

Texture Evolution in Hydroentangled Nonwovens

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We recently reported on a co-occurrence-based method for texture analysis. This paper uses this texture analysis method to examine the development of the texture during hydroentangling as a function process conditions. We report on the development of texture as a function of hydroentangling energy. Energy was varied by controlling the pressure and number of passes. All fabrics were produced using the same web on the same forming belt substrate. Our preliminary data indicate that the degree of texture definition increases as a function of pressure up to a point and then begins to deteriorate.

Key Words

Texture, Hydroentangling, Co-occurrence

Introduction

The hydroentangling technology in its various forms has existed for over forty years. Chicopee developed the basic concepts in the early 1950's using a low energy patterning process. DuPont started up the first high-energy spunlaced plant in 1974 using proprietary high-speed web forming and hydraulic needling (hydroentangling) technology [5]. The physical characteristics of hydroentangled nonwoven fabrics such as softness, flexibility, hand, drape, bulk, conformability, moldability, high strength and delamination resistance make this process unique among the other nonwovens process.

One of the goals of the hydroentanglement process is to produce fabrics with aesthetics and performance comparable to wovens or knits. While hydroentangled fabrics' tensile strength, resistance to tear, and bending behavior are com-

parable to those of wovens and knits, they exhibit low initial modulus, poor tensile recovery and wash durability. It is expected that this technology will strongly compete with weaving and knitting in the future.

There are many parameters that influence hydroentanglement and therefore, fabric performance. Fiber and web properties have primary effects on the performance of the finished product. The degree of fiber entanglement and the type of belt of drum used to support the web determine the ultimate properties of the fabric [7].

Broadly speaking, two types of hydroentangled nonwovens can be produced for two entirely different purposes. One is to make a nonapertured product; here hydroentangling is merely a mechanical bonding process. The other is to make an apertured or patterned end product. Here the water jets are used to entangle as well as to sculpt the fabric. The requirements of the forming wires in these two end uses are vastly different. In manufacturing a nonapertured product, the intent is primarily to impart strength to the final fabric by hydroentangling. Alternatively, hydroentangling can also be used to combine two or more different webs into a composite end product. In this case, the forming wire surface typically does not produce a distinct pattern in the final product. In the apertured nonwovens manufacturing process, however, a textured product surface with a distinct mark from the forming wire is desired [8].

The total specific energy of water applied to the fiber web is a key process variable responsible for the efficiency of the transfer of the patterns onto the fabric surface. Naturally, the energy is also going to have a profound effect on the physical and structural properties of the fabrics.

The energy transferred to the web can be controlled by

1. Manifold pressure
2. Residence time
3. Number of manifolds and passes

As the target weight and density of product increases so does the water energy requirement, to a point where web pen-

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etration can no longer be achieved without major fiber damage. The theoretical formula for specific energy, E , in kJ/kg applied to the fiber web by water jets in a manifold is given by [2,3]:

$$E = K \frac{CD^2NP^{2/3}}{\rho^{1/2}WS} \quad (1)$$

Where K is a constant ($60 \cdot 10001.5 P / 81/2$), C is the orifice discharge coefficient (assumed 0.64), D is the diameter of jet orifice (m), N is the number of jets/m per manifold, P is the water pressure (N/m^2) in the manifold, ρ is water density (g/m^3), W is the basis weight of the web (g/m^2), and S is the line speed in m/min. The total specific energy applied to the fabric (Kj/kg) is calculated by equation (2)

$$\text{Total Specific Energy, } E_t = \sum_{i=1}^p \sum_{j=1}^m E_{ij} \quad (2)$$

Where E_{ij} is the specific energy applied to the fiber web by manifold, j ($j=1,2,\dots,m$), calculated by equation (1), in the pass i ($i=1,2,\dots,p$).

Very few articles have appeared in the scientific literature dealing with the tensile properties of hydroentangled fabrics [1-4]. Tactile properties and the fabric appearance or surface texture, are also major performance characteristics that influence the consumers like or dislike of the final product. We focus on the fabric appearance or surface texture. In general, the term “texture” refers to the overall surface properties of the object, with no exact definition [9]. Surface texture, and thus fabric appearance, is usually evaluated subjectively by a panel following the procedures set in a number of standardized methods [1, 2]. But, these methods are characterized by poor accuracy because of their subjective nature.

The term “texture” originates from the Latin word “textura” which means, “to weave”. Thus, texture generally refers to repetition of basic texture elements called texels. A texel contains several pixels, whose placement could be periodic, quasi-periodic or random. Natural textures are generally random, whereas artificial textures are often deterministic or periodic.

In periodic assemblies, the placement of the objects (texels in the case of textured surfaces) determines the appearance. Texture may be coarse, fine, smooth, granulated, rippled, regular, irregular, or linear. These properties refer to the spacing of the units or what we would refer to as the texture period. Additionally, the degree of exactness of the placement determines the degree of order. If one considers the texture in the Fourier space, then the period would refer to the spacing and the power would refer to the strength of the degree of order within the texture.

We consider textures as a continuum between two extremes. At one end is the deterministic texture, which has a regular pattern. Here, a texture is defined by elements that occur repeatedly according to some placement rules. The other extreme is the stochastic (or random) texture, well exemplified by white noise. Most textures however, occur

somewhere between these two extremes. Indeed, loss of appearance is merely moving along this continuum. That is, strong textures move towards randomness.

The viability of this approach is firmly established in literature [10-18]. Here, we report on an investigation dealing with the evolution of the surface texture in hydroentangled fabrics at varying degrees of specific energy. Note that the fabrics used in this study are apertured. Therefore, what we refer to as texture is not only the surface properties of the fabric, but the placement and clarity of the holes in the samples. In cases where there are no holes in the fabrics, the surface texture is imaged using a dark-field illumination system to bring out the variations of the surface. We will deal with this issue in a subsequent paper.

Materials and Methods

1.7 dtex PET was selected as the fiber. A pilot-scale Honeycomb hydroentangling machine was used to produce fabrics under varying pressures and number of passes. The machine has three manifolds. The pressure on each of manifold can be independently controlled. The jet strips have two lines of orifices. The orifice diameter is 0.127mm and the density of the jets is 16 orifices/centimeter. The pressure can be as low as 13 bars for pre-wetting, and as high as 110 bars for hydroentangling. The fibers were opened, carded and cross-lapped in our facilities. The same web was used for all fabrics. Initially, we used a web density of 50 g/m². However we observed that, a light fiber web without any bonding does not give satisfactory results, and its texture is destroyed at higher pressures and number of passes. An example is given in *Figure 1*. It is clear that in the absence of any bonding, the water jets displace the fibers. Thus, better texture can evolve if the web is consolidated to some degree first before it is subjected to higher pressures. Consequently, we decided to use heavier webs and produced two sets of fabrics, respectively from 100 and 150 g/m² carded and cros-lapped webs. These webs were first consolidated at a pressure of 55 bars. Our final samples are shown in *Table 1*.

Image Capture and Preprocessing

Our capture device consists of a high-resolution mono-

Figure 1
TRIALS USING A 50-G/M² WEB AT
A PRESSURE OF 96.5 BARS

1 Pass

2 Pass

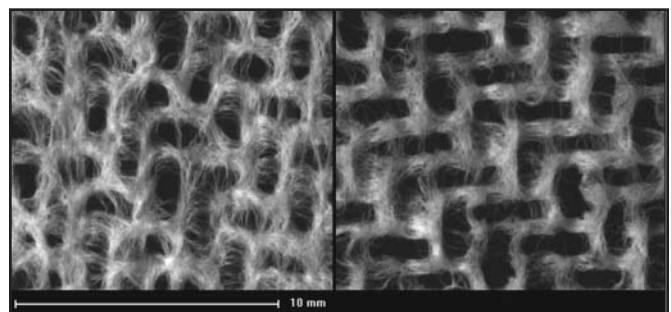


Table 1
FABRIC TYPES AND SPECIFIC ENERGY GIVEN TO THE FABRIC

No. of passes	No. of manifolds	Pressure (bar)	Web Weight = 100 g/m ² Specific Energy (kJ/kg)	Web Weight = 150 g/m ² Specific Energy (kJ/kg)
1	3	27.6	6311.82	4208.68
1	3	41.4	6939.12	4626.88
1	3	55.2	7681.96	5122.11
1	3	69	8524.55	5683.83
1	3	82.7	9456.23	6304.95
1	3	96.5	10469.17	6980.24
2	3	27.6	7435.85	4958.04
2	3	41.4	9004.10	6003.53
2	3	55.2	10861.20	7241.60
2	3	69	12967.67	8645.91
2	3	82.7	15296.86	10198.70
2	3	96.5	17829.21	11886.93

chrome camera, a frame grabber and a lighting system configured in our laboratory to provide a directed dark-field illumination [18]. The images were captured perpendicular to the focal plane of the camera. Our light source consists of a uniform LED light panel. Our images covered an area measuring 20x20 mm². Three images were captured for each sample and the data reported are the mean and the standard deviation for the three replicates.

Images were preprocessed before co-occurrence analysis. We used histogram equalization, where gray level values are reassigned to produce a flattened histogram therefore, making a more uniform gray level distribution, and removing any biases caused by the variations in the overall image intensity [19].

Texture Analysis

In this paper, we use spatial co-occurrence for evaluating texture periodicity and definition in fabrics. Spatial co-occurrence examines the second-order, joint-conditional probability density function, $f(i,j/d,\theta)$ for the probability of sampling a pair of pixel positions with intensity values i and j , separated by distance d in direction θ . In practice, we systematically sample an image by examining every pixel of an image for which a neighboring pixel exists d units away in direction θ . The intensity of the current pixel, i , and that of its neighbor, j , constitute a single co-occurrence of i and j for given sampling parameters d and θ . The frequency of all co-occurrences are stored in a matrix, M , of dimensions N by N . Thus, entry i, j in the matrix is the number of i, j pairs sampled in the image. Typically, these frequencies are normalized by the sample size. For a rectangular raster, there are eight directions: 0 (right), 45 (up right), 90 (up), 135 (up left), 180 (left), 225 (down left), 270 (down) and 315 (down right).

The degree of spatial correlation will be reflected in the co-occurrence matrix. If the intensities change over short distances, the frequencies will be spread more evenly across the matrix than if intensities change gradually over distance. A number of statistics have been devised to describe this spread,

or moment, away from the main diagonal, where $i=j$ (for a full description of this technique refer to [13]). We concentrate here on *contrast* (otherwise known as *inertia*), defined as:

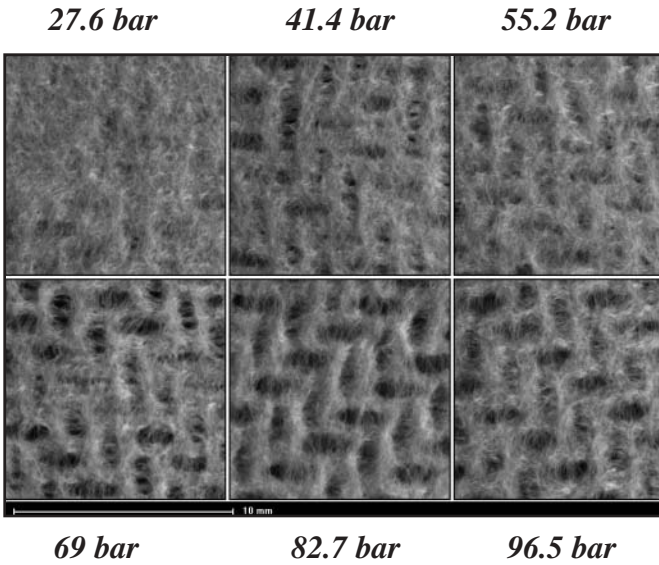
$$\sum_{i=0}^n \sum_{j=0}^n \{(i-j)^2 M_{i,j}\} \quad (3)$$

Contrast is a moment statistic and is proportional to the degree of spread away from the main diagonal of M .

Spatial co-occurrence may also be utilized to investigate periodic patterns since aspects of texture periodicity (amplitude, frequency, direction) will be reflected in the co-occurrence matrix [16]. For example, a repeating pattern with a period ϕ , for which $\phi > d$ implies that sampled pairs will have similar intensities, thus increasing the frequencies about the diagonal of M . If $d \sim \phi$, sampling will generate a relatively uniform M . Each M is defined for a given set of d and θ , but one may compute a series of matrices for a range of d , say 1 to 100. Such a series would represent changing texture features over 100 pixels.

We use the contrast statistic in order to measure texture differences for a range of d . Contrast then becomes a function of distance. For an image generated by randomly sampling a uniform distribution, this function assumes a constant mean value. By contrast, an ordered texture produces a periodic function as the spatial correlation alternately falls and rises with distance. We have previously shown that the period of such a function is the period of the texture, and that the amplitude is an indication of the relative strength of the signal in terms of periodicity [13,16,18].

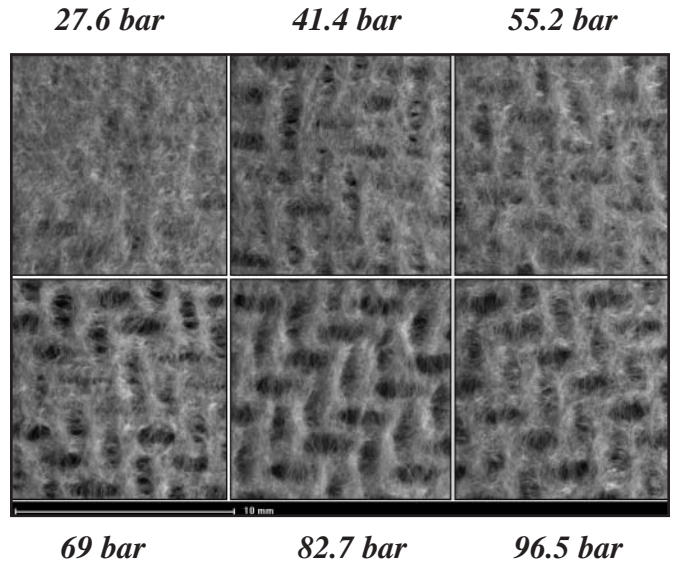
The contrast statistics for spatial co-occurrence matrices were computed for the horizontal and vertical directions, for $d = 1$ to $d = 256$. The latter value of d was chosen to facilitate spectral analysis of the contrast function. Sobus and Pourdeyhimi have shown that the spectral densities can be used by using a finite Fourier transform to compute the periodogram or power spectrum (the sums of squares of the sine



27.6 bar 41.4 bar 55.2 bar

69 bar 82.7 bar 96.5 bar

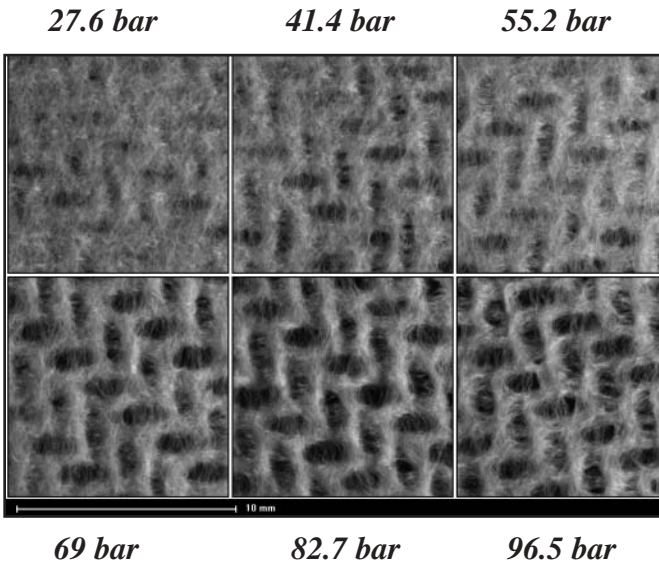
FIGURE 2
IMAGES OF FABRICS USING A PET 100 G/M²
WEB - 1 PASS UNDER DIFFERENT PRESSURES



27.6 bar 41.4 bar 55.2 bar

69 bar 82.7 bar 96.5 bar

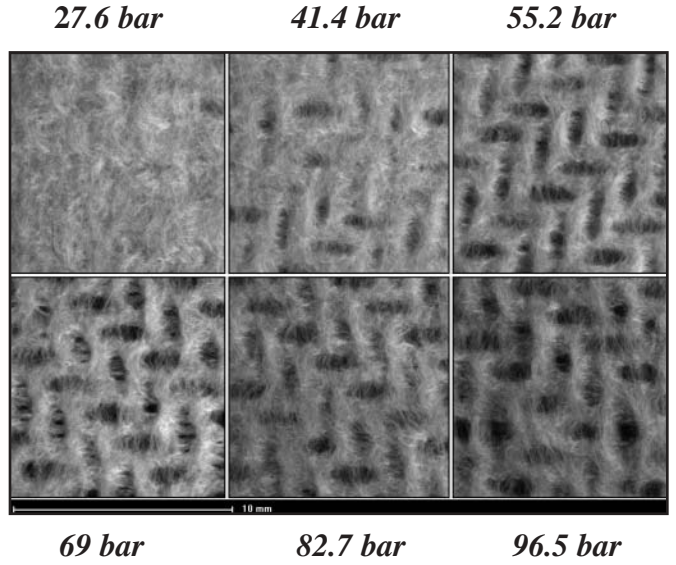
Figure 4
IMAGES OF FABRICS USING A PET 150 G/M²
WEB - 1 PASS UNDER DIFFERENT PRESSURES



27.6 bar 41.4 bar 55.2 bar

69 bar 82.7 bar 96.5 bar

Figure 3
IMAGES OF FABRICS USING A PET 100 G/M²
WEB - 2 PASSES UNDER DIFFERENT PRESSURES



27.6 bar 41.4 bar 55.2 bar

69 bar 82.7 bar 96.5 bar

Figure 5
IMAGES OF FABRICS USING A PET 150 G/M² WEB
- 2 PASSES UNDER DIFFERENT PRESSURES

and cosine coefficients for each of the Fourier harmonics), and that the magnitude of the periodogram (referred to as power) indicates the statistical “strength” of the indicated frequency or the texture period [13,14].

Results and Discussion

All of the hydroentangled fabric images are shown in *Figures 2-5*. However, for the sake of brevity, we have demonstrated contrast results of 4 fabric types. Contrast graphs and their respective powers are illustrated and grouped according to web weight and number of passes.

Contrast as a function of distance is plotted against pressure for PET 150 g/m² webs, 1-pass samples in *Figure 6*. This typifies the results obtained for all samples. It is clearly seen that the horizontal contrast becomes more pronounced as pressure or energy is increased (*also see Figure 4*) up to a point and then begins to decrease in amplitude. It is possible that at higher pressures, the web is disturbed because it is not sufficiently consolidated. The same behavior is also observed in the spectral analysis of the contrast data for all samples shown in *Figures 7-10*. Regardless of the sample or the number of passes or the web density, the trend is consistent. The

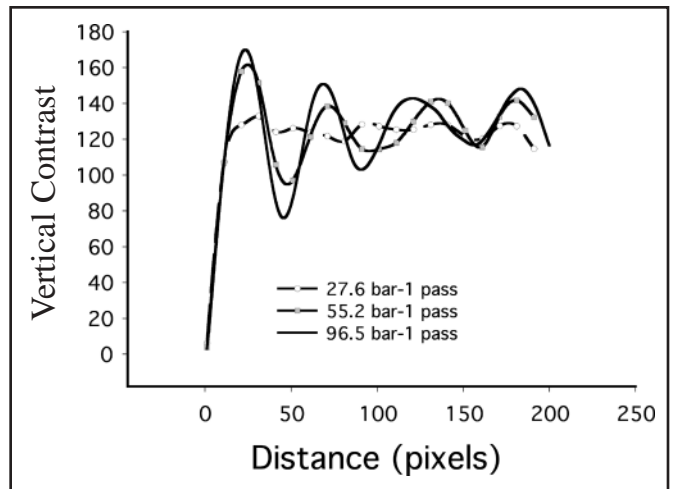
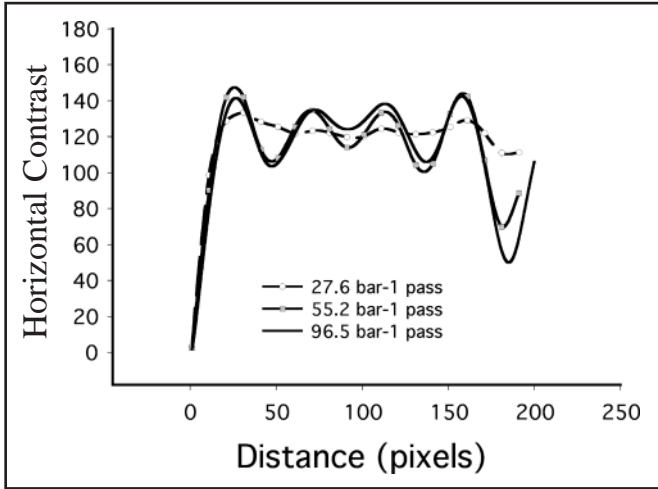


Figure 6
CO-OCCURRENCE ANALYSIS USING A PET 150 G/M² WEB - 1 PASS

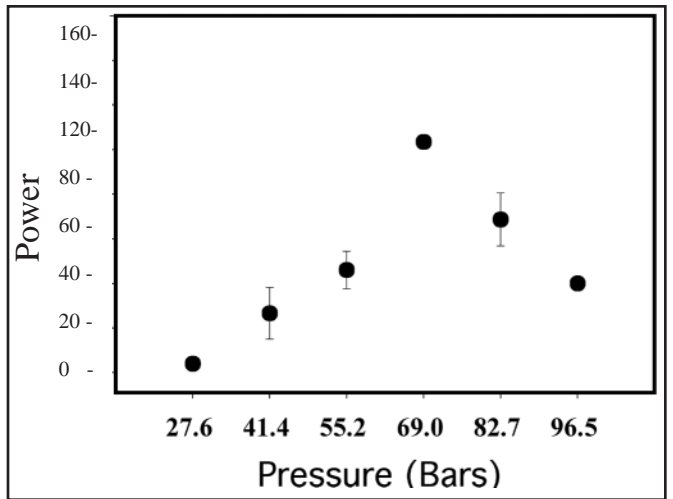
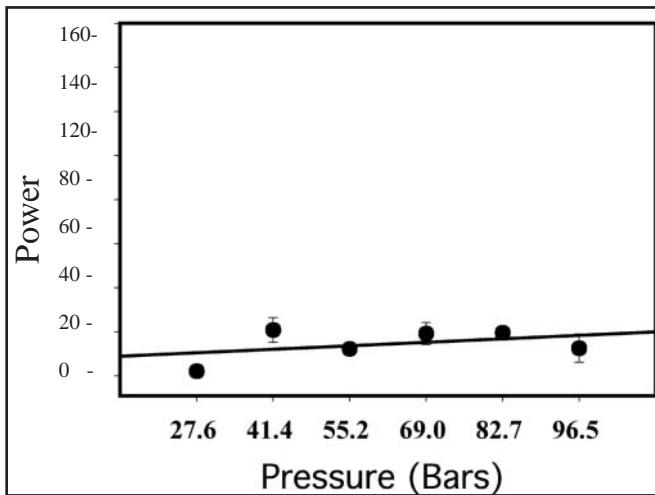


Figure 7
TEXTURE POWER OF PET 100 G/M² WEB - 1 PASS: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

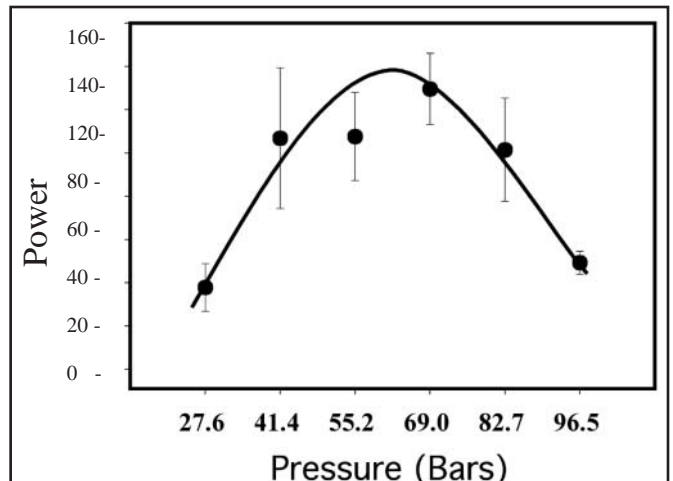
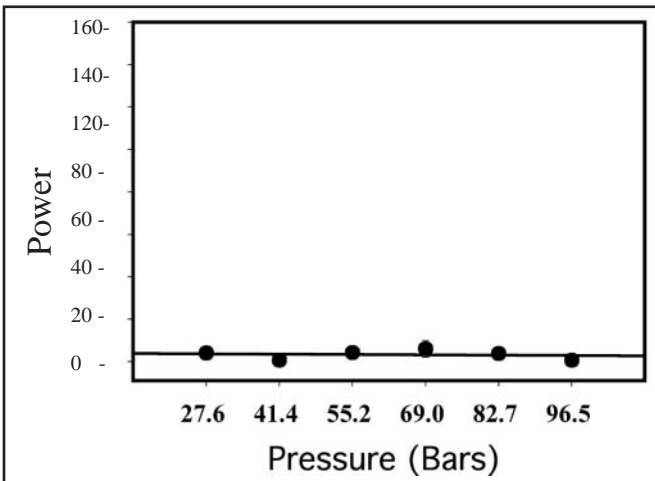


Figure 8
TEXTURE POWER OF PET 100 G/M² WEB - 2 PASSES: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

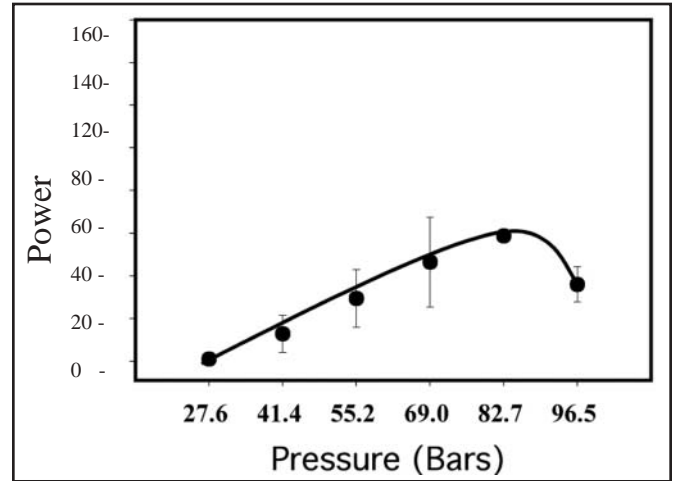
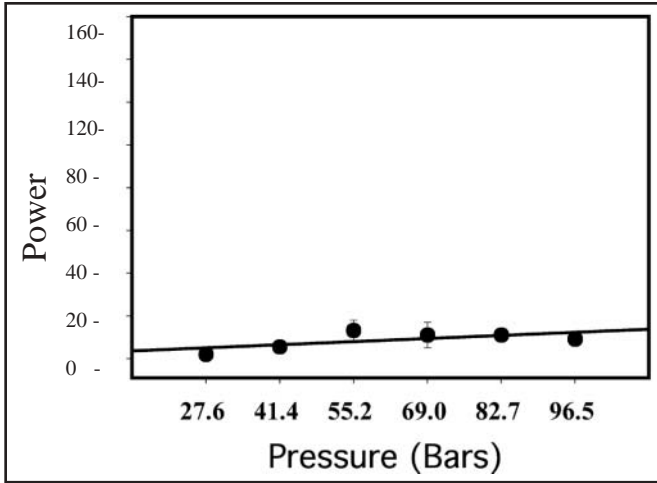


Figure 9

TEXTURE POWER OF PET 150 G/M² WEB - 1 PASS: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

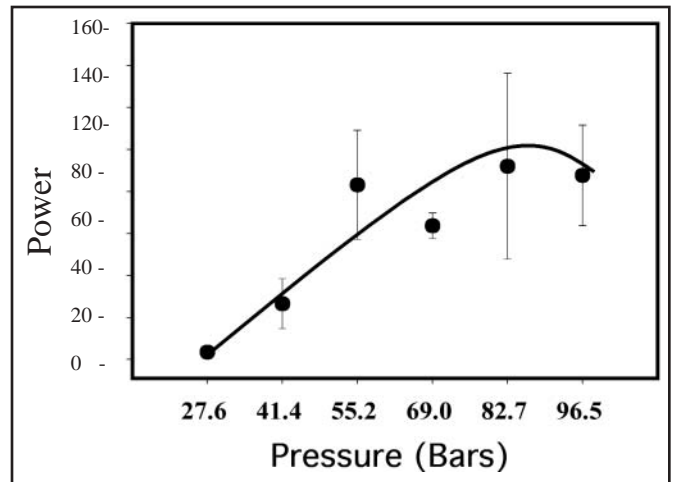
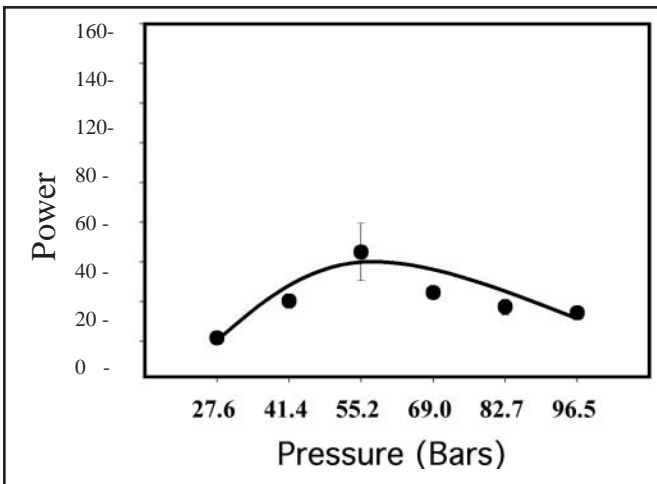


Figure 10

TEXTURE POWER OF PET 150 G/M² WEB - 2 PASSES: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

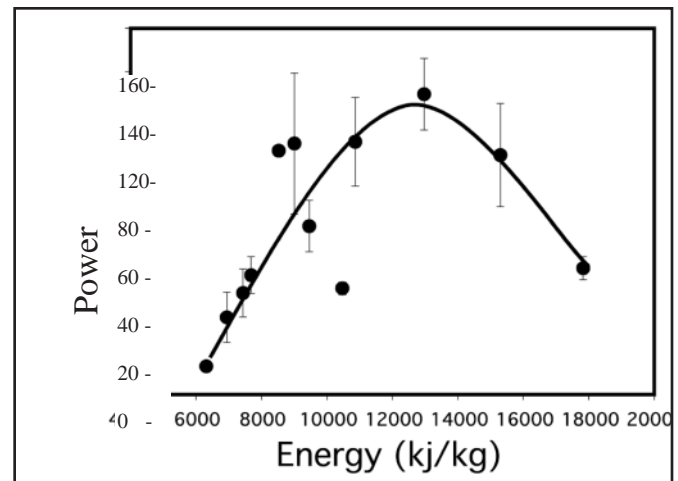
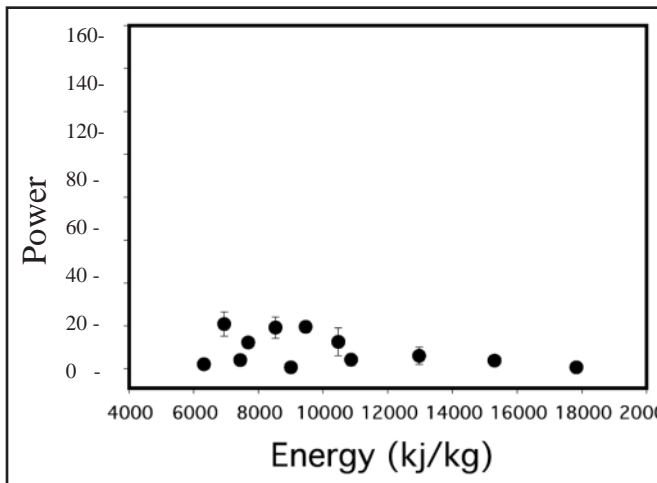


FIGURE 11

TEXTURE POWER OF PET 100 G/M² WEB: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

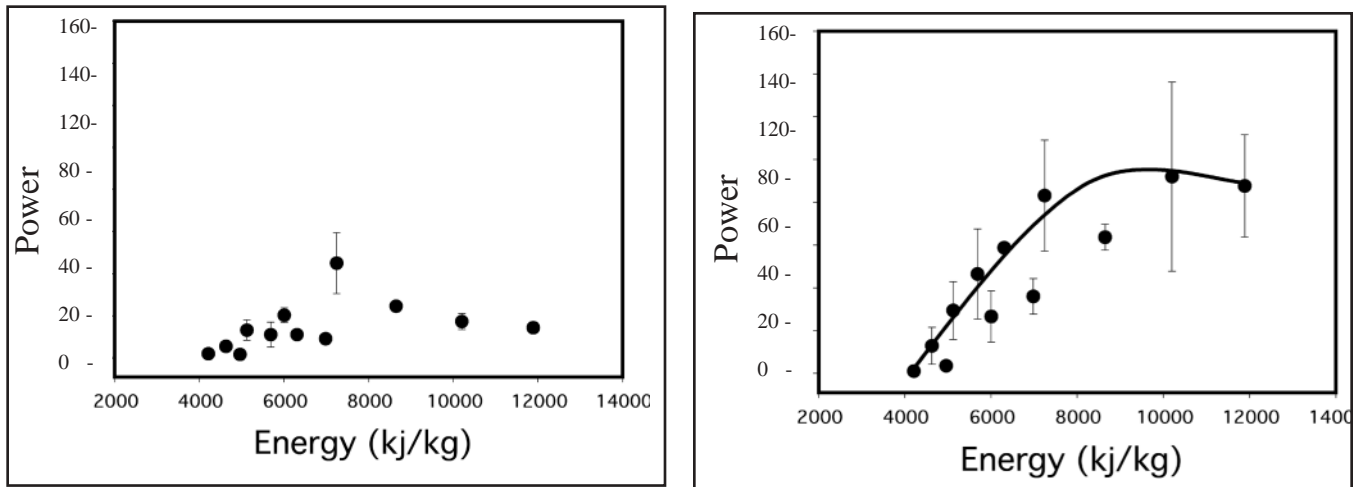


Figure 12

TEXTURE POWER OF PET 150 G/M² WEB: HORIZONTAL (LEFT) AND VERTICAL (RIGHT) CONTRAST

texture definition increases with pressure and then decreases. Even in energy vs. power graphs (Figures 11-12) this trend is clear and it seems that in these samples 13000 kj/kg is the threshold energy for the texture loss. As noted above, the loss of texture definition at higher pressures may be due to the lack of web density and absence of any bonding when subjected to hydroentangling. As shown in Figure 1, and also in the last image in Figure 2-5, at high pressures, it appears that the fibers are spread away from the holes of the screen by the action of the jets, thereby resulting in a lower texture definition.

Since there are more fibers to be entangled in a heavier web, the specific energy transferred to the web would be less (see Table 1). Thus, it would be expected that the texture definition would not be developed as well by using the same manifold pressures (Figure 11-12). Our results however, do not show these differences conclusively. We feel that this is because the range of pressures available on the pilot equipment is too narrow. We plan however, to examine this issue on our new pilot facility in the near future.

In general, it appears that increasing pressure and the number of passes will result in a better texture definition up to a certain point provided that the web is sufficiently consolidated so that it is not disturbed.

Conclusions

We have showed that co-occurrence analysis is a good indicator for determining the texture properties of hydroentangled fabrics. We have demonstrated that horizontal and vertical contrast functions and their respective power spectral analysis data will provide a useful tool for quantifying texture.

We have demonstrated also that hydroentangling pressure has a marked effect on the manner in which texture develops during the process. In general, increasing pressure and the number of passes will result in a better texture definition up to a certain point provided that the web is sufficiently consolidated. If the web is not bonded, higher pressures may

result in perturbing the web with a concomitantly lower texture definition.

There were several limitations to the current study. The pilot equipment used can only apply pressures of up to 100 bars unlike current commercial equipment allowing 400 bars or more. The belt speed was also not realistic and there was no facility for controlling the tension on the fabric. The energy levels therefore, should only be used in a relative manner. We plan to complete a full study using NCRC's new Fleissner high speed, high pressure hydroentangling unit. The results of the current study are only used to demonstrate the viability of the techniques employed.

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