Nonwoven Uniformity — Measurements Using Image Analysis

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Abstract

Statistical measures have been developed for quality control as well as characterization of mass distribution in fibrous substrates. The mass distribution in 2D space has been measured by imaging the substrate. The intensity distribution of reflected/transmitted light has been used as a representative of the mass distribution. Spatial mass uniformity has been measured in terms of a standardized index of dispersion and mass anisotropy ratio that are reasonably independent of fiber mass density. The dispersion index is standardized between the limits of -1 and +1, with -1 representing uniform distribution and +1 representing aggregated distribution. Furthermore, the standardized values have been combined with the qualitative grades to categorize and differentiate uniform patterns. Standardized index of dispersion and mass anisotropy ratio have been evaluated for a wide range of nonwoven webs and adhesive lay down patterns.

Introduction

Mass uniformity in fibrous structures, such as nonwoven, paper, or sprayed adhesives in nonwoven/film-based laminates, plays an important role in defining appearance, performance, and processability of such structures. For example, in filtration processes, web performance is largely dependent on the uniformity of the web. Thin spots in the fibrous sheet affect filtration performance by allowing large particles to pass through the filter. Similarly, thin spots in nonwoven web allow the adhesive bleed through during nonwoven lamination process. As raw materials and finished products, fibrous structures (from now on referred as webs) are expected to have a uniform mass distribution for better performance and aesthetics. For aesthetics (e.g., opacity), webs need to be uniform over areas easily perceivable by humans; for example, non-uniform areas as small as about 10 mm^2 are noticeable to human eye as viewed from a distance of about 30 cm. However, during post-processing of webs for making hygiene products, wipes, and filtration products, non-uniform areas much smaller than that perceived by humans are important to avoid defects and material failures. Realizing the need to describe mass uniformity in fibrous structures for hygiene products and wipes, a method was developed at the Procter & Gamble Co. This article describes that method and its application to characterize web mass uniformity.

Typically, nonwoven webs are characterized in terms of basis weight, structure, and visual uniformity. A number of methods and techniques, both subjective and objective, are used in the nonwovens and paper industry to quantify web uniformity. These techniques range from expert-panels rating against benchmarks to using sophisticated image analysis techniques for quantifying mass uniformity in fibrous networks. The nonwovens industry uses the coefficient of weight variation as a standard quality index to quantify the web uniformity. Beta rays and electromagnetic radiation (gamma rays and lasers) have been used for online measurement of the web mass and uniformity. See Boeckerman [2] for details on the application of beta rays for measuring web uniformity. Aggarwal, Kennon, and Porat [1] used a scanned-laser technique to monitor both weight and cover factor of a web. Huang and Bresee [5] correlated the coefficient of web mass variation to the coefficient of pixel gray level variation of the web image. Ericson and Baxter [4] correlated the tensile strength of the web with the filament separation and the visual uniformity of spunbonded webs. Trepanier et al. [18] developed an image analysis method to quantify formation and print quality of paper in terms of a statistical parameter, “specific perimeter” that measured the graininess per unit area of the formation. Pound [10] developed a web-uniformity metric called “Coverage” and correlated it to basis weight, air porosity, and hydrohead. Coverage was defined as a web-color value using a color meter measuring 50 mm spot size. Pound also used coefficient of variation of gray-level intensity of web image to quantify uniformity of large areas (8 in. x 14 in.) of webs. Kallmes, Scharcanski, and Dodson [7, 14, and 15] described paper as a stochastic structure with local grammage following a Gaussian distribution. They measured spatial variability from ß-radiographs or light-transmission images of paper in terms of local spatial anisotropy of flocs. Shambaugh and Chhabra [16] described melt blowing web formation process as a stochastic process. They showed that mass distribution in a melt-blown web follows a bivariate Gaussian distribution. Chhabra [3] correlated fiber web distribution to the fiber diameter, a function of web formation process variables.

Spatial uniformity of fibrous structures has been described statistically in terms of an index of dispersion. Conventionally, coefficient of mass variation (standard deviation/mean) has been used as dispersion measure of mass uniformity in fibrous structures [1, 2, 4, 5, and 12]. Local mass variation is determined either directly by measuring mass of small samples from various sections of the web, or indirectly as visual uniformity via transmitted or reflected intensity (representative of mass) of electromagnetic radiation irradiating the fibrous web structure. Though the web mass variation is quite well represented in images of the web, the above techniques differ in the mass-representing variable selected for dispersion calculation. Typically, researchers have used the image gray-level intensity distribution as a representative of web mass distribution (higher intensities representing denser region for reflected light images) and its coefficient of variation (COV) as a measure of web uniformity [4, 5, and 10]. However, COV only describes how much variation is present in the intensities (or web mass) and does not address the spatial variation of web mass, i.e., fails to quantify mass aggregation or uniformity.

The work of previous researchers described above either assumes an underlying statistical distribution for the fibrous web or uses a simplistic approach to define a statistic for web uniformity that may or may not be applicable to all types of fibrous structures and laydown patterns during web formation. Heretofore, the techniques used lack a standardized index (having confidence limits) to quantify the webs or laydown patterns across a broad range of basis weights: from less than 10 gsm to more than 100 gsm.

Present work describes spatial mass uniformity in terms of a standardized index of dispersion (varying between -1 and +1) that is reasonably independent of mass density. Furthermore, anisotropy of mass uniformity has been quantified by a CD/MD dispersion ratio: a value greater than 1.0 means a greater variation of mass in the cross-direction than in the machine direction and vice versa; a value of 1.0 means isotropic mass distribution. Measured from images of web, the dispersion index is quantified as variance-to-mean ratio of image relief statistic (described later in the article), a metric similar to the one used by Pourdeyhimi [12] to measure uniformity of spatial patterns. The present article discusses the mathematical formulation and application of the standardized index of dispersion to measure the mass uniformity and mass anisotropy at length scales as small as 2 mm^2 to as large as 100 mm^2 of real and simulated nonwoven webs as well as that of adhesive laydown patterns in laminated nonwovens. Though applied to fibrous web structures, the methodology described herein is applicable to any two-dimensional pattern, gray-scale image, or data set.

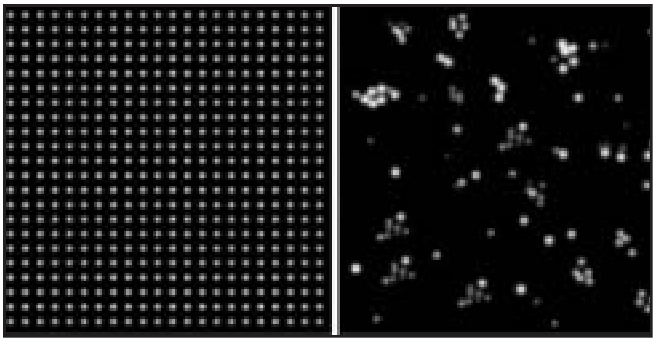
Spatial Uniformity of Fibrous Structures

Uniformity Metric: Concept and Mathematical Formulation

Spatial uniformity of fibrous structures can been described statistically using an index of dispersion. In the present work, spatial uniformity of web mass is described by dispersion of its surface relief distribution. Surface relief is representative of mass density gradients in local regions. In principle, this concept is similar to topographical surface relief that represents the variations in elevation of the earth's surface: the higher is the elevation, the greater the mass present on a surface. The surface relief in a local region is representative of the average mass density gradient in that local region. Figure 1 depicts the two simulated extremes of mass distribution: uniform versus clumped distribution. A non-uniform or clumped distribution, as in *Figure 1 (right)*, exhibits local regions with a large deviation from the average surface relief. However, if all regions in consideration have a surface relief similar to the average surface relief, a uniform distribution is observed as seen in *Figure 1 (left)*. In the present work, dispersion of surface relief of the web was used to quantify the web mass uniformity. Surface relief of a web can be measured from its gray-scale images taken in transmitted or reflected light or any other radiation. Pourdeyhimi [11] has described a method for measuring surface relief area from gray-scale images of webs. Each pixel of a gray-scale image (with 256 gray-levels or 8-bit) is considered a column of cubes with each cube having area (1 pixel) X (1 pixel) and height equal to one intensity level. *Figure 2* shows the translation of square pixels of *Figure 3* into columns of cubes.

Surface relief of a pixel is the difference in height (or gray-level intensity, G) of two adjacent pixels sharing a side. The surface relief area was calculated as the total number of exposed faces of cube columns in a "quadrat," which is

Figure 1
EXTREMES OF MASS DISTRIBUTION: SIMULATED UNIFORM (LEFT) AND CLUMPED (RIGHT) PATTERNS



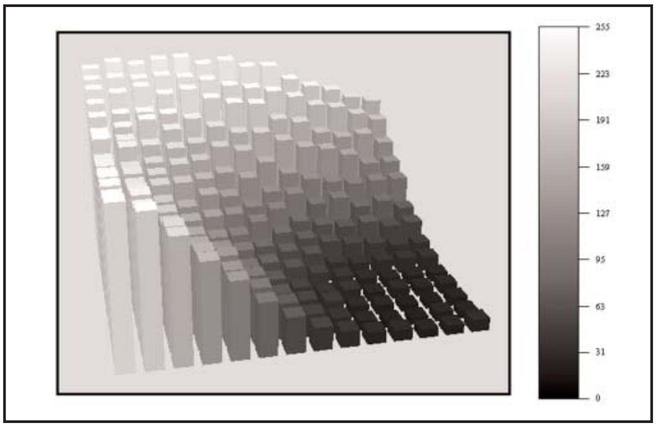


Figure 2
PIXELS REPRESENTED AS COLUMNS OF CUBES

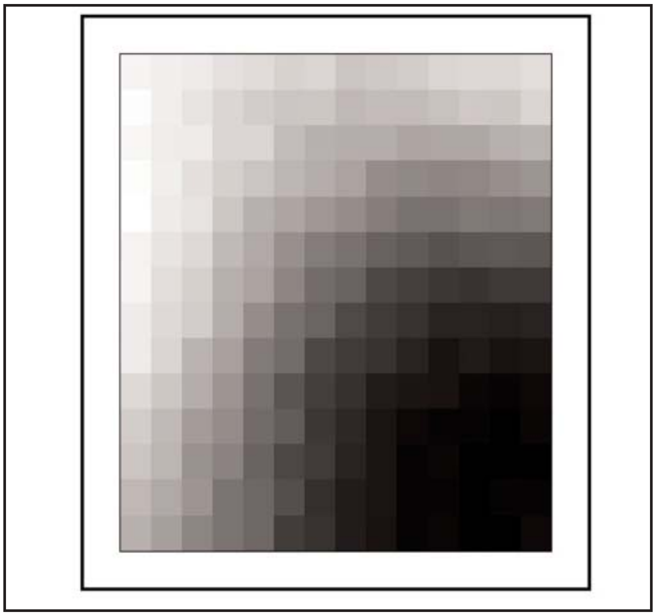


Figure 3
DETAILED IMAGE PIXELS

defined as a rectangular region of interest (the term “quadrat” should not be confused with the word “quadrant”). Only lateral surfaces were considered and flat tops of columns were ignored in the calculation of relief area. Mathematically, equation (1) gives surface relief area *q* of a quadrat, *m X n* pixels in size.

$$\text{Surface Relief Area,}\quad q = \frac{\sum_{quadrat} D}{P} \qquad (1)$$

where

$$\text{Relief of pixel } (i,\, j),\quad D_{i,j} = \begin{cases} G_{i,j} - G_{i+x,j+y} & \text{when } G_{i,j} \ge G_{i+x,j+y}, \\ 0 & \text{otherwise} \end{cases}$$

$$\text{Position pairs in the quadrat,}\quad P = 4 \times m \times n$$

In the current work, denser regions of the web were represented by lighter regions in images, and vice versa. Since lighter regions were high mass areas of web, lighter regions were weighted in favor of darker regions by multiplying equation (1) by a bias factor as shown in equation (2)

$$q_R = q \cdot bias \qquad (2)$$

where *bias* = $(\mu_{Gq} - G_{min})/(G_{max} - G_{min})$; μ_{Gq} is the mean gray-level intensity of a quadrat; G_{min} and G_{max} are the minimum and maximum gray-level intensities in that quadrat, respectively.

The dispersion of the quadrat surface relief area represents the uniformity of mass distribution. Selection of an appropriate measure of dispersion was based on the following criteria: (a) it should describe the complete spatial variation in mass (from maximum uniformity to randomness to maximum aggregation), (b) it should be relatively independent of total mass and mass density in the region, and (c) it should be standardized to compare the uniformity two or more spatial distributions (an important aspect from the quality control perspective): a standardized scale should include the confidence limits on the randomness of the spatial distribution. Based on above criteria, the variance-to-mean ratio was selected as the index of dispersion.

$$\text{Index of Dispersion, } I_d = \frac{\sigma^2}{\mu} \qquad (3)$$

Since the surface relief is a measure of the local mass density gradient, a small deviation in the local mass density gradient from the average mass density gradient (small σ^2) suggests the presence of a uniform mass distribution (small I_d) as exhibited in *Figure 1 (left)*. Consequently, the dispersion index in the equation (3) appropriately captures the physical meaning of uniformity of the mass distribution. Interestingly, the variance-to-mean ratio is one of the simplest and most commonly used indices of dispersion in the spatial pattern analysis in the field of ecology [8]. For a random pattern, described by Poisson distribution, the variance is equal to the mean, or $I_d = 1$. Therefore, the interpretation of statistics becomes significantly straightforward: $I_d > 1$ means clumped distribution; $I_d = 1$ means random distribution; and $I_d < 1$ means uniform distribution. A major limitation of the variance-to-mean dispersion measure is in the case of aggregated distributions, where the upper limit is a function of the maximum value of the population count variable [8]. However, Myers [9] showed through the simulation analysis of multiple dispersion indices that the variance-to-mean ratio was weakly correlated to the statistical population density but was the best predictor of clumping.

Spatial randomness (non-uniform, yet not aggregated) was evaluated via fitting the observed distribution to the Poisson distribution. The null hypothesis of randomness was tested by a χ^2-statistic obtained from the dispersion metric using the following equation:

$$\chi^2 = I_d(n-1) \qquad (4)$$

where n = number of quadrats in the selected web area.

The spatial pattern was considered random if the observed χ^2-statistic was between the 95% confidence limits. If the observed value was lower than the lower confidence limit, the spatial pattern was uniform, while a value higher than the upper confidence limit was indicative of an aggregated pattern. The dispersion index was standardized between –1.0 and 1.0 based on the confidence limits using the following equations [17]:

$$\text{Limit below which the pattern is uniform} = \text{Uniform index, } M_u = \chi^2_{0.025}/(n-1) \tag{5}$$

$$\text{Limit above which the pattern is clumped} = \text{Clumped index, } M_c = \chi^2_{0.975}/(n-1) \tag{6}$$

where $\chi^2_{0.025}$ is the value of chi-squared variable with 2.5% area to the left of χ^2-distribution curve at (n – 1) degrees of freedom; $\chi^2_{0.975}$ is the value of chi-squared variable with 97.5% area to the left of χ^2-distribution curve at (n – 1) degrees of freedom.

The following cases describe the standardized index for aggregated, random, and uniform distributions:

Case I: When I_d $M_c > 1.0$, the standardized index is between 0.5 and 1.0, and the pattern is maximum aggregated at 1.0

$$\text{Std. Index, } I_s = 0.5 + 0.5\left(\frac{I_d - M_c}{I_m - M_c}\right) \tag{7}$$

where I_m, the maximum possible dispersion, occurs when variance is maximum and mean is minimum. This condition is possible when each row and column has only one quadrat with maximum possible relief. In an 8-bit gray-scale image, unbiased maximum possible relief area of a quadrat is 127.5 when a quadrat has alternating black (0) and white (255) pixels [11].

Case II(a): When $M_c > I_d$ 1.0, the standardized index is between 0.0 and 0.5, and the pattern is random-to-aggregated, with random at 0.0

$$\text{Std. Index, } I_s = 0.5\left(\frac{I_d - 1}{M_u - 1}\right) \tag{8}$$

Case II(b): When $M_u < I_d < 1.0$, the standardized index is between –0.5 and 0.0, and the pattern is uniform-to-random, with random at 0.0

$$\text{Std. Index, } I_s = -0.5\left(\frac{I_d - 1}{M_u - 1}\right) \tag{9}$$

Case III: When $I_d < M_u < 1.0$, the standardized index is between –1.0 and –0.5, and the pattern is maximum uniform at -1.0

$$\text{Std. Index, } I_s = -0.5 + 0.5\left(\frac{I_d - M_u}{M_u}\right) \tag{10}$$

Quadrat analysis was used to evaluate web uniformity. This methodology is commonly used in the field of ecology [8]. Based on the desired scale (e.g., length scale from post-processing), the image was divided into N x M quadrats. *Figure 4* shows an image of adhesive laydown pattern divided into 49 quadrats. Quadrat relief area of each quadrat was calculated using the equation (2). Both row-wise (representing machine direction, MD) and column-wise (representing cross-direction, CD) mean and variance were evaluated. Mean and variance of MD and CD were pooled from N rows and M columns, respectively. MD and CD indices of dispersion were calculated as their respective ratios of variance-to-mean. Since most webs have preferred mass orientation in the machine direction, mass distribution is anisotropic. Therefore, anisotropy of mass dispersion (not to be confused with fiber orientation) was calculated as the ratio of CD-to-MD dispersion: a value greater than 1.0 means a greater variation of mass in the cross-direction than in the machine direction and vice versa; a value of 1.0 means isotropic mass distribution. The overall index of dispersion was calculated by pooling MD and CD variance and dividing it by mean quadrat relief of the image as follows:

$$I_{d,\,overall} = \frac{\left(M \cdot \sigma_M^2 + N \cdot \sigma_N^2\right)/(M+N)}{\mu_{qR}} \tag{11}$$

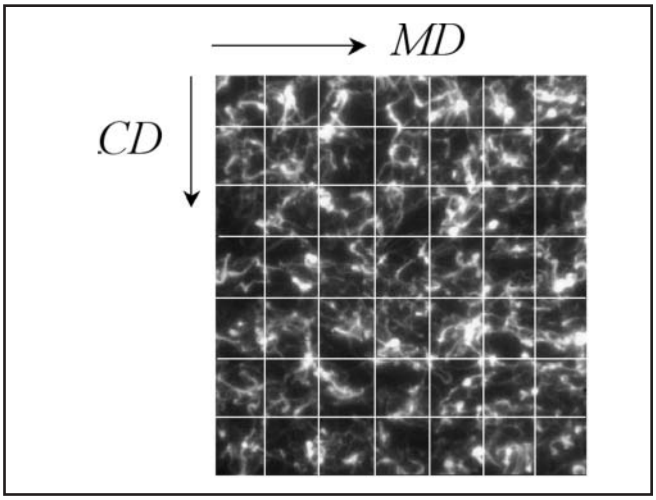
The overall dispersion index calculated from equation (11) was standardized in the range of –1 to +1 using equations (5) to (10). In the case of fibrous webs, the statistics were interpreted as the uniform mass distribution more desirable than the random distribution, which in turn was more desirable than the aggregated distribution, unless otherwise needed. Based on above statistics, webs were ranked in the order of their standardized uniformity values.

Implementation and Results

Implementation

The standardized index of dispersion was tested on real as

Figure 4



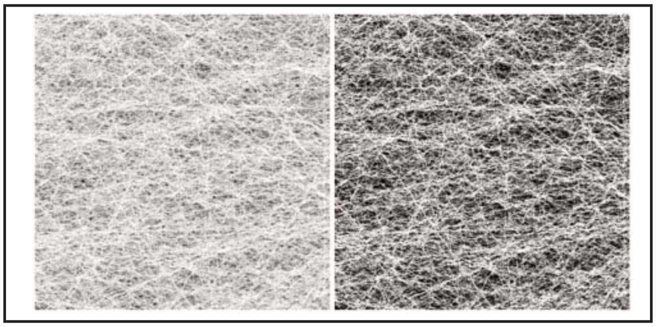


Figure 5
SIMULATED CONTINUOUS FIBER WEB
(10 MM X 10 MM)

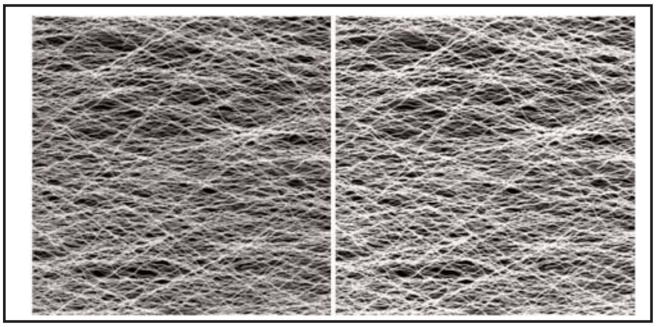


Figure 6
SIMULATED STAPLE FIBER WEB
(10 MM X 10 MM)

well as simulated patterns by dividing the patterns into quadrats of different areas ranging from 2 mm^2 to 100 mm^2. For a given quadrat size and number, the same image was sampled multiple times by shifting the position of horizontal grid lines by a known amount (10% of height) in the downward direction (CD) while keeping the column positions constant. This was done to minimize the dependence of dispersion index on quadrat positioning, which could potentially render the same pattern clumped or uniform. The variance and mean of all samplings were pooled to evaluate the standardized dispersion index and dispersion anisotropy. Statistical stationarity of images was assumed during multiple samplings of the same image. The dispersion evaluation algorithm was implemented using FORTRAN 90, and critical values of χ^2-distribution were evaluated using IMSL routines [6].

Images of webs were taken using digital cameras with field of view at least 5 cm x 5 cm. Nonwoven webs were imaged under reflected white light with a resolution of 84 pixels/cm. Images of adhesive laydown patterns in nonwoven laminates were captured under ultraviolet light that caused adhesive to fluoresce. Transmitted ultraviolet light (350-380 nm) was used for imaging. Image resolution was 86 pixels/cm. Colored images were converted to gray-scale using digital color separation that kept the channels having maximum amount of intensity information (evaluated using information entropy [3]). Gray-scale images were preprocessed by applying Gaussian filter and 2-D FFT filter, if needed (e.g., for digitally removing thermal bonds from nonwoven images). Histogram equalization (flattening) was done to remove any illumination intensity variation within and between images [13]. Removal of illumination variation (lighting instability) via histogram flattening improves the repeatability of data. In all images, lighter regions represented denser regions of webs. Dispersion evaluation was then performed on the preprocessed images.

Uniformity evaluation was performed on four simulated patterns, four nonwoven webs, and four adhesive patterns. *Figure 1* shows images of the simulated clumped and uniform distributions (85 pixels/cm). *Figures 5 and 6*show the simulated nonwoven patterns and their pre-processed images. *Figure 5* shows a simulated 30 gsm, 4.1 denier, continuous fiber web, while *Figure 6* shows a simulated 20 gsm, 10.5 denier, staple fiber web. Both simulated images had a resolution of 500 pixels/cm.

Of the four nonwoven webs tested, there were two spunbond (15 gsm and 60 gsm), one carded-thermobond (31 gsm), and one spunlace (58 gsm) nonwoven. Four different adhesive patterns (12 gsm) were also tested for mass uniformity. *Figures 7 and 8*show raw images of nonwoven and adhesive patterns, respectively.

Results

Results show that patterns with different mass densities can be compared using the same standardized index. Furthermore, with an increase in quadrat area, patterns tend to become more uniform. This result is expected since larger size quadrats will average out the variation of relief in local neighborhoods and the pattern will appear uniform.

Figure 9 shows uniformity grading of nonwovens as a function of quadrat area. Five uniformity grades are defined in *Figure 9* with the grade 1 assigned to the most uniform distribution and the grade 5 assigned to the least uniform distribution. All four real nonwovens and two simulated nonwovens had standardized index of dispersion between -1.0 and -0.5 (between grades 1 and 5), making them uniform patterns. However, simulated nonwovens were far more uniform than the real webs for all quadrat areas. All real nonwovens were least uniform (greater than grade 2 uniformity) for 2 mm^2 size quadrats and most uniform (grade 2 uniformity) for 100 mm^2 size quadrats. Interestingly, for the samples considered in this study, web uniformity did not vary proportionally with basis weight: nonwovens of different basis weights could be compared on the same uniformity grading scale.

Figure 10 shows the uniformity grading of four adhesive patterns. Pattern 3 was the most non-uniform pattern and graded as clumped pattern up to 4 mm^2 size quadrats. However, as the quadrat size increased, pattern 3 started becoming more uniform because of averaging out of local relief variation for larger quadrat sizes. Other three adhesive patterns varied between grade 1 and grade 3 uniformity. On comparing *Figures 9 and 10*, it can be observed that web unifromity did not correlate to basis weight; therefore, patterns of different mass density could be graded using the same scale of uniformity.

Figure 11 shows the variation of dispersion index for sim-

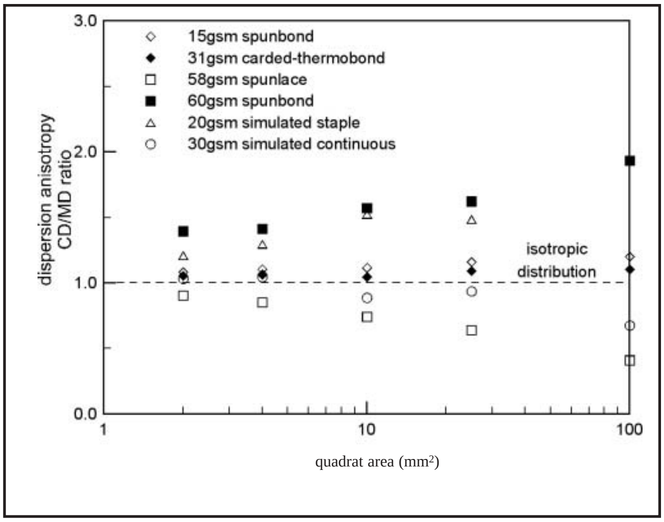


Figure 12
ANISOTROPY OF MASS DISTRIBUTION IN NONWOVENS

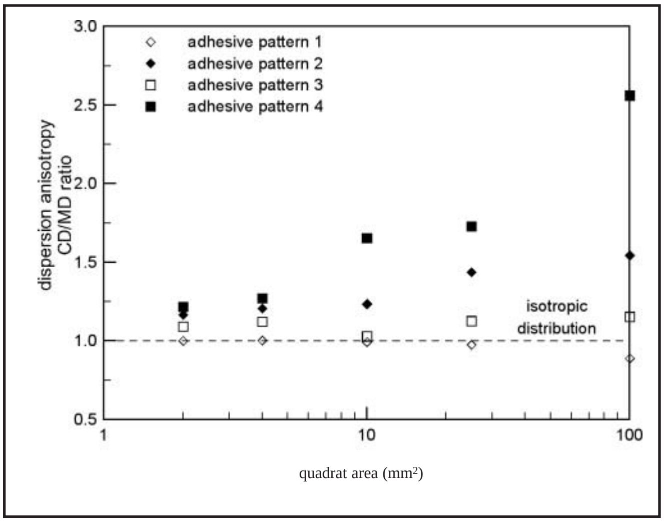


Figure 13
ANISOTROPY OF MASS DISTRIBUTION IN LAY DOWN PATTERNS

mm^2. Interestingly, for 100 mm^2 quadrat size, simulated clumped pattern had maximum uniformity since the aggregates are uniformly spaced for 10 mm x 10 mm quadrat size.

Figures 12 and 13 depict the anisotropy in mass uniformity as function of quadrat size. Mass anisotropy increases with increasing quadrat size for both nonwovens and adhesive laydown patterns. In *Figure 13*, except for adhesive pattern 1, all other adhesive patterns had greater dispersion in CD than in MD; therefore, the mass distribution was anisotropic, though patterns 2 and 4 were reasonably uniform on the standardized index scale as illustrated in *Figure 10*. In *Figure 12*, similar anisotropic behavior was observed for 60 gsm spunbond and 20 gsm simulated staple fiber web, though both patterns are reasonably uniform on the standardized index scale as illustrated in *Figure 9*. *Figure 12* also shows spunlace web to be more dispersed in MD than in CD. Again, such anisotropic behavior is not captured by the standardized index of dispersion in *Figure 9*.

Conclusions and Discussion

A standardized measure of mass uniformity has been developed for fibrous structures. The standardized index of dispersion is reasonably independent of basis weight. Therefore, the standardized index can be used to compare nonwovens or adhesive laydown patterns of different basis weights (from less than 10 gsm to more than 100 gsm). The standardized scale can be correlated to customer specifications or pre/post-processing variables. Furthermore, the standardized scale has been combined with the five qualitative grades to categorize and differentiate uniform patterns. Therefore, it can also be used for quality control purposes.

Anisotropy of mass uniformity has been measured for different webs. When combined with standardized index of mass uniformity, the anisotropy ratio can be a very useful tool to differentiate between different webs with a similar standardized index of dispersion. A robust test methodology can be developed by combining the standardized index of dispersion with the mass anisotropy ratio for quality control as well as characterization of mass distribution in nonwovens, adhesive laydown patterns, or any other substrate. In principle, the methodology can be applied to any two-dimensional pattern or data set to quantify spatial uniformity.

The metrics developed in the present work are reasonably good in evaluating mass uniformity when the size of quadrats (local regions of interest) is relatively small: about 1% of the sampled area. However, as the quadrat size increases, the surface relief variation in local regions starts averaging out, thereby exhibiting uniform distribution that may or may not be accurate. This can lead to potential errors in evaluation. Therefore, users of this technique must be aware of uniformity length scale important for their end use. Additional work is required to capture the local aggregation effects so that dependence of the dispersion index on the local region size can be minimized.

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