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MEASURING FLOCCULATION USING IMAGE ANALYSIS

J. Gorres, Department of Pharmacy, University of Manchester, UK
H. W. Kropholler, Department of Paper Science, UMIST, U.K.
P. Luner, Empire State Paper Research Institute, Syracuse, NY, USA 13210

ABSTRACT

Experimental and theoretical measures of flocculation were studied using image analysis. An experimental study of commercial board samples led to the proposal of three descriptive floc features, namely, size, 'definition' and contrast. Numerical values were obtained from an ensemble averaged linear auto-correlation function.

In addition a theoretical model of formation was simulated to compare degrees of flocculation. The theoretical structure was created by using a poisson cluster model in conjunction with a coverage model. This led to the superposition of fibrous micro-flocs whose floc centre radii, R_f, and fibre content ,N_f, determine the severity of the formation. The variance and p.t.p. correlation of the resulting image textures were computed. These measures were found to have a lower limit which is set by the fibrous structure of the flocs.

The findings from the simulation study were then applied in principle to the variance and size information extracted from the board samples to explain their structure. The versatility of programmable image analysis systems was demonstrated for formation measurement.

INTRODUCTION

The term formation is often used synonymously for a whole range of expressions describing various physical maps of a sheet of paper and the properties of such maps. Formation is, here, referred to as a general term which includes all two dimensional planar maps of a sheet. Thus, the distribution of mass density, optical density, thickness and the number of fibre density (point coverage), as well as look-through, are classed under this term. Within each one of these maps one may find features that uniquely describe the formation of a particular sheet of paper. Such features can be wiremarking, shake markings and flocculation etc. These features, when severe, can impair the quality of a product. Each feature can cause specific problems and ways to measure one particular feature may need to be found to solve such problems. Indeed, this is done by using single purpose instruments. A variety of formation meters is available. Equally varied are the measures of formation and the different ways to measure each of these features.

To illustrate this, the example of flocculation is chosen. Brecht's and Wesp's 'Wolkigkeitsmeter' (1) measured flocculation following a model based on Weber-Fechner's law, the law of logarithmic response to stimuli in human perception. Andersson et al (2) described a formation meter that accounted for Weber-Fechner's law as well as for a second property of human vision, that of edge detection performed by the receptive fields of the eye. Other instruments like the QNSM (3) do not aim at formation measurement in terms of human vision. The QNSM, an analogue harmonic analyser, attempted to quantify flocs as the power in a dominant floc frequency outside the wiremark range. Corte's 'unevenness number' (4), seen as an indicator of any deviations from the random, ideal structure of paper, including contributions from flocculation, was based on measurements from β-radiographs and thus was claimed to have no similarity with human perception.

In order to obtain these four flocculation measures, traditionally, four different instruments are needed. This indicates the advantages of a programmable image analysis system. The use of such a computer system allows the measurement of many formation maps and features. It further offers the greatest possible flexibility for defining and measuring relevant formation features. In the following, flocculation, as one such feature, will be investigated with image analysis. Firstly, flocculated board formation was quantified. Then a new flocculation model is developed in order to interpret the board formation.

DEVELOPMENT OF THEORETICAL MODELS

Parker and Attwood (5) implied a model of flocculation when they assumed that paper formation could be treated as a superposition of a stochastic and a periodic component. This model was used to reconstruct obscured wiremark, which constituted the periodic part of the formation process. However it is hard to develop these ideas further to formulate a flocculation model. Corte and Kallmes (6) presented a flocculation model in which flocs were presented by solid circles of given radii which were randomly distributed over a sheet of paper. Kallmes and Bernier (7), on the other hand, rearranged the fibre centres of a random network in order to render them less dispersed, that is, to achieve fibre clumping as seen in flocculated sheets.

A theoretical approach of how one might treat textural maps like formation comes from image analysis. There, so-called coverage models are developed that generate image textures by randomly placing figures of a given geometry onto a plane. The figures seen in an image synthesised in this way, however, are not the primitive figures used in the generation but are superpositions of such primitives.For flocculated textures, this suggests that they may be made up from smaller flocs than seen in the finished sheet of paper. To generate flocculated sheet textures on an image analyser, solid circles of given sizes and densities could be superposed at random in an image under the condition that densities are additive when circles intersect. However, flocs are fibrous objects and the use of solid circles in that sense is not adequate.

The process of positioning fibres from this point of view becomes important. Corte and Kallmes (6) and Kallmes and Bernier (7) used a simple random process of fibre centres to achieve random and less dispersed sheets. Realising that such a process would not generate flocculated formation, Dodson (8) proposed that a superposition of several poisson processes should be used. In connection with the clustering of galaxies, Neyman and Scott (9) described a superposition of random processes. Their process involved two individual elementary processes. First a 'parent' process distributes cluster centres in a given space. Then a 'daughter/son' process randomly distributes a random number of points about each cluster centre. When one treats flocculation in analogy with the

Neyman-Scott process, the floc centres are regarded as the cluster centres and the process of fibre centres becomes the daughter/son process. An effective fibre clumping can be achieved by confining the fibre centres, associated with the floc centres, to finite areas, for example, to circles of a given radius, around the floc centres. The resulting point pattern is dependent on both process rates and on the local confinement of the fibre centre process. By fitting fibres to the fibre centres a fibrous flocculation model can be achieved.

A DESCRIPTIVE MODEL OF FLOCCULATION

A descriptive model of flocculation has to be formulated in terms of human perception. Three floc features can readily by named as influencing the appearance of flocculated formation,

1) floc size
2) contrast between floc and background
3) 'definition' of the floc against the background.

An illustration of these properties is seen in Figure 1.

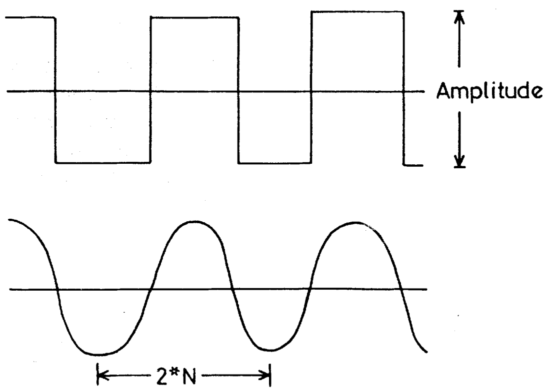

Fig 1—Floc features from flocs with high (top figure) and low (bottom figure) definition. The Amplitude is related to 'Contrast'.

The realisation of such a model is not straightforward. The difficulty of measuring floc size lies in that edges of flocs are not defined clearly. The flocs blend into the background of the formation maps. A fact that is reflected by features 2 and 3. These describe the relationship between floc and the background and are responsible for the intensity with which the patterns are perceived (Weber-Fechner's law and the action of perceptive fields as edge detectors).

Image analysis usually detects objects by observing a density (grey) threshold above or below which the image analyser accepts an image feature as a desired object. Because of the blurred edges of the flocs it is not possible to threshold flocculated formation textures with the aim of extracting individual flocs for measurement. Other ways of measuring size distribution are spectral methods (10) and the autocorrelation function (11).

ESTIMATORS OF FLOCCULATION

The properties of spatial patterns are often described in terms of the autocorrelation function (ACF). This function describes the degree of correlation between a functiion and a shifted version of itself. In one dimension the ACF is commonly defined as:-

$$g(\tau) = (1/2L) \int f(t)*f(t-\tau)dt \tag{1}$$

It is possible to relate the ACF to the elementary units that make up a pattern. For example, the dimensions of fibres in a random sheet are related to the variation in $g(\tau)$ by Dodson (8). Ahuja and Schachter (12) quote a more general relationship between the behaviour of the ACF and textural primitives. Their ACF depends on the shape and the size of the textural primitives in the image and the rate of the process at which they were covering the image. In both Dodson's and Ahuja's version, the ACF at τ depends on the overlap A_I of the figures (textural primitives) originally distributed over the picture and their τ-shifted images.

Ahuja's version, valid for binary patterns which are generated by placing objects of one colour on a white background, is given by:-

$$g_I = (e^{-\lambda A}/(1-e^{-\lambda A}))*(e^{-\lambda A_I} - 1) \tag{2}$$

λ is the areal process rate, A the area of the primitive and A_I is the intersected area of the original and its I-shifted image.

The three flocculation features associated with the descriptive model outlined above can intuitively be derived from the one dimensional ACF as given in equation (1). A typical ACF of a single line scan across a sheet of paper can be seen in Figure 2. The graph is divided into three parts. The value at g(0) is the variance of the density changes along the scan line. The second part is the initial drop to the first minimum. This part is mainly influenced by the characteristics of objects in the image. The third part shows, typically, a variation about $g(\tau) = 0$ and reflects periodicities in the signal. For the investigation of flocculation the second part of the ACF is the significant one. Ahuja's ACF, in Equation (2), for binary patterns becomes minimal when the term in the second bracket becomes 0. This happens at $A_I = 0$. This is achieved when the figures making up the pattern are completely separated. The floc size in this model is thus defined as the lag value at the first minimum of the autocorrelation function. However, it has to be noted that the distances between the flocs contribute to this measure of 'floc size' too. It may, for this reason, be more accurate to call this measure 'characteristic size' of the texture.

Contrast in this model is defined as the difference

$$C = \frac{g(0) - g(N)}{g(0)} \quad (3)$$

Where N is the value of the lag at the first minimum of the ACF.

The 'definition' of the flocculation pattern is intuitively conceived as the rms of the curvature of the initial decay of the ACF from g(0) to g(N).

$$D = (1/N)\sqrt{\Sigma\Delta^2 g/\ \Delta n^2} \quad (4)$$

For example, for a top hat function the ACF decays linearly. Thus the curvature of the ACF in that interval is 0. The greater the rms of the curvature, the lower the 'definition' of the floc pattern, i.e. the better the appearance and uniformity of the sheet.

It is not always necessary to generate the complete ACF to

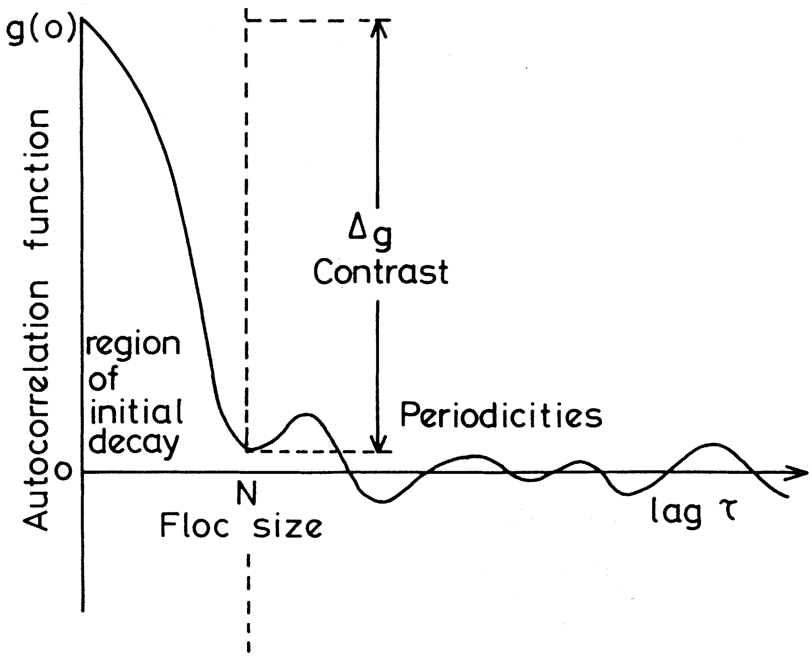

Fig 2—An example autocorrelation function with floc features 'Contrast', 'Floc Size' and 'Variance' at g(o).

sufficiently describe formation, especially when patterns of known properties are investigated. The investigation of flocculation with the fibrous floc model was carried out on synthesised floc textures and under the assumption that variance and the first autocorrelation coefficient (p.t.p. correlation) were sufficient to characterise flocculation behaviour when floc properties were altered.

Variance was chosen as it represents a classical formation measure. The average p.t.p. correlation was chosen to obtain a size estimate for the floc/fibre systems generated in the simulations. The latter measure was estimated by the grey co-occurrence, or second order statistics described by Haralick et al (13).

EXPERIMENTAL

The Descriptive Model Applied to Five Board Samples.

Five board samples, named A,B,C,D,E, of the same commercial grade, served as a test for the descriptive model. They had previously been ranked visually for their formation. With decreasing formation quality the samples take the order

E A C B D

Because of their weight, 240gsm, β-radiography could not be used to image the board's mass variations. Contact photographs of the samples were prepared instead. These photographs were presented to the image analyser, a Joyce-Loebl Magiscan, which digitised the board images into an array of 512x512 pixel points (one pixel point is the elementary resolution cell of a digitised image). The spatial resolution was 0.12mm/pixel. Averaged ACFs were computed from the digitised pictures using 100 equidistant scan lines of 512 pixel length. This was done for both machine and cross directions of the boards.

From these averaged ACFs, size, contrast and 'definition' were extracted. The results are tabulated in Table 1. The rankings of the boards with respect to individual features quoted in Table 1 are very close to the overall visual rankings of the samples. Only the best and second best samples are interchanged in the rankings. The similarity between the visual and the measured feature rankings was expected as we accepted that a descriptive model would have to satisfy terms of human perception.

In addition to the features of the 0.12mm/pixel field, in Table 1, the variance g(0) and the characteristic size were measured at a smaller effective resolution of 0.044mm/pixel. These values are listed in Table 2 and will be referred to below in connection with the simulated formations.

Samples		A	B	C	D	E
Size	MD	2.86	4.81	5.20	7.41	4.42
(mm)	XD	3.12	5.46	3.51	11.05	4.29
Mean		2.99	5.13	4.36	9.23	4.36
Ranking		1	4	2	5	2
Definition						
	MD	.119	.081	.071	.053	.087
	XD	.171	.070	.102	.036	.086
Mean		.146	.076	.085	.045	.087
Ranking		1	4	2	5	2
Contrast						
	MD	.832	.896	.952	.933	.785
	XD	.757	.939	.860	.971	.870
Mean		.795	.918	.907	.983	.827
Ranking		1	4	3	5	2

Table 1: Descriptive floc features from the board samples at 0.12mm/pixel resolution.

Samples	A	B	C	D	E
Size (mm)	1.2	3.4	2.0	3.4	3.6
Variance	80	150	115	200	110

Table 2: Variance and floc size of board samples at 0.044mm/pixel.

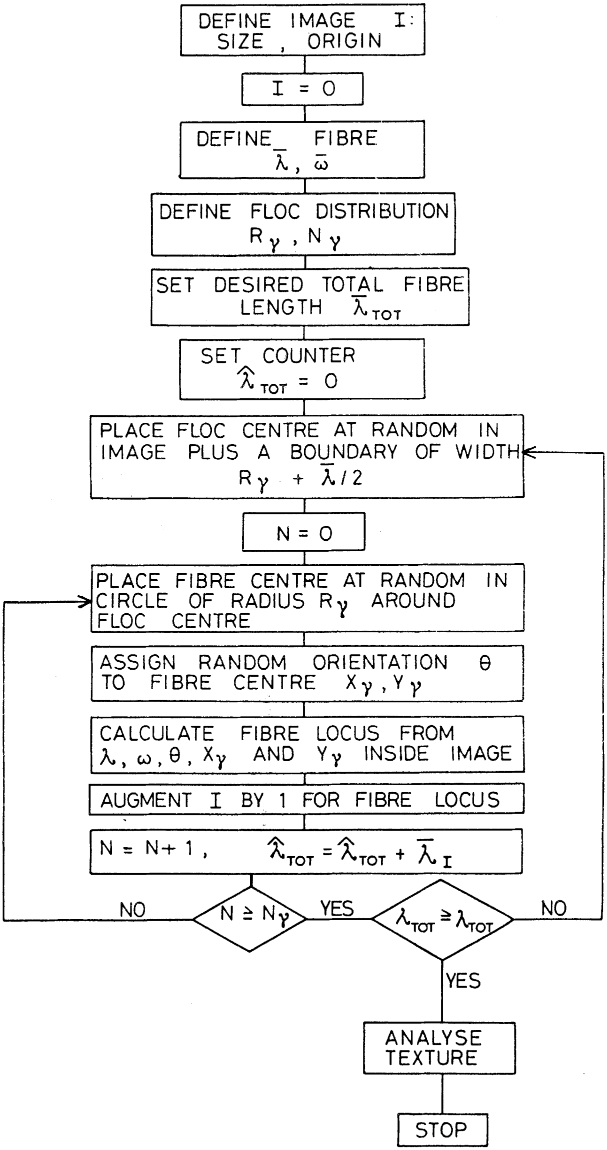

Fig 3—Algorithm "FLOCOV" stimulating flocculated formations.

A Simulation Study of Flocculation

The following study was carried out with an Oktec 2000 board which has an image memory of 320x240 pixels and can distinguish 16 grey levels.

By applying a cluster point process as developed above, flocs can be constructed and superimposed in an image following the algorithm in Figure 3 which achieves the combination of a poisson cluster point process and a coverage model that employs fibres as its textural primitives (i.e. straight lines of given length and width). In the realisation of this model, fibres were fitted to the fibre centres. These fibres were defined by a random orientation, Θ a length λ and a width ω. The image values at the fibre loci were augmented by an integer value, usually equal to 1. The number of fibres per floc, N_f, and the radius, R_f, of the circle into which all fibre centres N_f fall, play an important role. In this investigation, a set of simulated textures was generated that contained thirteen different degrees of flocculation. This was achieved by varying R_f and N_f.

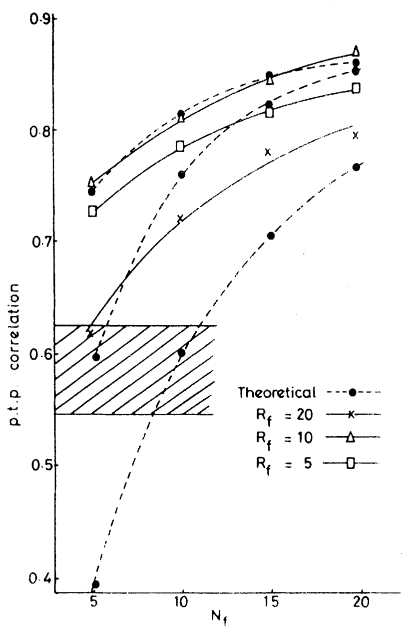

Fig 4—P.t.p. correlation against floc fibre number, N_f

One class out of the thirteen had zero flocculation, i.e. $R_f = 1$ and $N_f = 1$. This led to random sheets. Within this class, three groups of sheets could be distinguished by their fibre lengths. For these sheets

$$\lambda \quad \varepsilon \quad (10,\ 30,\ 40) \qquad \text{pixel points.}$$

for the flocculated sheets was chosen to be 20 pixels. In the class of flocculated sheets, 12 different degrees of flocculation were achieved through combinations of

$$N_f\ \varepsilon(5,\ 10,\ 15,\ 20) \quad \text{fibres}$$

and

$$R_f\ \varepsilon(5,\ 10,\ 20) \qquad \text{pixel points.}$$

For all 150 sheets the total fibre length, λ_{tot}, i.e. their grammage was conserved. The fibre width, ω, was also set to a constant = 2.

The equation

$$N_F * N_f * \lambda \ = \ \lambda_{tot} \tag{5}$$

where N_F is the number of flocs in the image, can be regarded as the fundamental equation ruling the behaviour of flocculation as it controls the rate of the parent process, that is the process of floc centres.

For constant λ_{tot}, N_f is the floc parameter that influences the appearance of the sheets. N_f determines the degree of localisation of the available fibres. Although this was not investigated here, the fibre length and curl can be considered as other localising factors. Figures 4 and 5 show the influence of R_f and N_f on the p.t.p. corelation when measuring at full resolution, i.e. at a resolution of 1/2 of a fibre width per pixel point. The broken lines in Figure 4 represent theoretical values of p.t.p. correlation calculated from Ahuja's ACF for a binary circular model in which the circles are deposited at a rate of N_F and have a radius of R_f . For the circles with small radii, i.e. $R_f = 5$, the measured values and the theoretical values are almost identical. At small radii the flocs are saturated, that is the image values in parts of the floc areas have reached 15, the maximum grey level that the Oktec board can store. For this reason the image is similar to a binary pattern.

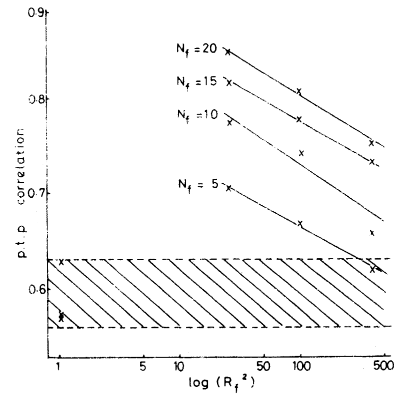

Fig 5—P.t.p. correlation against log (R_f^2)

It can further be observed that for larger flocs theoretical and actual values differ. Where the theoretical values rapidly drop below the shaded area, which signifies the correlation range of the thirty random sheets, the values for the generated sheets do not fall below this range. The fibrous nature of the flocs thus provides a lower limit for formation measures at this resolution. The fibrous nature of the flocs also changes the concept of some of the formation measures. In particular, the correlation measure is no longer a measure of floc size as such but one of the concentration of fibres in the floc. This becomes apparent in Figure 6 in which the floc point coverage or density,

$$C_F = N_f * \lambda * \omega / (\Pi(R_f + \lambda/2)^2) \quad (6)$$

is plotted against the p.t.p. correlation. For high C_F, high correlation is registered.

Figures 7 and 8 are plots of variance as a function of R_f and N_f. The degree of localisation again appears important for the behaviour of this particular formation function. The variance does not provide any further information about the texture of the flocculated sheets. Variance and p.t.p. correlation, when seen as features of the ACF, that is as g(0) and g(1), are very closely related measures.

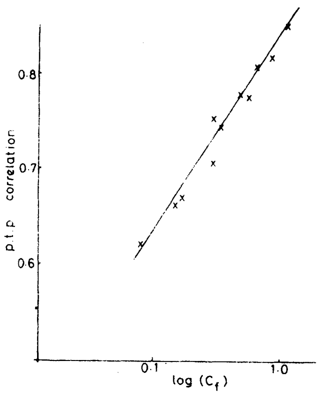

Fig 6—The variation of p.t.p. correlation with floc density C_f.

To put the above into the perspective of papermaking, the results of the simulations ought to be interpreted as the outcome of attempts to control flocculation during paper manufacturing. This parallel can be drawn since the furnish and the grammage of the sheets were not changed. To complete the parallel it is necessary to point out that the flocculation control (the change of floc parameters) is analogous to controlling flocculation before the forming stage. The control is exercised on flocs that are not those that appear in the finished sheet but on smaller primitives of a given fibrous substructure.

INTERPRETATION OF BOARD SAMPLES WITH THE CLUSTER MODEL

Before the features of the board formations can be interpreted in terms of the results of the simulation study, several points about the differences between board and generated flocculation textures have to be made.

Firstly, the formation resulting from the simulations are maps of point coverage. That means that each image point signifies a number of fibres that cross at that point. Image values are directly related to the number of fibres present at the image co-ordinates. There is no diffusion effect as would be expected in light and β-ray transmission images. Diffusion is, however, present in the images obtained from the board samples. This decreases point and area variance values.

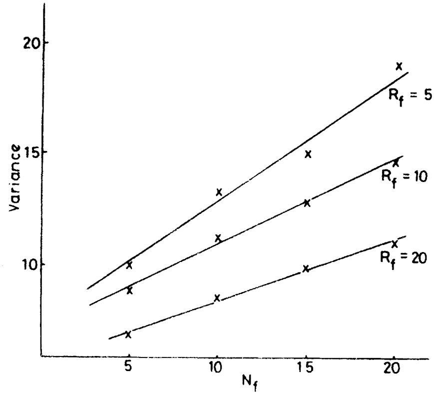

Fig 7—Variance against number of fibres per floc.

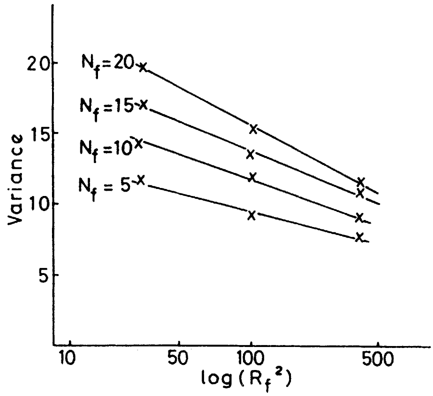

Fig 8—Variance as a function of floc radius R_f.

Secondly, the resolution in the simulated textures was equal to 0.5 of a fibre width. For the board samples two resolution levels were used for the measurements. These samples were 0.12mm/pixel and 0.044mm/pixel. Accepting that on average fibre width is about 0.04mm, then the simulation results are more comparable to the features listed in Table 2 than with those in Table 1.

Thirdly, boards are multi-layered structures. These layers may differ in both structure and furnish. The simulations used a single fibre furnish, representing effectively only one layer. The Oktec 2000 limited this aspect of the work as it can only store one such layer. Despite these these differences, the basic superposition principles for 'microflocs' and for poisson processes remain valid. Thus the principles formulated in the simulation study can be applied to the formation of the boards as long as one is aware of the points made above.

Because of these differences it is not useful to compare 'definition' and 'contrast' to possible similar features in the simulated formations.

Table 2 presents variance and size data on the board formations. The first measure finds a direct counterpart in the variance measure for the simulated formations. Referring to Figure 7 and 8, two statements can be made about the variance in the presence of flocculation.

The larger the variance, the smaller the floc size at a constant level of fibres per floc. The larger the variance, the smaller the number of primitive flocs for constant primitive floc sizes. In other words, the higher the primitive floc densities, the higher the variance.

It was proposed that the figures seen in a flocculated texture were superpositions of primitive micro-flocs. The apparent floc sizes are dependent, thus, on the size of the micro-flocs and the areal rate at which they appear. Large apparent flocs could, for example, suggest many small micro-flocs or few large ones or many large ones.

The variance of the samples suggest that sample D has the highest primitive floc density and that sample A has the lowest. Sample E also has low density micro-flocs.

The comparison of A and E shows a discrepancy between size and variance information. Sample A has a low variance and small apparent floc sizes. Sample E has a low variance too, but is outstanding by virtue of having the largest floc size in the set of boards. Similarly for samples E and D, the floc sizes are high, but the variances of the samples differ immensely.

In the board samples size information, as measured by the ACF, and variance no longer develop together as they would in homogeneous sheets in which most fibres are present within similar floc structures.

This leads to the supposition that a flocculation model of board samples should be formulated using a mixed random and flocculated formation model. Some of the board layers will thus be random and some will be flocculated in structure. The superposition of such layers is expected to yield floc structures that range from dispersed low density flocs within a random distribution of fibres (Sample A) to severely flocculated through all layers (Sample D). Sample E would have mild flocculation in most layers.

CONCLUSIONS

The measurement of flocculation in boards has inspired a study of the origin and properties of flocculated textures.

Board formation was expressed in terms of three floc properties computed from averaged one-dimensional ACFs. These features measured a characteristic size and the relationship between floc and background.

Using a flocculation model that employed a poisson cluster process and randomly oriented fibres, it was found that the figures of flocs seen in paper were, in terms of the model, made up from smaller 'micro flocs'. The relationships between variance and p.t.p correlation and micro-floc properties were established.

In the simulation studies the model did not produce board-like formation. It was concluded that the layered structure of the boards made board formation distinctly different from paper formation. A model that superimposes simulations of individual board layers made from fibres that were flocculated to different degrees is seen as more appropriate than the single layer, single furnish model presented in this paper.

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Transcription of Discussion

Measuring Flocculation using Image Analysis

by J. Gorres, H.W. Kropholler and P. Luner

Prof B. Norman Royal Inst. of Technology, Stockholm, Sweden

You have given some figures in Tables 1 and 2 using the image analyser to characterise floc size and you mentioned five different board samples. In the first table, sample D has large flocs from 7 - 11 mm. Then, in Table 2, you have increased the measurement resolution by a factor of 3 and then the floc size goes down to 3.4 mm. On the other hand, looking at sample E, starting from 4.4 mm, it goes down to 3.6, so it is an adverse relationship between floc size and D.M.D. whether you measure it with .1 or .04 mm measuring area. How can you explain this?

Dr. J. Gorres When you change the magnification in an image analyser, you do two things. First, you change the sampling distance between points. Secondly, you change the averaging over every Pixel. Dr. Dodson found that there was a relationship between the variance and the degree of magnification in terms of our image analysis system.

Norman I agree that the variance will increase when you go to higher magnification to look at your flocs, but the large size flocs will appear the same size whether you scan ever decreasing sample areas. You haven't said how large the sample is in your paper and I assume that you have an extremely small sample in Figure 2. How large was the sample?

Gorres In the first case, 6 cm and in the second case about 2.4 - 2.6 cm.

Norman This means that the sample size is such that it is not representative of the board you are trying to look at.

Gorres You need a lot of samples before you can draft any conclusions.

R.W. Dent Albany International, Dedham, U.S.A.

Could you define point to point variance and secondly how you get this from your analysis?

Gorres You could obtain it in two ways. Firstly, you can use an ordinary autocorrelation function which allows you to shift the image by one Pixel and you calculate the sum of the products of the greys of the shifted and the original image. This gives you the point-to-point correlation. Secondly, you can use the Haralick method of calculating a co-occurrence matrix which counts the grey transitions of all image point pairs that are a given distance apart. For the point-to-point correlation, this distance would be one Pixel point. This matrix you can treat as a two dimensional histogram of grey co-occurrence or as a scattergram. The point-to-point correlation would be the correlation defined on this scattergram.

Parker What is the real practical importance of formation to the end use performance of paper? Should the formation be uniform or what is the optimum formation? What wavelengths, for example, are acceptable and what are unacceptable? How do we justify all our efforts to improve the dispersion of fibres and control of flocculation? We are assured the assessment of the formation of calendered paper by optical means and by visual inspection is next to useless as a guide to the real variation of grammage. Should we therefore tell all our practical papermaking colleagues that they are wasting their time by visual inspection of paper, or should we suggest that they should inspect paper samples taken before the calender stack? Or, should they decalender calendered paper by wetting it and redrying it before they inspect it? I merely commend these questions for your attention in the hope that when we reassemble at Cambridge in four years time, we may have the benefit of a sounder basis on which to pursue this very important discussion.

A. Komppa Jaakko Poyry, Helsinki, Finland

Dr. Gorres defines formation as general two-dimensional planar maps including many properties:- distribution of mass density, distribution of optical density and look through.

As almost all available formation testers are based on optical measurements and are usually claimed to not only quantify look through, but also distribution of mass density, I would just like to make a comment on optical measurements.

Let me take as an example, a machine made paper with a given distribution of mass density subjected to three different levels of calendering. One would obtain, from optical measurements of that paper, three different distributions of optical density, one for each of the three calendering conditions, despite the fact that all three papers had exactly the same mass distribution.

This example illustrates how optical measurement can provide misleading information on the mass distribution in a sheet and demonstrates that there is no universally applicable, unambiguous relationship between grammage and light transmittance.

We have carried out many assessments of production papers using co-axial measurements of grammage and light transmittance through the same aperture.

In some cases, the optical measurement is totally meaningless, but even in the best cases, there is a remarkable ambiguity in the relationship between grammage and light transmittance.

This contribution is not intended to criticise at all Dr. Gorres and his colleagues for their excellent work, but merely to caution papermakers that optical or image analysis measurements should be interpreted very carefully with frequent re-calibrations even within one grade of paper.