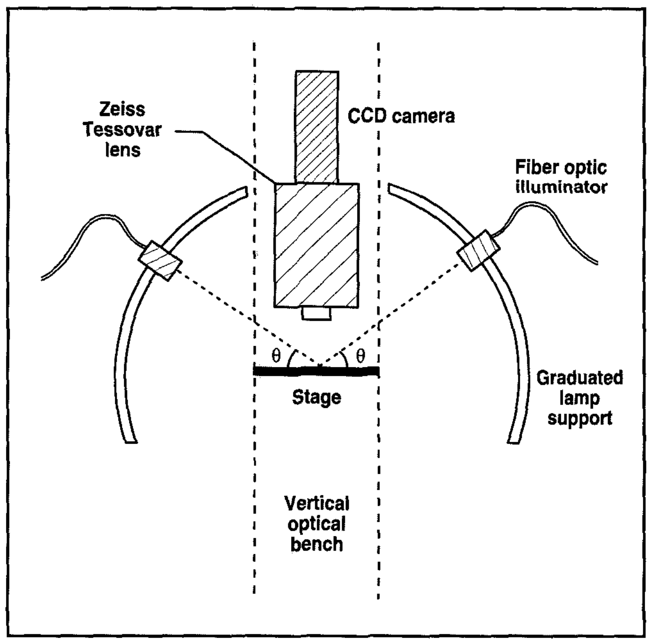
3. At higher magnification, lenses usually must come close to the surface of the paper. This may limit the available angles of illumination.



4. Nearly perpendicular illumination returns gloss from the fiber surface; higher angles can return gloss from fiber edges or may permit a fiber to "light up" with diffuse reflectance.



5. The apparatus used to measure the angular variations in reflectance pattern.



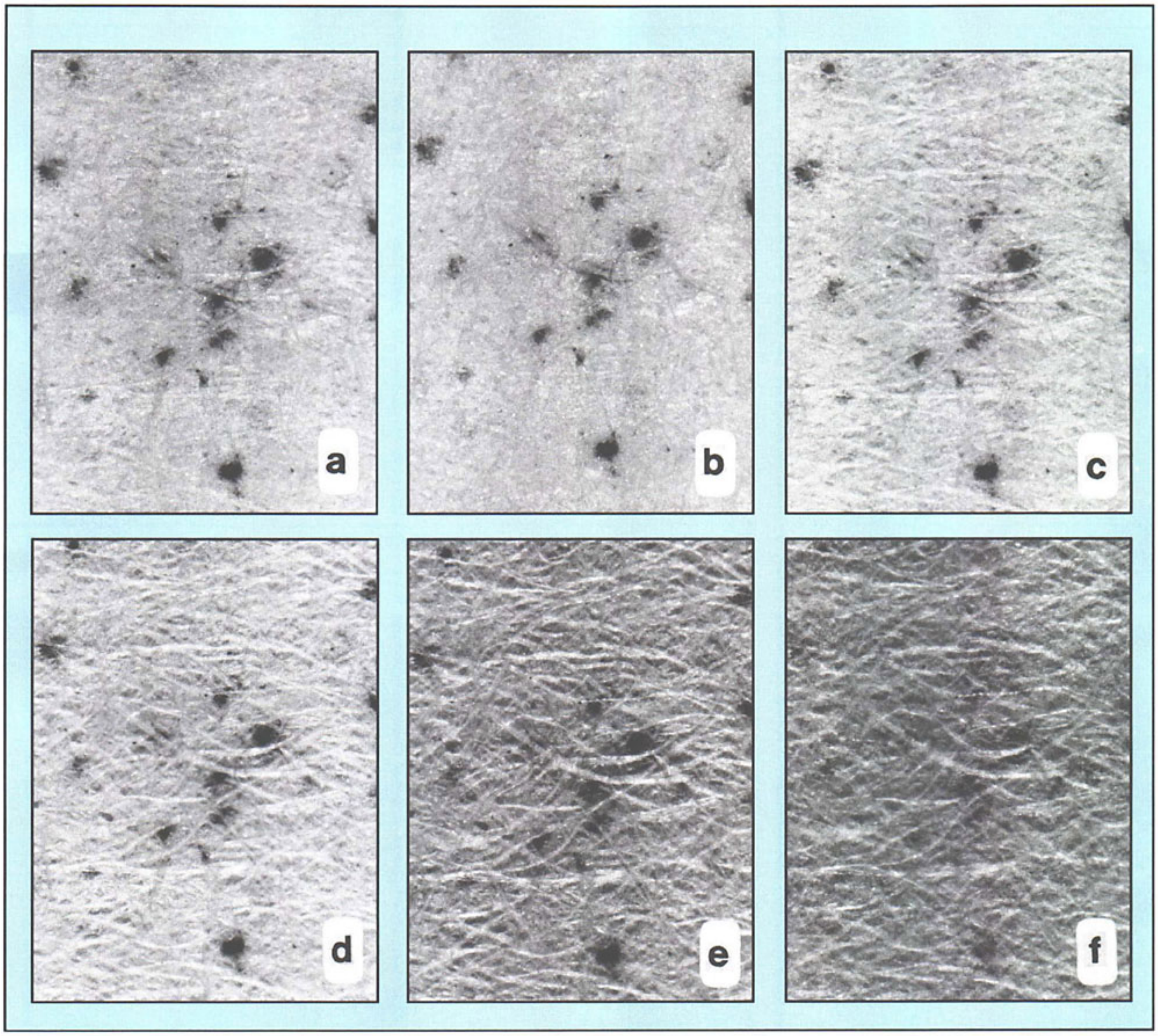
ever, stem from the use of collimated light. If light falls diffusely upon the surface from many angles, then the shadows are filled in and all fibers have an opportunity to light up. The reduction in shadows under diffuse lighting is illustrated in **Fig. 9**.

Diffuse illumination from an integrating sphere can provide such an even background that we have measured an average COV of only about 2% on the surface image of newsprint or fine paper and only twice that for handsheets. **Figure 10** shows a field of view about two millimeters wide photographed with the illumination system of the commercial instrument to be called the Paprican InkScanner. The background is more uniform than in any view of Fig. 6.

Ink behind surface fibers

A very uniform background permits the use of a low-contrast threshold for particle detection without detecting shadows. A low-contrast threshold is useful because a single layer of fibers is not quite opaque enough to obscure a large black speck behind it. If a bold ink speck is partially occluded by a

6. The same view of residual ink in a handsheet illuminated at (a) 40°, (b) 45°, (c) 50°, (d) 60°, (e) 70°, and (f) 80°. With oblique illumination the background variations in reflectance obscure our view of the ink.



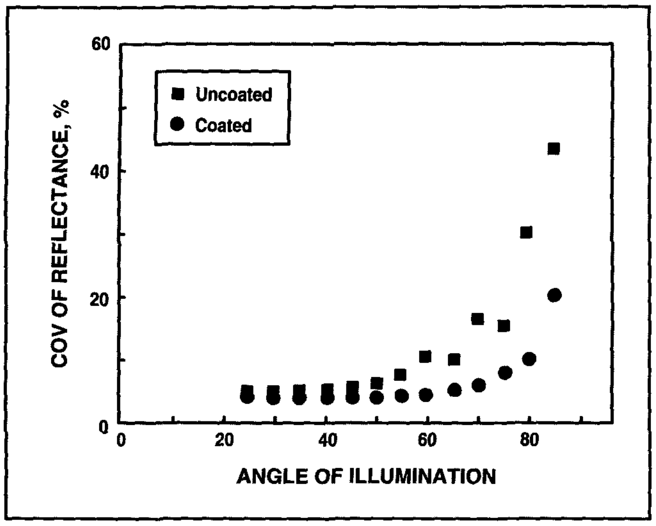
surface fiber, that fiber will appear gray rather than white where it passes over the ink. Both Fig. 6 and Fig. 10 have been chosen to contain examples of this. Such particles can be detected as complete units if the contrast threshold can be set low enough. However, a speck must provide a wide enough backing to the surface fiber if that fiber's reflectance is to be lowered sufficiently. If the fiber segment is not completely backed by black, enough light will scatter into the back of the fiber from its immediate neighbors to keep the fiber light. A small speck completely covered by a surface fiber will usually escape detection.

Design features of the InkScanner

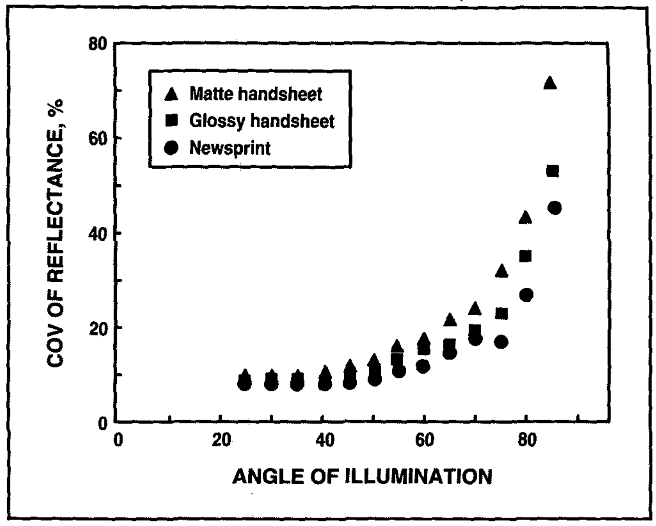
A field of view 2.7 mm^2 is illuminated via an integrating sphere from a very stable solid-state lamp. The wavelength has been chosen to maximize the contrast with the sensitivity profile of the digital camera. A digital camera with 512 x 512 independent pixels captures the image to an 80386-based dedicated computer. Each field of view can be processed in less than two seconds. All camera adjustments and focus are fixed in the factory, but digitization parameters are adjustable with software.

A pneumatic cylinder presses the specimen at constant force against a 3-mm-diameter aperture. This is the only moving part in the system. The aperture is small enough that the specimen will remain flat across the field of view without the use of a cover glass. As noted above, a cover glass can be the source of artifacts.

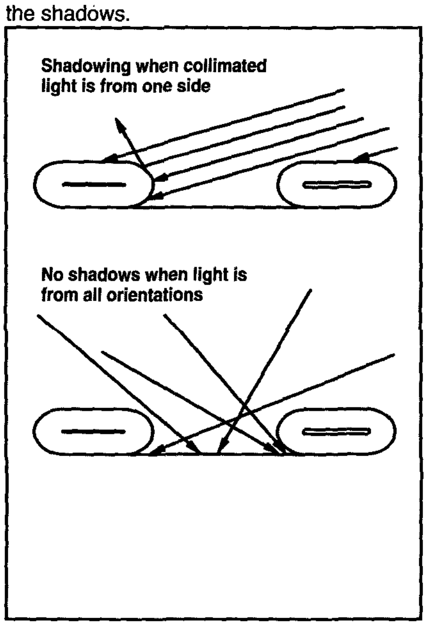
7. The measured coefficient of variation of the surface reflectance of a coated and an uncoated fine paper as a function of illumination angle



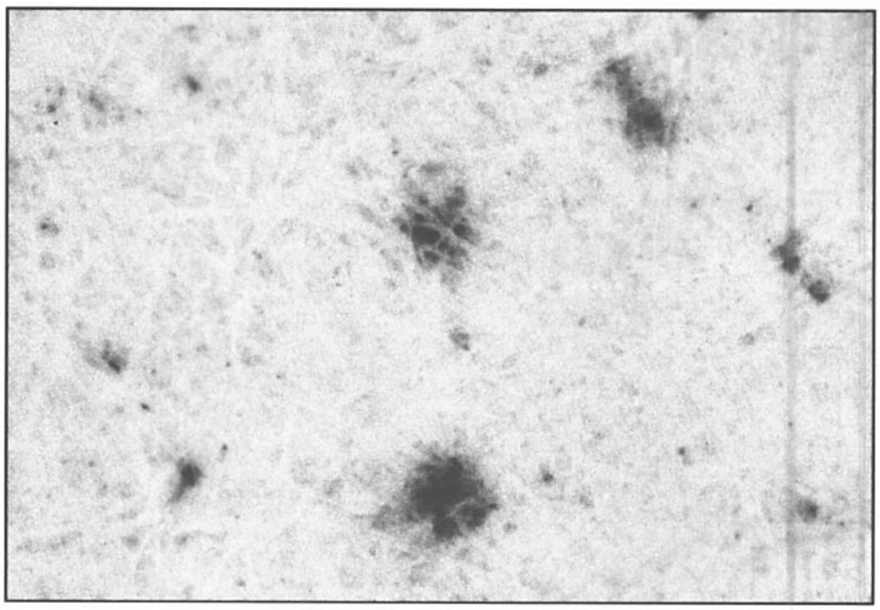
8. The measured COV of the surface reflectance of a newsprint sheet and a handsheet as a function of illumination angle. A high COV can frustrate the automatic detection of the real ink specks.



9. Diffuse illumination can remove most of the shadows.



10. A micrograph of residual ink in a handsheet illuminated diffusely. The field of view is 2 mm wide.

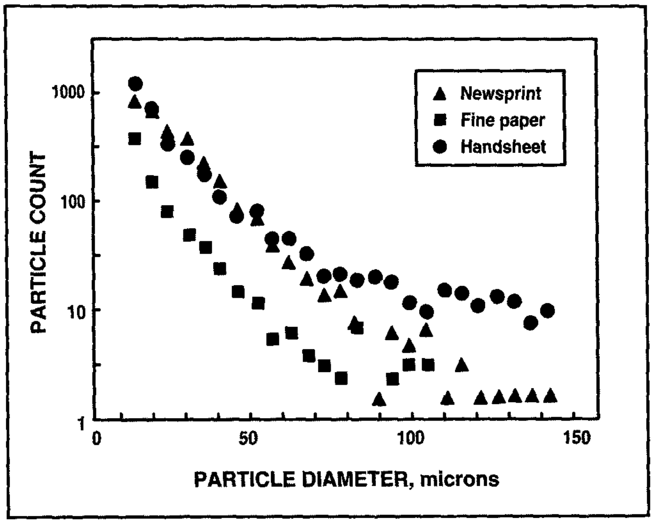


The center-surround detection algorithm needed for dirt detection *(10)* is not needed here because emulation of the visual process is no longer needed and because the 2.7-mm^2 field of view is small in comparison to the formation variations corrected by that algorithm. The average reflectance within a field of view, however, may vary from position to position on the sheet. Some form of field-to-field adjustment of the detection threshold is needed. In this system, we generate a grey-level histogram of each field of view and set the threshold based on the shape of that histogram.

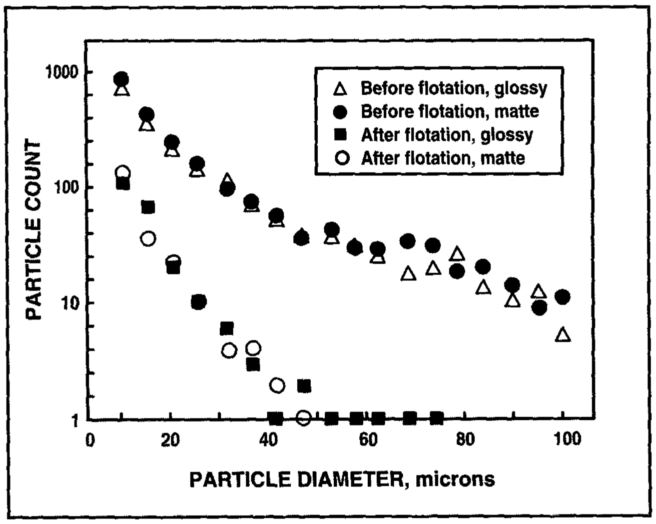
Presentation of data

The final form of data presentation and the most useful parameters of the distribution are yet to be determined in light of feedback from a users' group and applications research at Paprican. It is neither difficult nor time consuming to measure a population of a few thousand features on a sample. The mean extracted from such a population should be very precisely established, but the mean may be overly sensitive to the likelihood of sampling the occasional feature of extraordinary size. It has been convenient to display histograms of the common log of the count versus particle diameter. This compresses the hundredfold difference between the number of tiny particles and the number of marginally visible particles.

11. The measured histogram of residual ink particles in a fine paper, a newsprint, and a handsheet



12. The measured histogram of carbon black particles in handsheets sampled before and after a laboratory flotation deinking



I. Residual ink histogram statistics

Sample	*Fields*	*Count*	*Mean diameter, microns*	*Percent coverage*
Fine paper				
Side 1	130	1026	19.7	0.06
Side 2	130	2531	17.4	0.10
Handsheet				
Glossy	100	3372	29.1	0.87
Matte	100	3165	40.9	2.14
Newsprint				
Side 1	70	2020	22.4	0.23
Side 2	70	1465	24.0	0.21
Brightness pad before flotation				
Glossy	100	1994	33.6	0.74
Matte	100	2451	38.0	1.2
Brightness pad after flotation				
Glossy	100	221	16.0	0.01
Matte	100	215	14.2	0.01

Examples of residual ink histograms

A few sample histograms are shown here to illustrate the technique. The residual ink histogram for three paper sheets is shown in **Fig. 11**. The first is a fine paper made with deinked fiber, the second a newsprint made from deinked fiber, and the third is a handsheet made from a newsprint furnish mixed at 10% consistency with 1.5% offset ink paste. All three exhibit high counts for the tiniest ink specks, and the two commercial papers exhibit almost an exponential decrease in residual ink particle size right up to a vanishing point at a diameter of 120 microns. While the others continue to diminish exponentially, the histogram of the handsheet remains high from 60 microns to above 150 microns. This extra population of dirt extends into the range of easily visible features. This handsheet looks much dirtier than the corresponding newsprint.

As another example, we show in **Fig. 12** the histogram of a brightness pad from the same pulp as the handsheet. Brightness pads were sampled before and after a laboratory flotation deinking process. Some sidedness is evident. The sheet-forming process appears to be filtering the ink differently in the handsheet than in the brightness pad. Flotation has removed a greater fraction of the larger particles. About 15% of the 10-micron particles remain after deinking, but only 2% of the 50-micron particles remain and even fewer of the larger particles remain.

Some sidedness is resolvable in most of the sheets. The sidedness may be in the fractional coverage, the particle count, or the particle size, as shown in **Table I**. In the fine paper, the side with twice the coverage merely had twice the count of comparably sized particles. In the newsprint, one side contains a quarter fewer particles without loss of coverage because the lost particles are mostly tiny ones. The matte side of the "before flotation" handsheet contains more ink; there are more particles and they are larger. However, no sidedness is evident after flotation in this experiment.

Summary

Diffuse reflectance imaging can provide adequate spatial and photometric resolution to measure residual ink particles on the surface of paper to a minimum diameter of 10 microns. An instrument has been described utilizing this kind of illumination. Because it is sensitive to ink particles on the surface of the sheet, it can distinguish sidedness factors readily. This instrument is designed to count a statistically meaningful particle histogram quickly and easily.

Literature cited

1. McCool, M. A. and Taylor, C. J., *Tappi J.* 66(8): 67(1983).
2. McCool, M. A. and Silveri, L., *Tappi J.* 70(11): 75(1987).
3. Zabala, J. M. and McCool, M. A., *Tappi J.* 71(8): 62(1988).
4. Lowe, G., Licht, B., and Leighton, G., *Tappi J.* 74(1): 125(1991).
5. Nguyen, N. G., O'Neill, M. A., Jordan, B. D., *et al., J. Pulp Paper Sci.* 18(5):J193-J196(1992).
6. Heintze, H., *Technical Section CPPA Annual Meeting Proceedings*, Canadian Pulp and Paper Association, Montreal, 1991.
7. Schriver, K. E., Bingham, S. J., and Voosen, L. L., *TAPPI 1991 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, p. 1009.
8. Larsson, A., Stenius, P., and Odberg, L., *Svensk Papperstid.* 18: R165(1988).
9. Gray, R. T., Simon, G. C., Gibbon, D. L., *et al., TAPPI 1992 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, pp. 247.
10. Jordan, B. D. and Nguyen, N. G., *J. Pulp Paper Sci.* 14(1): J16–J19(1988).
11. Clarke, B. and Charman, W. N., *J. Phys. E. Sci. Instrum.* 22: 162(1989).
12. Huynh, V. M. and Luk, F. M., U.S. pat. 4,878,114 (Oct. 31, 1989).
13. Beland, M. C., Nguyen, N. G., de Silveria, G., *et al., J. Pulp Paper Sci.* 19(3): J114-J118(1993).

The authors thank G. Dorris for helpful discussions and for providing the handsheets of laboratory deinked pulp.

Received for review March 16, 1993.

Accepted May 20, 1993.

Presented at the TAPPI 1993 Recycling Symposium.