Preferred citation: B. Norman. Overview of the physics of forming. In **Fundamentals of Papermaking**, *Trans. of the IXth Fund. Res. Symp. Cambridge, 1989*, (C.F. Baker & V. Punton, eds), pp 73–149, FRC, Manchester, 2018. DOI: 10.15376/frc.1989.3.73.

OVERVIEW OF THE PHYSICS OF FORMING

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Abstract

In this overview forming covers all processes from the dilution of thick stock into a *mix*, using recirculated white water in the *short circulation* , to the dewatering in the wire section.

Grammage nonuniformity in the paper web is to a predominant degree generated by the forming process, and especially the small scale variations summarized in the term *formation*. The term *mass formation* is recommended when only grammage is considered and not the optical impressions thereof. The forming process also generates the main part of the large scale variations, that is the MD-, CD- and residual grammage variance.

Mass formation has traditionally been evaluated using beta radiography, combined with microdensitometry or image analysis. A new technique involving thedirect recording of electron beam transmission is under development, with promises of faster processing, perhaps even on-line, and high geometrical resolution. Characterization techniques based on the *co-occurrence matrix*, applicable to image analysis, can be a useful complement to the traditional power spectra techniques.

It has recently been conclusively demonstrated that in flowing fibre suspensions, flocs are kept together by the bending forces of interlocked fibres. To study the dynamic behaviour of flowing fibre suspensions, modern video techniques, high speed movie pictures and image analysis are applied.

To improve grammage uniformity, the mix should be fed to the headbox directly after the dilution of thick stock with white water. No processes like screening or cleaning, from which uncontrolled reject fibre flows are drawn should be allowed in the short circulation. Further the consistency of each material component in the recirculated white water should be controlled, if the content of the different components in the sheet produced is to be held constant.

First pass retention is shown to be a badly defined retention value, and should only be used in comparisons for one paper machine when no changes of the material content in the long circulation occurs.

In the *headbox*, the tapered manifold is the commonly used means for achieving the coarse distribution across the machine width. From the cross distributor, a tube package can lead either to a stilling chamber, or directly into the outlet nozzle. The nozzle has to be fed using maximum *open area* to avoid flow instability, and the *nozzle contraction* must be large enough to reduce velocity streaks and relative turbulence to an acceptable level. Mathematical models are now being applied to the calculation of water flow patterns in headboxes.

Local slice lip adjustments, especially on headboxes with outlet nozzles of low convergence angle, can cause considerable sideways flow on a fourdrinier wire, and this will have a large effect on the CD grammage variations as well as on the final sheet anisotropy profiles.

There are two basic headbox designs for *stratified forming*. In one of these, thin, pointed vanes separate the different furnishes. In the other, thicker separation walls generate air wedges, which may separate the furnishes up to the actual starting point for dewatering. In the first case, layer mixing can start already at the headbox, while in the latter four new surfaces between air and mix jets are created, all four being potential sources of disturbance generation.

High consistency headboxes have been developed, with which paper is formed according to an extrusion process. To reduce mix flocculation, various channel shapes are used inside the headboxes.

Sheet build-up generally takes place according to a *filtration process,* which has an inherent self healing effect. Therefore, the mass formation of a laboratory sheet is better than that of a *random sheet.* For a machine-made sheet, the comparatively high mix consistency causes floc generation, which may result in a worse large scale mass formation than that of the random sheet.

When evaluating the mechanical and optical characteristics of a machine-made paper sample, its properties relative to those of a laboratory sheet from the same furnish may be expressed as the *Forming Efficiency*.

The *Kozeny-Carman* equation describing flow through porous beds can not be used to predict filtration dewatering rates during web forming. This is because of the gradual compression of the web by the dewatering forces, the closing of some pores, turbulent flow situations etc. Dewatering capacities must so far be predicted using empirical equations, and parameters evaluated on the basis of dewatering experiments.

The development of forming wires has led to multi-layer designs where both the paper side and the wear side can be optimized simultaneously.

Pressure pulses in hydraulic headboxes are detrimental to fourdrinier dewatering, since attenuation due to standing wave generation on the wire can create large MD grammage variations.

In fourdrinier dewatering, several new dewatering elements have been developed, allowing a better control of the *activity* in the mix on the wire, and thus also of the mass formation of the web formed.

In conventional twin-wire forming, the dewatering pressure is generated by wire tension according to one of two basic principles: roll dewatering with constant or blade dewatering with pulsating dewatering pressure. A combination of these two principles may result in an improved combination of mass formation and retention. Recently a new method for the generation of dewatering pressure has been demonstrated, in which the pressure along the forming zone can be controlled freely, since it is generated by application of local forces and thus not by wire tension.

Multi-ply products manufactured through *simultaneous forming* are now used for low grammage products. The problem is to achieve acceptable *layer purity* as well as layer mass formation. Controlled pressure pulse dewatering could provide the means to reach optimum dewatering conditions.

The influence of forming conditons on product properties is a vast area within which two subjects are discussed: the interrelationship between mass formation and paper strength and finally fibre orientation anisotropy.

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1. Introduction

In this overview, *forming* is defined in a wide sense as all processes involved in transforming the thick stock flow into a wet web. Conventional forming includes three stages as in *Table 1*.

Table 1: The forming process

Mix preparation, by dilution of thick stock with recirculated white water in the short circulation.
Mix distribution by the headbox,through transformation of the pipe flow of mix into a high precision thin jet of wire section width.
Mix dewatering in the wire section, during which process the fibres are interlocked to form a wet web.

The actual processes included in the forming of a paper web are extremely complex, and many random (or with a more popular physics term: chaotic) events are involved. The interaction between all processes involved, both in the "forward" and in the "feed-back" sense, further adds to the complexity.

No detailed theoretical treatment of the complete sheet build-up process has yet even been seriously attempted, and this is in sharp contrast to for instance the wet pressing process, where extensive models have recently been set up at several universities and research establishments. In some cases however, basic models have been developed for individual parts of the forming process, with which qualitative predictions can be made.

1.1. Background

Peter Wrist's excellent paper *Dynamics of sheet formation on the Fourdrinier machine* at the 1961 Symposium (1) deals with the forming process in the light of basic knowledge. Among many other things, Wrist discussed the basics of air cushion headboxes with perforated rolls , the dewatering mechanisms of table rolls and foils as well as quantitative descriptions of dewatering capacity.

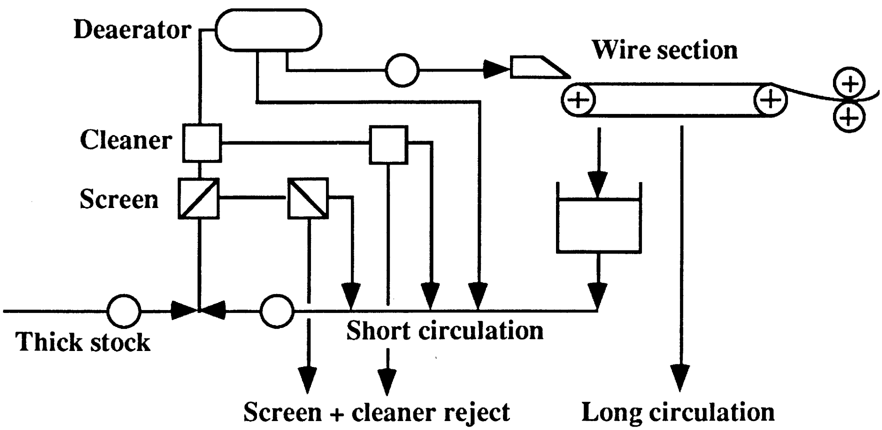
Joe Parker´s now classic book from 1972, *The Sheet Forming Process* (2), gives a good picture of basic forming knowledge around 1970. 60% of Parker´s 140 literature references were published after the Wrist paper, which indicates the amount of fundamental forming work undertaken during the 1960's. Parker treated fibre networks and their reaction to turbulence energy, dewatering resistance, material distribution in the plane as well as in the z-direction of the sheet and in a final chapter "Practical applications", headboxes and forming methods were discussed. "Two-wire formers" were mentioned, but it should be remembered that Parker's book was published just before twin-wire forming made its large industrial breakthrough. Within the TAPPI Fluid Mechanics committee, work is under way to update Parker´s original book.

Ben Radvan´s chapter *Forming* , in the "Wiggins Teape Epos" *Papermaking Science* (3) covers mainly the same areas as Wrist and Parker did, and adds basic work published from 1970 to 1977.

A serious reader, not well aquainted with the background described in these contributions, should make a break here, study the three references , and then continue with this overview.

During the last decade, the demands on machine speed, production efficiency, product quality, quality evenness and environmental control have all increased at an accelerating rate. It follows that, today more than ever before, not only the basic sheet build-up process in the wire section has to be considered when a forming section is designed.

A typical layout of the forming process is shown in *Fig. 1*.



Fig, 1: Forming, from thick stock addition to a wet web.

As indicated in fig 1, screening and cleaning which basically belong to stock preparation are normally placed within the forming domain. This is however an unsatisfactory solution since it leads to a large number of internal circulation loops with inherent concentration variations and variable fibre reject rates.

The increasing requirement for control of recirculated material through the white water system will focus interest on the retention level. This in turn stresses the use of process chemicals, a subject that is dealt with in a separate review by Lindström (4)[1].

Dry forming has attracted increased interest for special products, but space does not allow its discussion in this overview.

In the following, the physical forming areas listed below will be discussed:

Sheet quality
Fibre suspensions
Mix preparation
Mix distribution
Fibre deposition
Mix dewatering
Product properties

Since these seven areas each have a large enough background to motivate an individual review, it follows that it will be impossible in this overview to go in any detail into all the vast literature covering the whole field. The choice of literature references is therefore highly personal with some older, original references and some more recent ones. All those which space and time did not allow to be included this time may be just as significant.

Finally, it should be pointed out that to manufacture efficiently an end product with given properties, the forming process cannot be studied in isolation. There has to be an overall optimization including the preceding raw material preparation as well as the downstream pressing, drying and surface treatment operations.

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[1] Setting an all time symposium record with 103 pages and 260 references!

2. Mass formation

The forming process, as defined in table 1, has a large impact on resulting sheet properties and especially on their variability. All grammage variations, apart from long term variations in the machine direction, are exclusively generated during forming.

Of increasing importance for the sheet properties is also the distribution of material and fibre orientation at different levels in the z-direction of the sheet, which is to a high degree determined during forming. The final development of sheet properties can however be manipulated during the pressing, drying and surface treatment operations.

Mix preparation and mix jet generation are the main sources of grammage variations. Large scale grammage variance is usually subdivided into *MD variance*, *CD variance* and *Residual variance* and can be evaluated on-line using beta ray absorption. However, on-line equipment today cannot record grammage variations smaller in geometrical size than about 20 mm.

Small scale grammage variations, often referred to as *formation*, are mainly caused by the flocculation tendency of fibre suspensions, and can be strongly affected during forming. Formation is a very general term according to the ISO definition: "The manner in which the fibres are distributed, disposed and intermixed to constitute the paper". This is a very wide definition of the complete forming process, including the resulting sheet structure.

Wahren (5) tried to connect the term *formation* with small scale grammage variations and *look-through* with the appearance of sheet unevenness, viewed in transmitted light. This has not however been generally accepted, since today "formation" is used to denote both "look-through" and "formation" as well as "forming". A new term is therefore necessary to specify strictly small scale grammage variations.

Corte (6) used the term Distribution of Mass Density, DMD, which has never been generally accepted, probably because of its being too complicated.

In this overview, the term *mass formation*[2] will be used to denote small-scale grammage variations. Formation can then continue to be an unspecified characteristic, denoting for example the optical unevenness of paper. There is however no need to use it also to denote forming, as Peter Wrist already did.

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[2]Introduced by Douglas Wahren, STORA.

2.1. Formation measurement

The classical formation meter is the QNSM-meter (7) from the 1960's, while today the NUI meter (8) in North America, and the M/K-formation meter (9) are usually used to quantify optical formation. All three meters record the variations in light transmission through a paper sheet. They are valuable for the comparison of similar products from one paper machine, but they are not useful for further quantitative evaluation.
Recently, equipment using image analysis techniques for recording variations in light transmission has been developed by Papworth (10).

Light transmission measurements can never be used to evaluate mass formation of sheets made of components with different optical properties, such as filled sheets, or of calendered sheets where local variations in light scattering coefficient make the correlation between light transmission and local grammage ambiguous (11,12).

2.2. Mass formation measurement

Beta ray absorption is commonly accepted for on-line measurements of large scale grammage variations. Corte (6) used direct measurement of beta ray absorption, with 1 mm geometrical resolution to evaluate mass distribution.

In *beta radiography* , the complete picture of beta ray transmission through a test sheet is recorded on an X-ray film. As beta ray source, C-14 is useful, although the particle energy limits maximum local grammage to around 120 g/m^2 with reasonable exposure times (13). The maximum geometrical resolution using diffuse beta radiation is of the same order as the sheet thickness.

Cresson has studied the details of exposing and developing beta radiographs (14).

Local grammage variations can be evaluated from an exposed x-ray film by optical scanning using a micro-densitometer (15), see *Fig. 2*, or an image analyser (14, 16).

With soft x-rays , a more parallel beam of radiation can be generated. This permits an improved geometrical resolution, allowing individual fibres to be reproduced (17). Further advantages are the short exposure time and the unlimited grammage range. A problem is the difficulty of obtaining a low energy x-ray beam of acceptable cross sectional size, without too disturbing gradients in radiation intensity.

A recent development which looks extremely promising is to record local grammage via the absorption of electron beams, a method under developement by Luner and co-workers (18). This could be the ultimate way of evaluating mass formation, with possibilities even of on-line measurement.

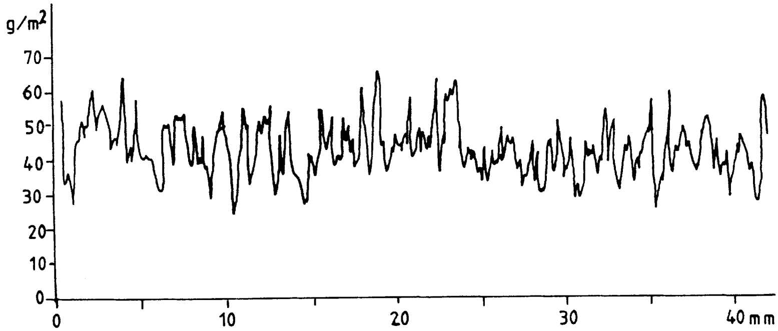

Fig. 2: Local grammage variations along a standard newsprint sample. Beta radiograph scanned in a microdensitometer using 0.1 mm resolution (15).

2.3. Characterization of mass formation.

The simplest way to characterize local variations is by the standard deviation σ. It is suggested that the dimensionless coefficient of variation, i.e. the standard deviation divided by the mean value, be called the *mass formation number* and denoted F. In turbulence research, the coefficient of variation of local flow velocity is called the *degree of turbulence.*

It should be pointed out that the geometrical resolution of the measuring equipment directly determines the amount of variations recorded.

It should also be pointed out that mean grammage has a large effect on the mass formation number. For a random fibre distribution there is an inverse relationship between the mass formation number and the square root of the mean grammage. For a comparison between sheets of different grammage, the following equation can be used for normalisation[3]

$$F_0 = F\sqrt{w / w_0} \qquad (1)$$

where the mass formation number F is measured at grammage w and F_0 is the corresponding mass formation number at the reference grammage w_0 (19).

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[3]"The inclusion of mathematical expressions in this publication is intended only to clarify the contextual descriptions of the processes. They are not intended as analytical supplements. In keeping with this function, units of the terms are unnecessary and have been omitted" (2).

2.3.1. The Power Spectrum

For a more complete characterization of grammage variations using beta radiography, a two dimensional description is useful. Besides a variation number some measure of the geometrical size of the variations is needed.

Already during the 1930's, the *autocorrelation* and its Fourier transform, the *frequency power spectrum*, were introduced (20). The frequency power spectrum describes how the variance, σ^2, is distributed in different frequency ranges. The power spectrum is especially useful to characterize variables with normal amplitude distribution, but it does not quantify the occurence of gradients.

To characterize mass formation in paper sheets as well as turbulence and flocculation in flowing suspensions, it has proved useful to transform the frequency specrum into a *wavelength spectrum* . The wavelength l is calculated from the frequency n and the radiograph scanning speed (or flow velocity) u using the simple transformation

$$l = u/n \qquad (2)$$

and the *frequency spectral density* has to be transformed into a *wavelength spectral density* accordingly (21).

The advantage of the wavelength spectrum over the frequency spectrum is the possibility of directly evaluating the geometrical scales in the variations, i.e. flocs in paper sheets and fibre suspensions or eddies in fluid flows. It should be remembered, however, that under turbulent conditions the transformation is not entirely strict, since "the scanning speed u" in eq. (2) should then be replaced by the local flow velocity.

A beta radiograph can be analysed in a microdensitometer, and the wavelength power spectrum of mass formation recorded. By scanning in both the machine and cross directions, the anisotropy of fibre orientation can be evaluated from the difference between the spectra (22).

To condense the information of a complete power spectrum, it is possible to present the variations within a few wavelength ranges. An STFI standard is to express the mass formation number F for the two floc size ranges 0.3 - 3 mm (F_1) and 3-30 mm (F_2). The values F_1 and F_2 then represent the mean floc sizes of 1mm and 10mm respectively.

As already mentioned, the geometrical resolution of the measuring equipment determines the amount of variations recorded. There are approximately equal contributions to the variance of grammage variations for each decade of wavelength. If we assume that a measurement of mass formation covers a wavelength range of 2.5 decades, e.g. 0.1mm - 30 mm, 40% of the variance would be lost if the resolution were changed from 0.1mm to 1mm. Because of the quadratic relationship between variance and F-value, the latter would decrease by approximately 20% due to the change in resolution.

With an image analyser, the two dimensional power spectrum can be evaluated, which is useful when floc shapes and two dimensional structures of periodic variations like wire mark are to be characterized. For high resolution in the power spectrum, the computer of a standard image analyser is not enough. A mainframe computer is therefore needed for an accurate numerical evaluation of the one dimensional wavelength spectrum (16).

2.3.2. Mass formation scales

There are other ways of characterizing the scale of variations, such as *micro scale* and *macro scale* (23), which are also concepts from turbulence theory.

The *specific perimeter* is evaluated as the total periphery of fibre flocs, defined as areas of above average grammage (24). Mean floc size is then inversely proportional to the specific perimeter.

A comparison between different variation and scale values to characterize grammage variations is given in (14).

2.3.3. Co-occurrence matrix

In image analysis, the texture can be described by second-order statistics using different algorithms. *The spatial grey level dependence method* sometimes called the *Co-occurrence Matrix* (14, 18) has been applied to characterize mass formation. It quantifies the probability of occurrence of a specific grey level transition between two pixels of a given spatial separation.

In Cresson´s thesis, (14), several parameters, see *Table 2*, are used to characterize laboratory sheets and simulated sheets, see further section 6.3. Unfortunately, detailed comparisons with earlier results are not possible, since power spectra were never calculated.

Table 2: Parameters derived using the spatial grey level dependence method (14).

Floc Morphology	**Texture maps**	**2:nd-order statistics**
Floc probability	Probability peak	Energy
LWZ probability	Ellipse major axis	Entropy
Edge probability	Ellipse minor axis	Correlation
Floc size index	Ellipse area	Homogeneity
Floc distance index	Ellipse eccentricity	Contrast
Number of flocs per line	Formation index	

This new method of texture analysis could be be a useful complement to spectral analysis of mass formation.

3. Fibre flocculation

It can be shown that if fibres are added to water under very gentle mixing conditions, no fibre networks of appreciable strength are formed. However, the introduction of turbulent shear into the suspension causes local fibre deformations, which result in mechanical network forming when the turbulent shear energy decays.

The effect of fibre properties and hydrodynamic conditions on the forming and disruption of fibre flocs is therefore an important research area which has been dealt with by many researchers. Summaries have been published by, Parker (2), Norman et al (25), Kerekes (26, 27) and Wahren (28).

Just as old as the art of papermaking itself is the knowledge that fibre consistency during dewatering is the most critical parameter controlling the uniformity of the wet web. Wahren et.al. (29) showed that fibre flocs are formed by mechanical entanglement, and that a minimum of three contact points with surrounding fibres is required to lock a fibre in an unnatural shape. Fibre consistency and fibre slenderness were shown to be the main parameters determining the degree of fibre flocculation.

An approximate relationship between average number of contact points n, fibre consistency c and fibre slenderness L/d has been derived by Wahren and Meyer (30):

$$c_n = \frac{16\pi L}{\left[\frac{2L}{nd} + \frac{n}{n-1}\right]^3 (n-1)d} \qquad (3)$$

Sediment consistency, which is the final consistency reached when a highly diluted fibre suspension is left undisturbed and allowed to settle under the influence of gravity, is the lowest consistency at which fibre flocs form mechanical networks. Application of eq.(3) indicates that the average number of contact points at sediment consistency falls between 3 and 4, which agrees well with the minimum average value of n=3 for floc forming mentioned above. Usually, thick stock has to be diluted down to or below the sediment consistency, for a proper sheet to be formed with conventional forming systems.

Recently, Soszynski and Kerekes (31) performed an elegant experiment in which they formed flocs in a rotating vessel according to the Jacquelin method (32). At constant rotation they then diluted the suspension, and the lowest starting concentration at which flocs stayed intact during dilution they named *threshold concentration.* A comparison between threshold concentration and eq. (3) is shown in *Fig. 3.*

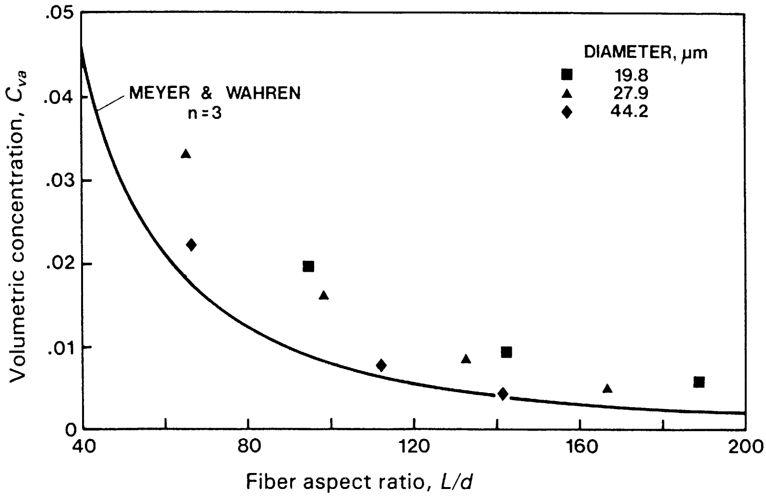

Fig. 3: Comparison between Threshold concentration (31) and Meyer-Wahren model (eq. 3) t

From fig. 3 it can also be concluded that stiffer fibres have a lower threshold concentration.

Soszynski and Kerekes further verified the concept of flocs forming from elastic bending of fibres. They formed flocs from nylon fibres, which were then treated at a temperature in excess of the glass transition point of the fibre material. The stresses in the bent fibres in the flocs could relax, and compared to untreated flocs, the treated flocs were much more easily broken up by stirring in a dilute suspension (33).

Riitala has applied percolation theory to evaluate sediment consistency in relation to eq. (3) with promising results (34).

Optical, "one dimensional", transmission or reflectance methods have generally been used to study local consistency fluctuations in flowing fibre suspensions (25). Recently advanced video techniques have also been applied (35). From video films it is possible to evaluate both floc shapes and floc behaviour.

A basic study of the forming and dispersion of fibre flocs was performed using high speed photography in a well defined Couette flow between two moving transparent walls (36). Two types of floc breakdown were found: one global, stochastic process in which a fibre floc is broken down by fragmentation or stretching and one rate-dependent local erosion process.

Laser Doppler Velocimetry is a common optical technique to evaluate variable flow velocities, usually with the help of seeded particles. In fibre suspensions, however, the technique is difficult to apply because of the large amount of naturally occurring scattering surfaces. These cause secondary scattering effects, making a correct signal evaluation difficult, unless the fibre consistency is very low.

Steen used a mixture of benzyl and ethyl alcohol for refractive index matching between fibres and fluid (37) and studied turbulence structure in pipe flow of fibre suspensions up to 1.2% fibre consistency (38),see *Fig. 4*:.

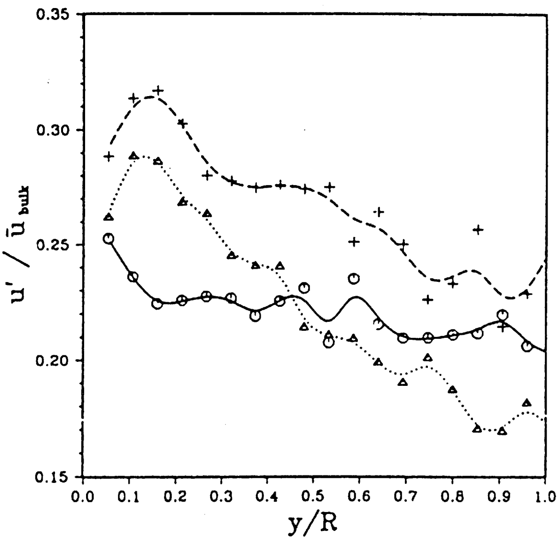

Fig. 4: Turbulent fluid velocity as a function of distance y from pipe wall at Re=8.5 10^3 (38).

————————	*no fibres*	*c = 0*
----------------	*l = 3 mm*	*c = 0.12%*
....	*l = 1 mm*	*c = 1.2 %*

4. Mix preparation.

The consistency of the thick stock delivered from the machine chest usually lies in the range 3-4%, which is much too high for conventional sheet forming. Therefore, the thick stock has to be initially diluted, using recirculated white water in the *short circulation loop* from the wire section,.to a *mix* which can be fed to the headbox. The mix should be at about the sediment consistency, with deviations from this value for different paper grades.

In the mix, for the first time, the fibre concentration is low enough for *screening* and *centrifugal cleaning* to be performed using conventional equipment, and they are therefore generally included in the short circulation loop, see fig. 1, although they really belong to the stock preparation domain. Screening and cleaning both require reject loops, in which consistency and flow rate fluctuations can be a serious cause of residual grammage variations in the final product.

The mix usually also passes a *deaerator*, where air originating from the white water is removed.

The ideal, as far as grammage stability is concerned, would be to feed the mix directly from thick stock dilution to the headbox, and thus avoid screening, cleaning as well as deaeration of the mix flow.

Since the *retention* of material in the wire section is below 100%, material will be recirculated by the short circulation loop as well as by the *long circulation loop*. The long circulation recirculates material to positions upstream in the stock preparation process, which means that internally recirculated material is also included in the thick stock.

4.1. Thick stock dilution

Traditionally, little thought had to be put into the process of mixing thick stock with white water. The *mixing pump* was always running at full speed, and the mix flow rate was controlled by a throttling valve.The pump was then generally operating far from its optimum design point, and all the excess energy was in reality used for mixing. Following the introduction of variable speed pumps, more attention has to be paid to mixing if the residual grammage variations are to be kept under control.

Norman and Tegengren (39) added the thick stock at a considerable excess speed centrally in a straight mixing pipe with white water surrounding it. This design works according to the jet pump principle, with good mixing properties at sufficient excess speed of the thick stock feed. As can be seen in *Fig. 5*, a velocity ratio greater than five is needed for good mixing.

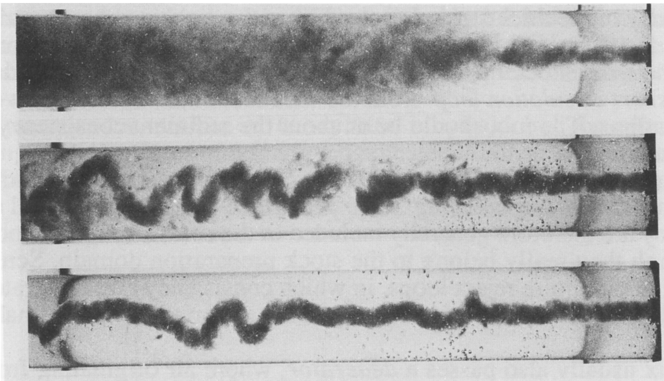

Fig. 5: Mixing of thick stock and white water at different ratios of Thick stock velocity / White water velocity (39).

Top: 1.5 - Centre: 5.3 - Bottom: 10.8

4.2. Screening, cleaning and deaeration.

Unfortunately, screens, and especially cleaners, require quite substantial reject rates. This necessitates up to two stages of screen reject recovery and five stages of cleaning reject recovery. This in turn introduces several new loops with different fibre consistencies, which may also vary in time. Finally brought together, the individual flows will generate consistency fluctuations in the mix fed to the headbox.

Today there are screens which run efficiently even at high consistencies. If the thick stock is screened, it would thus not be necessary to introduce mix screening. High consistency screening is made possible in one design by fluidizing the fibre suspension in front of the screen plate (40) and in another design by a flow situation which generates local dilution in the screen plate area (41).

It has so far been possible to perform centrifugal cleaning efficiently only at fibre consistencies below 1%. Above this consistency, so much turbulent shear has to be introduced to individualize shives, sand particles etc. from fibre flocs, that large-scale turbulent mixing overshadows the centrifulgal separation effects. A new cleaning process development is however under way, in which the fibre network is sufficiently fluidized to separate sand particles efficiently at 3% feed consistency (42).

The shive-removing task of cleaners could probably be taken over by properly designed screen systems, and this function could thus also be moved from mix to thick stock.

Since most of the air in the mix flow originates from the recirculated white water, it would be logical to deaerate the white water before adding the thick stock see *Fig. 6.*

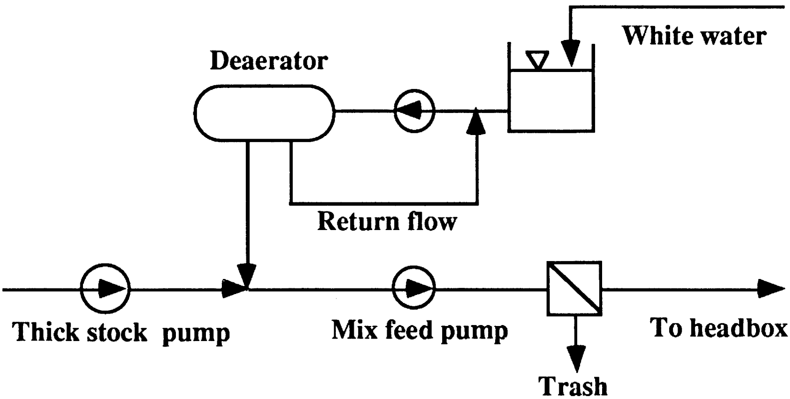

Fig 6: Short circulation design for maximum grammage stability

With a design according to the principle shown in fig. 6, all the fibres in the carefully controlled thick stock flow would be fed directely to the headbox, which would mean a much more stable operation than with today's conventional design, see fig.1.

In high consistency forming, the thick stock flow is fed directly to the headbox, which means that no short circulation loop is required at all.

4.3. Material recirculation

As mentioned aleady in the introduction, material with less than 100% wire retention is recirculated in both the short and the long circulation loops. Material in the short circulation will return directly in the dilution of the thick stock while material in the long circulation may take a considerable time before returning as part of the thick stock, see fig. 1.

Three parameters have to be specified to define a retention value.

A) material component,
B) starting position in process
C) end position in process.

The retention R is then defined as follows:

$$R = \frac{\text{Amount of component passing start position}}{\text{Amount of component passing end position}} \tag{4}$$

Any unspecified "retention" value would today be interpreted as "First Pass Retention" (FPR), which is defined as follows:

$$FPR = 1 - \frac{\text{Total consistency of white water in short circulation}}{\text{Total consistency in headbox}} \tag{5}$$

From a comparison of eqs. (4) and (5) it is clear that FPR does not even fullfil the basic requirements for a retention value, since consistency only and not mass flow is considered.

Further, all components are included instead of one specific. This is less suitable, since the retention value is then dependent on stock composition, and not only on the process as such.

The starting position in the process is defined as the headbox. The end position in the process is undefined however, since it depends on how white water is collected to the short circulation, and completely neglects all material going to the long circulation. On industrial newsprint machines, for instance, as much as 50% of the "fines" in the machine chest may be recirculated material in the long circulation.

The retention on twin-wire machines will often be overestimated compared with fourdrinier machines, if FPR only is the basis for comparison. This is because on a fourdrinier machine it is possible to separate the rich white water from the lean, and preferably bring the former to the short circulation. On twin-wire machines this separation is sometimes not possible, which means that the material concentrations in the short and long circulations are more equal.

Still, FPR can be of considerable value if applied to a specific system, and if the white water system is unchanged. To give even more useful results, however, component retention such as "fines retention" or "filler retention" should be evaluated, and the long circulation should be taken into account.

In a fully "closed" white water system, all material will finally end up in the paper web regardless of the retention level, but there are still several reasons for keeping wire retention values high and the white waters as clean as possible.

Cleaner white water means less problem with slime and dirt build up, which in turn will mean higher machine efficiency.

Cleaner white water means less circulating material, and therefore less changes in mix composition with fluctuating retention levels. This will mean a more constant quality of the product.

Cleaner white water means less material carry-over between machines with connecting white water systems.

Cleaner white water means a faster response to grade changes and other process changes, and thus a lower level of broke generation. This is especially important for the long circulation loop (43).

5. Mix distribution

The main task of the headbox is to transform the mix pipe flow into a thin jet with an extremely precise velocity, direction and thickness across the entire wire width. In this section, basics of flow in headboxes will be dealt with. Those interested in the design features of today´s headboxes are referred to an overview presented by Waller (44).

5.1. Cross machine distribution

The tapered manifold has been the completely dominating cross-machine distribution system for headboxes for over two decades, and a thorough description thereof was given by Trufitt (45). In principle, a large number of tubes, or holes, redirect the mix flow 90 degrees from the manifold channel into the machine direction.

An equal amount of mix flow is fed into each tube or hole, by keeping a constant static pressure along the manifold channel. This is possible by designing the channel cross-section area so that the pressure recovery through successively decreasing flow velocity along the channel (Bernoulli equation) is exactly balanced by the pressure drop along the manifold channel due to wall friction. The greater the pressure drop across the tube/hole section the less sensitive is the headbox flow profile to deviations from constant pressure along the channel.

To adjust the static pressure along the manifold channel, the amount of overflow from the exit side can be varied. If the mix flow in a headbox is increased too much above the original design point, it may be necessary to replace the channel to attain a constant enough pressure across the machine width.

The separation between the individual holes/pipes leading from the manifold channel must be sufficiently great so that fibre stapling on the downstream side of the openings is avoided. Further, the flow velocity into the tubes/holes must be comparatively large, if sufficient pressure drop is to be generated. This leads to a design with rather low open area on the upstream side of the tube/hole section.

The cross section of the tubes/holes is generally expanded towards the downstream side, or their centres are brought together. This is in order to give a large open flow area at the entrance to the next section, and thus to improve downstream flow stability.

Syrjälä, Saarenrinne and Karvinen (46) have studied manifold flow using three-dimensional numerical flow analysis, and compared the results with measurements in an air loop.

Bubik and Christ (47) described discrete increases of the tube cross sectional area, thus introducing the"step diffuser concept". This allowed a controlled turbulence generation with limited eddy size. Model experiments were performed with air, which allowed the use of hot wire anemometers for mean velocity and turbulence evaluation.

Lin (48) has made a numerical study of turbulent flow through a circular step diffuser.

The mix flow from a cross machine distributor is fed either directly to an outlet nozzle, or into a stilling chamber followed by some pressure drop generating device such as perforated rolls or tube bundles. In the stilling chamber, cross flow can occur, thus improving the cross machine evenness of the emerging jet.

5.2. Pressure pulse damping

In an air pad headbox, a compressed air volume above the stilling chamber can absorb pressure variations in the approach flow.

In hydraulic headboxes, a narrow channel may lead from a stilling chamber to a connected air volume, which can absorb high frequency pulsations. Usually, however, hydraulic headboxes exhibit a very stiff design from a flow viewpoint. If such a headbox is applied to a fourdrinier machine, special damping equipment may therefore have to be inserted in front of the headbox to avoid excessive grammage pulsations, see section 7.2.3. In the damper, an air volume may be located directly above the mix suspension surface or a membrane may separate the two.

5.3. Headbox nozzle

Already in 1961, Mardon discussed the relationship between headbox design and jet quality, and especially the degree of *wake effect* remaining in the emerging jet (49). During the late 1960's and the 1970's several investigations regarding jet quality were undertaken, mainly because of the increasing machine speeds and the introduction of hydraulic headboxes for twin-wire formers.

5.3.1. Headbox nozzle feed area and contraction ratio.

To keep a low degree of turbulence in the jet emerging from a headbox, a technique also used in e.g. wind tunnels is adopted. With a given *absolute level* of turbulent energy in the flow entering the outlet nozzle, the *degree* of turbulence in the emerging jet can be reduced in proportion to the acceleration of flow. The larger the nozzle contraction, the larger the reduction in degree of turbulence in the jet.

Reiner and Wahren studied the change in the turbulence spectrum in a headbox jet due to changes in headbox operating conditions (50). They analysed water flow in a headbox jet using an impact probe for turbulence recording. Considering the above mentioned relationship between turbulent energy and degree of turbulence as well as the fact that the degree of jet turbulence is independent of flow velocity u at constant slice opening h, the following equation was derived, with which a turbulence spectrum can be transformed to other running conditions.

$$E(l_2) = \left(\frac{u_2}{u_1}\right)^2 \left(\frac{h_2}{h_1}\right)^3 E(l_1) \tag{6}$$

E is the spectral density at wavelength l and indices 1 and 2 refer to measured and normalized conditions respectively.

The application of eq. (6) is demonstrated in *Fig. 7*. It is evident from the figure to the right that the equation holds well to normalize the turbulence spectra at different running conditions within the "linear" range investigated.

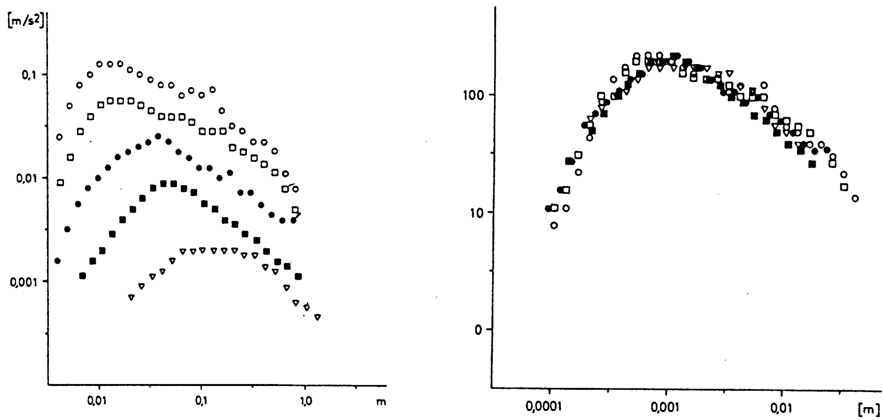

Fig. 7: Turbulence spectral density as a function of wavelength (50). Left: Recorded Right: Normalized

Symbol	∇	■	●	□	o
Slice opening mm	*10*	*20*	*30*	*40*	*50*
Jet speed m/s	*3.36*	*2.24*	*2.02*	*2.11*	*2.11*

To reduce the wake effects in a "Converflo" headbox, the nozzle is divided into a number of narrow channels using thin separation vanes (51). It is then possible to feed each channel from circular openings using a comparatively small open area, since the separation vanes prevent the generation of large-scale instabilities, see *Fig 8 (left)*.

As in the case of turbulence, velocity gradients are suppressed by the flow acceleration in a nozzle. Sanford (52) studied velocity profiles from Converflo channels, and the effect of slice opening is demonstrated in *Fig. 8 (right)*. A smaller slice opening means larger headbox nozzle contraction ratio, and thus also better evening out of the velocity streaks from the holes feeding the nozzle entrance.

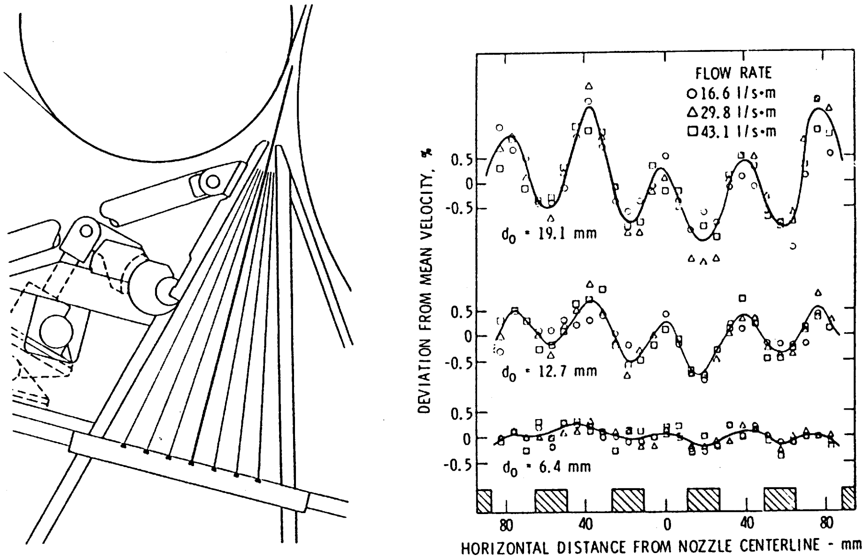

Fig 8: Left: Separate channels in headbox nozzle (divider sheet outside) (51)
Right: Flow profile at channel outlet (52).

During the early 1970's, a "high turbulence" hydraulic headbox was designed, with a tube bundle of nearly 90% open area feeding the headbox nozzle (53). To reach such a high open area, the pipes in the tube bundle were deformed into a hexagonal shape at the downstream end, and tightly packed at the entrance to the headbox nozzle. The same basic principle with high open area has later also been adopted by other manufacturers.

Valmet has studied the effect on jet quality of different geometries of the inlet section to the headbox nozzle. Turbulence spectra were measured, and the "half energy wavelength" of turbulence was calculated (54). This is the wavelength dividing the turbulence spectrum into two equal parts, and thus one measure of the mean scale of the turbulent eddies.

Fig. 9 shows some different inlet designs and corresponding turbulence characteristics. It can e.g. be observed that the entrance section of type E is three times as high as type B, and the turbulence level correspondingly lower. Pictures of the jets, *Fig. 10*, confirm the turbulence values in fig. 9.

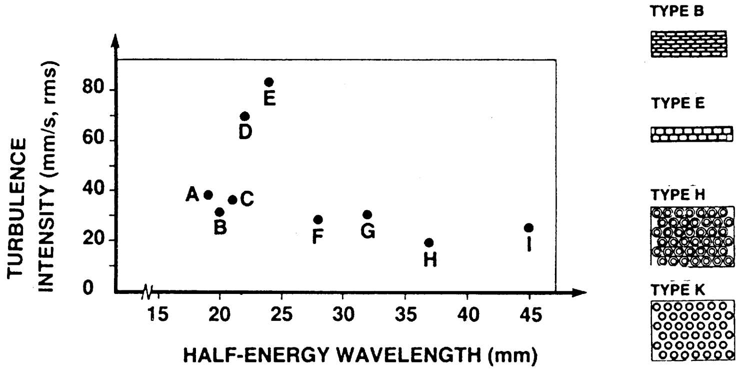

Fig. 9: Different inlet designs to headbox nozzles and corresponding turbulence characteristics (54).

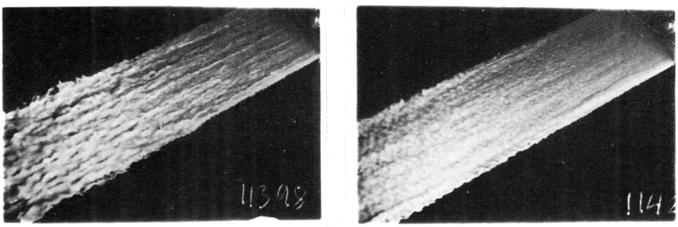

Fig. 10: Jets for type E (left) and type B (right) entrance sections.

At the outlet end of a headbox nozzle, a sharp contraction may be applied sometimes referred to as the "Parrot's beak". Compared to a straight headbox nozzle, a parrot's beak will generate a lower level of turbulence in the emerging jet. This is because, at a given jet thickness, the inner part of the nozzle is more open, and thus less turbulence is generated.

The degree of contraction of a headbox nozzle equals the degree of acceleration of the mix flowing through that nozzle. Flow elements will stretch during acceleration, and their cross section will contract correspondingly. This flow pattern causes fibre alignment, and the fibre orientation anisotropy in the jet is then a function of the degree of contraction in the nozzle.Already during the 1930's Moss and Bryant found that the fibre orientation in a headbox jet may be far from random (55).

It should be pointed out that nozzle contraction in a conventional air pad headbox is generally much higher than that in a modern hydraulic headbox, and thus also the fibre orientation anisotropy in the emerging jet.

Attempts have recently been started to calculate the turbulent flow pattern in headboxes using numerical FEM techniques. In one example, simple newtonian fluid properties are assumed, and only the first order of variations, i.e. the degree of turbulence, is considered (56). However, not until it is also possible to evaluate turbulence scales, i.e. the complete turbulence spectrum, will the theoretical methods be useful for predicting the effect on jet quality of changes in headbox design. Today's empirical development could then be made much more efficient.

5.3.2. Jet speed, angle, contraction and thickness.

To optimize the papermaking conditions, it is necessary to set the correct jet speed in relation to the current wire speed.The jet flow velocity can be calculated from the flow rate, the slice opening and the jet contraction ratio.

Maximum contraction and thus maximum jet speed, occurs at *vena contracta,* some distance away from the slice opening. After this position, the jet speed decreases due to air friction. The geometrical configuration of the outlet nozzle, and in particular the position of the top lip in relation to the bottom lip, determines the degree of contraction of the free jet.

Usually headbox flow rate is unknown, and the jet velocity then has to be calculated from headbox pressure. For conventional air pad headboxes this is a straightforward calculation using the Bernoulli energy equation. The flow velocities inside the headbox are so low that friction effects can be neglected.

In hydraulic headboxes, the internal flow velocities are so high that frictional effects have to be considered, and so has the velocity head at the position of static pressure measurement inside the headbox.

The jet speed can be adjusted at constant slice opening, which will mean a change in mix consistency. If mix consistency is to remain constant after a jet speed change, a corresponding change also has to be made in the slice opening.

Besides setting a correct jet speed, it is necessary to adjust the jet landing conditions (position and angle) in the wire section, see further section 7.2.1.

Detailed calculations of jet contraction and angle have been performed by Appel and Yu (57, 58). Kerekes and Koller (59) derived numerical equations to handle the data from the complex equations in ref. (57).

To generate a desired grammage profile, it is further necessary to control jet thickness across the machine width.The outlet nozzle is therefore generally provided with a deformable *slice bar* , controlled by a number of *slice screws* across the machine. To an increasing degree, control of local slice opening is made automatically using special algorithms, taking into account the actual slice opening profile as well as the difference between actual and target grammage profiles (60).

It has long been hypothesized, and it has recently also been theoretically shown (61), that a local deformation of the slice lip, apart from locally changing jet thickness, will also cause transverse flow. The transverse flow component can have a large effect on the final grammage profile, but will also affect local fibre orientation in the final product. The shape of the outlet nozzle is very important in this context, and the transverse flow component increases with decreasing contraction angle of a nozzle, see *Fig 11.*

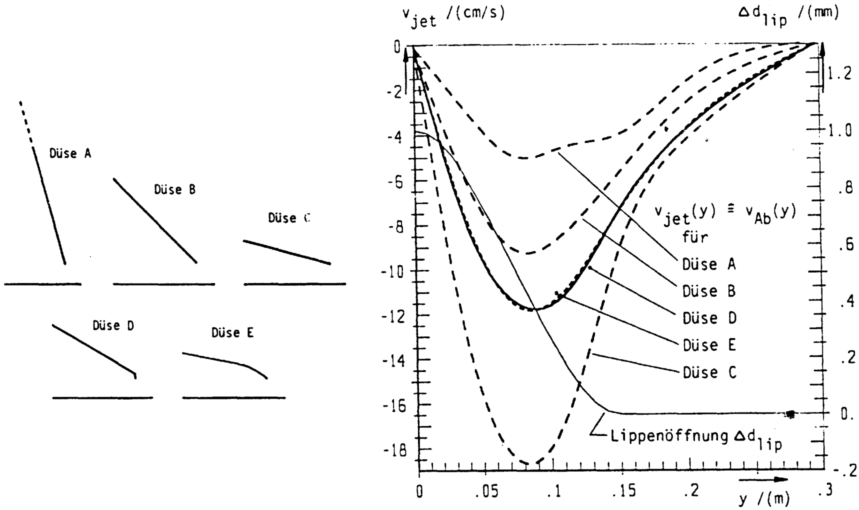

Fig 11: Effect of nozzle contraction angle on cross direction flow (61).

Ideal flow conditions in a headbox can occur only with a constant pressure along the manifold channel and a constant slice opening profile across the whole machine width, see further section 8.2. If the slice profile is deformed from this ideal state, transverse flow is inevitably generated.

Due to later deformation in the wire section as well as in the drying section of the grammage profile actually delivered from the headbox, the target profile for the headbox is never constant grammage across the whole wire width.

As an example, preferential cross machine shrinkage at the edges in the drying section require low grammage edges to be delivered from the headbox, to achieve even grammage profile at the reel. This in turn requires distortion of the slice at the edges, and as a consequence transverse flow is generated, causing local variations in fibre orientation anisotropy. The prevention of uneven cross machine shrinkage is therefore a prerequisite if anisotropy profiles as well as grammage profile are to be even all across the paper machine.

Finally, it could be mentioned that the target fibre weight profile at the reel-up may have to be adjusted because of moisture considerations.

5.4. Stratified headboxes

The simplest way to form a stratified sheet is from a stratified jet. A stratified jet can be delivered using a headbox with different mix suspensions in different layers.

There are two main types of headbox in industrial use today for stratified forming of two-layer or three-layer products.

In one design, the mix layers are separated by thin foils (62), which may or may not protrude from the slice opening, see *Fig. 12*.. The longer the foil, the later the mixing between the different layers can start. In a three-layer design, however, the friction conditions in the centre layer differ from those in the outer layers, and this generates velocity differences between the layers.

The degree of mixing between the different mix layers is very sensitive to the shape of the downstream end of the foils. They have to be tapered, since blunt edges cause severe layer mixing.

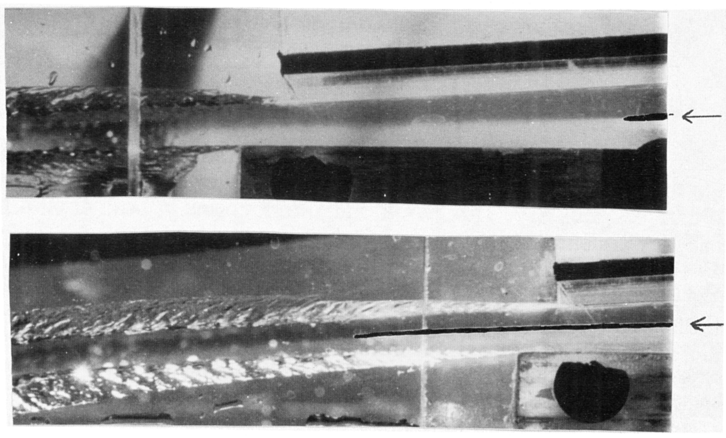

Fig. 12: Multi-ply headbox with thin separation foil (62)
Top: Foil ends inside Bottom: Foil extends outside headbox.

In a second design, the layers are separated using comparatively thick walls which protrude from the slice opening, and behind which air wedges form, (63). In this case, one individual jet for each layer is delivered from the headbox, see *Fig 13*.

With air wedges between the different layers, these can be kept separated until dewatering actually starts. However, air wedges mean that extra surfaces between mix and air are created, and instabilities in these surfaces will affect mass formation for the individual layers in a negative way.

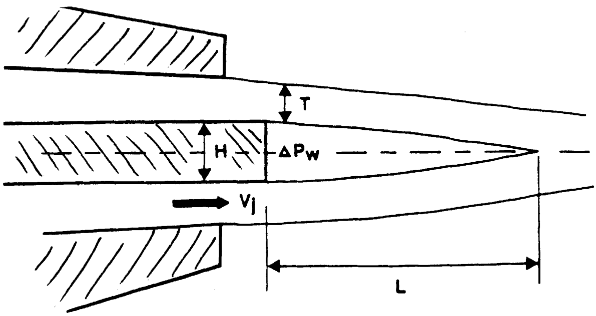

Fig 13: Thick separation wall and air wedge in multi-ply headbox (63).

5.5. High consistency headboxes

Forming at a fibre concentration as high as thick stock consistency, 3 - 4 %, would mean large process simplifications, since the short white water circulation would be unnecessary. This would mean reductions in both capital investment and energy consumption.

The basic difference between high consistency forming and conventional forming is the same as that between thickening and filtration dewatering, see section 6. To form high quality HC-paper, a uniform network of fibres has to be delivered from a high consistency headbox, since no radical improvements in fibre distribution can be imposed during the dewatering process, in contrast to what is possible in conventional forming.

Pioneering work in high consistency forming was performed by Reiner and Wahren (64) around 1970. The basic idea was to introduce dispersing turbulence energy into a high consistency fibre suspension, by forcing it through a narrow forming channel with high local pressure drops. After dispersion, the local energy input was decreased to a level low enough for the turbulence to decay. The flowing fibre suspension then transformed into a fibre network, and the generation of large scale flocculation during the turbulence decay phase was avoided "mechanically" by the narrow dimension of the channel. Different flow channel shapes were introduced, to induce shear of suitable levels, resulting in an improved fibre distribution (65), see *Fig. 17.*

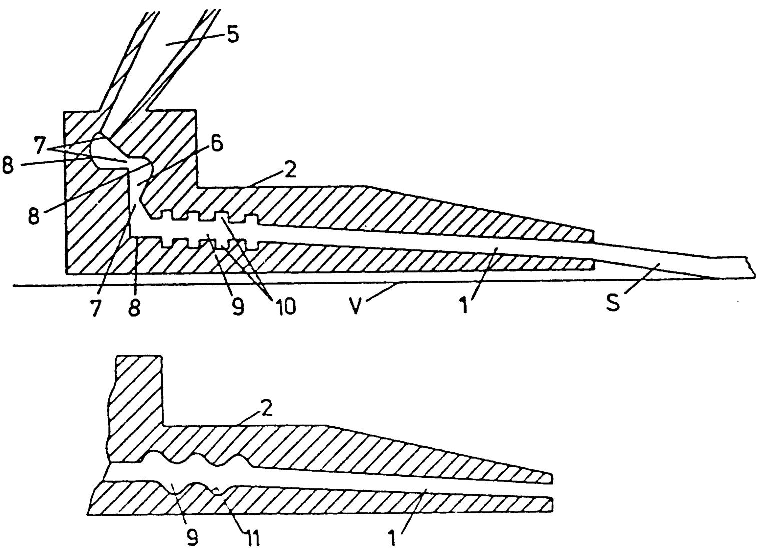

Fig 17: High consistency forming channels according to patent drawings (65)

A further improvement was the introduction of an "eddy chamber", fed from the individual pipes of the cross machine distributor (66).The fibre suspension is fed tangentially into the chamber, and to reach the outlet, the flow has to make a sharp turn. This causes a large contraction of the flow into the forming channel. A high pressure drop is generated, which is benificial for the final cross distribution of fibre suspension inside the eddy chamber. Furthermore, this design has good runnability, since it can even be started filled with a high consistency fibre suspension.

Recently high consistency headboxes with flow channels similar to those described in ref. (65) have also been tried in a Japaneese development project (67).

6. Fibre deposition

Radvan et.al. demonstrated that fibre suspension dewatering can be either a filtration or a thickening process (68). *Fig 15* illustrates the principle difference between the two.

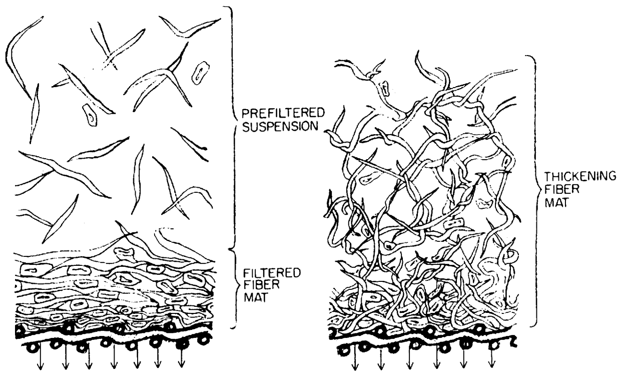

Fig. 15: Fibre deposition by:
Left: Filtration process Right: Thickening process (2).

In the filtration case, the fibres are laid down individually from a dilute fibre suspension. The result is a strongly layered sheet structure with rather poor mechanical properties in the z-direction. Conventional sheet forming of the fourdrinier type and of the twin-wire type are thought to be mainly filtration processes.

6.1. Laboratory sheets

The main reasons for making laboratory sheets is to evaluate the potential of a given pulp, and not to simulate industrial forming conditions. In laboratory sheet forming processes, a high degree of dilution is therefore used, to avoid fibre flocculation and thus to make as uniform a sheet as possible. These processes are therefore typical filtration processes.

The *British Standard Handsheet* is the traditional laboratory sheet, formed from a fibre suspension of about 0.02 % consistency, which is about 25 more dilute than in industrial forming. Because of the high dilution, the sheet build-up follows an ideal filtration process, resulting in a far better than random fibre distribution, see section 6.2. The result is a laboratory sheet with mechanical and optical properties superior to those of machine-made paper.

On the other hand, the retention using the original British Standard Handsheet Machine is comparatively low, due to the absence of white water recirculation. For mechanical pulps, or for products where fines or filler content is important, means of recirculating the white water should therefore be considered (69).

The fines and filler tend to be concentrated to the wire side in laboratory sheets, while the opposite is true for machine-made fourdrinier sheets. In twin-wire sheets, the distribution generally shows a symmetrical form with maxima somewhere between the centre and the surfaces (2).

Formette Dynamique (70) is a rotating laboratory sheet former developed in Grenoble. It dewaters a sheet on a removable bronze wire, placed against the inside of a perforated drum, and the dewatering pressure is generated through centrifugal forces. One advantage of this former is the large sheet size of 250 mm x 800 mm, which allows more complete testing than the smaller, circular British Standard Handsheets. Furthermore, Formette Dynamique is well suited to the making of multi-ply sheets.

The fibre consistency in the feed to the former is as high as 0.3-0.4 % but normal fibre flocculation is still avoided since the actual fibre deposition onto the web takes place by centrifugation through a 10 mm thick water layer. This makes it easy to align fibres in the direction of rotation, and thus to make oriented sheets. With Formette Dynamique, it is in fact difficult to make isotropic sheets.

When evaluating paper samples taken from industrial machines or pilot machines, a comparison with laboratory sheets made from the same furnish is useful. The ratio between the properties of a machine sample and those of a laboratory sample is a measure of how well the potential of a specific furnish is developed on the machine, i.e. of the *Forming Efficiency* . When evaluating FEX samples, Formette Dynamique laboratory sheets made from the same furnish are used as reference for the calculation of Forming Efficiency, (71).

6.2. Random sheets

It was already suggested by Wrist (1) that dewatering on the Fourdrinier was to some extent a self-healing process The reason for this was that areas of lower than average local grammage also exhibit lower than average dewatering resistance. Therefore, extra dewatering would take place at areas of low grammage, and the extra fibres deposited would then result in an overall levelling of grammage over the sheet area.

Early simulations of a random sheet structure by Corte and Kallmes (72) were made by drawing black lines, representing fibres, with random position and orientation. In this way, however, only very low grammages sheets could be represented, since at realistic sheet grammage the random sheet would appear almost completely black, with no floc structures. The grammage was therefore limited to a few g/m^2, see *Fig 16* . The simulated random sheets were compared with real sheets of corresponding grammage and fibre dimensions.

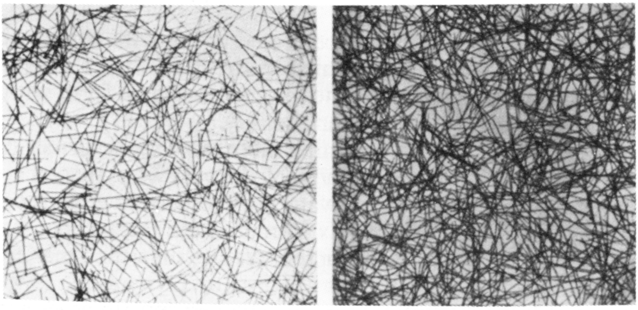

Fig. 16: Sheets with grammage 2.5 g/m^2 (72)
Left: Random network of straight lines
Right: Real sheet.

Because of the low grammage, with a correspondingly open sheet structure, no true conclusions could be drawn from these experiments regarding a self-healing effect. The improvements for real sheets could be expected to start at a much higher grammage, probably greater than 10 g/m^2, and to increase with grammage.

Corte also calculated the mass formation for random sheets and compared the results with measurements of beta ray transmission through real sheets (6). His conclusion was that the random sheet had the ultimate degree of uniformity, at which to aim in the sheet forming process.

Norman et al calculated the mass formation wavelength spectra of random sheets and compared them with the corresponding spectra measured on beta radiographs of well formed laboratory sheets (22). The results clearly demonstrated that random sheets were much more uneven than laboratory sheets in the small scale wavelength range. This was thus a confirmation of the idea suggested by Wrist, regarding the self-healing effect of the dewatering process on local grammage variations.

The difference in geometrical resolution is one possible explanation of the different results obtained by Corte and Norman. Corte used a square measuring area of 1 mm size, and also calculated the grammage variations for a random sheet at the same resolution. Small-scale variations, below 1 mm, were therefore never considered. Norman, on the other hand, used a resolution of 0.1 mm both in the measurement and in the calculations.

In Norman´s case, the large amount of random variations in the small- -scale region overshadowed the more even random structure at large wavelengths, in comparison with the real sheet. In Corte's case instead, the larger variations obtained for real than for random sheets could have been caused by the more frequent occurence of fibre flocs in the real sheets.

To make a more subjective comparison possible, a picture of a random sheet was prepared by Norman et al (22),using a method in which fibres were computer drawn on an oscilloscope screen. The grey level of each fibre was set so low that up to ten fibres could be placed on top of each other without reaching grey level saturation. This made it possible to study the details of a 40 g/m^2 random sheet and to make comparisons with the corresponding laboratory sheet, see *Figs. 17a and b.* From these pictures it was clear that there are more small- -scale variations in the random sheet than in the real sheet.

Norman et al also analysed anisotropic random sheets. Mass formation wavelength spectra were calculated both in the direction of main fibre orientation (MD) and in the perpendicular direction (CD). The two spectra cross each other, with the MD spectrum below at small wavelengths and above at large.The difference between the spectra is a measure of fibre orientation. The mass formation number is the same in both directions, however. Corresponding results were obtained in actual measurements on paper sheets as well as on highly oriented nonwoven sheets.

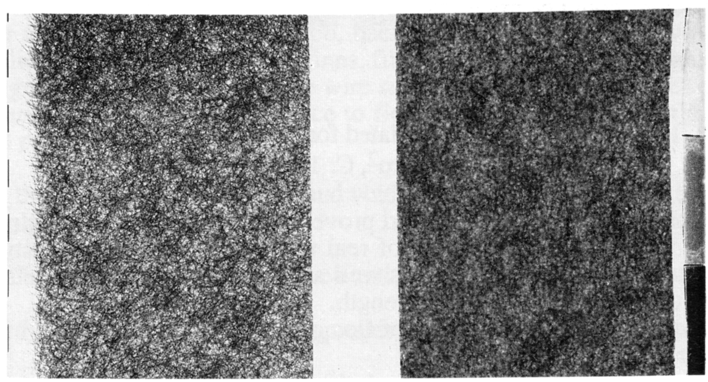

Fig. 17: Mass distribution in 40 g/m^{2}sheets (22)
Left: Computer drawn random sheet.
Right: Beta radiograph of laboratory sheet.

Cresson (14) in his thesis, which can also be recommended for its excellent litterure reference coverage, besides simulating isotropic and oriented random sheets also simulated the improving effect on mass formation of drainage levelling. Introducing two-dimensional fibre flocculation made it possible to simulate the structure of laboratory sheets made with delayed drainage. Further simulations on dewatering of flocculated structures are reported by Gorres, Cresson and Luner (73), see *Fig 18*.

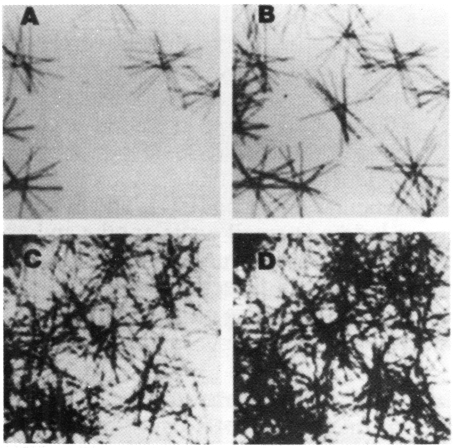

Fig. 18: Simulation of flocculated forming (73).
A: 1 g/m^2, B: 2.5 g/m^2, C: 10 g/m^2, D: 22.5 g/m^2

Further work along these lines should prove useful to improve the understanding of the forming process. To be of real use, however, more realistic fibre characteristics should be included as well as three-dimensional models, shear flow conditions and fibre network strength.

Steen will discuss the process of floc generation and breakdown in a contribution at this symposium (74).

6.3. Filtration dewatering.

Early studies of dewatering resistance were carried out by Ingmanson and coworkers (75), according to the theories of filtration. They based their analysis on the Kozeny-Carman equation:

$$\frac{dQ}{dt}=\frac{1}{K}\frac{(1-C)^3}{S^2C^2}\frac{1}{\mu}\Delta p \tag{7}$$

where dQ/dt is rate of drainage per unit area of the web, Δp is the pressure gradient across the web, C is the volume fraction of the web occupied by solids, S is the specific surface area of the solids per unit volume, μ is the viscosity of the fluid and K is the Kozeny constant.

The Kozeny-Carman equation assumes laminar flow through a bunch of parallel capillaries in an incompresssible medium. Neither of these assumptions are true in the case of wet paper webs. The Kozeny-Carman equation in its present form can thus not be used for useful predictions. Substantial modifications must be incorporated, before it can successfully be applied to paper webs. Application of the equation results in values of the surface area S an order of magnitude different from the surface area estimated using other methods (3).

In connection with his discussions of the hydrodynamics of dewatering, Radvan states that "the progress of technology has overtaken the need for detailed understanding of the original process". There may be reason to put a question mark to the use of the word "need" in this context, but there is no doubt whatsoever that the rapid development of fourdrinier as well as twin-wire dewatering principles, which has taken place also after Radvan's statement, has completely outpaced the corresponding theoretical understanding.

During the dewatering process in the wire section, a suspension is forced against a compressible, porous web, backed by the surface of a woven wire. The solid particles such as fibres, fines, filler etc. in the suspension are to a certain degree trapped, initially by the wire surface and later in the pores of the accumulating wet web. The resistance to flow through the web is influenced by several parameters, such as:

the distribution of material and voids in the z-direction and in the plane of the web

the chemical properties of web and suspension components

the mechanical compression properties of the web

the mode of flow (laminar, turbulent) through the pore system

the time event of the pressure driving the dewatering

It follows, that the dewatering of a well defined furnish subject to a known pressure (or force) event is extremely difficult to describe. Schopper Riegler number or Canadian Standard Freeness level, as evaluated in standard laboratory equipment is not enough to predict the actual dewatering capacity on a paper machine.

Fundamental work on dewatering has been summarized by Radvan (3). Several devices to study filtration dewatering resistance have been developed. They are based on constant filtration rate, constant filtration pressure or combinations of these two modes. Since these idealised conditions differ significantly from those prevailing in a real wire section, attempts have been made to make realistic modifications of the laboratory devices.

One example is the development by Pires, Springer and Kumar (76), who used a Britt Jar device (77) and with some modifications designed a "Drainage and Vacuum Retention Tester". The introduction of six electrodes made it possible to follow the drainage event, and shear rates in the fibre suspension as well as pressure events on the downstream side of the wire comparable to those encountered in paper machines were introduced. They used the device in connection with modelling of fourdrinier drainage on a pilot plant machine, see further section 7.2.5.

For practical use, empirical equations are often used to predict the influence of process conditions on dewatering. One example is the equation of Wahlström and O'Blenes (78):

$$t = \frac{G}{C} w^{\alpha} (\Delta p)^{n} \qquad (8)$$

where t is the time to form a web of grammage w, under a constant pressure drop Δp. C is the suspension consistency and G, α and n are empirical constants.

6.4. Thickening dewatering.

Even in a conventional forming process, all fibres are not free to move individually during dewatering. Some fibres are mechanically connected in fibre flocs, which are successively compressed during dewatering. This event can be described as a thickening process. Compared to filtration dewatering, the resulting sheet structure will be more "three-dimensional", since the fibres are more entangled in the z-direction. This can be expected to give improved properties in the z-direction, together with some losses in the plane of the sheet.

Britt, Unbehand and Shridharan (80) suggest that the level of fines retention is a measure of the distribution between filtration and thickening dewatering. A low retention level indicates mainly thickening dewatering, while a high retention level is an indication of filtration dewatering. In experiments using a Britt Dynamic Drainage Jar with controllable dewatering vacuum, they could apply a desired degree of dewatering pulsation. They thus claim to be able to simulate real dewatering processes by applying suitable dewatering pulses. A uniform dewatering pressure would result in pure filtration dewatering, while pressure pulses would generate their definition of thickening deatering.

When the filtration process is finalized on a fourdrinier wire or in a twin--wire section, further dewatering will cause consolidation by thickening. In the twin wire case, when the web is squeezed between the two wires, the web will be subject to mechanical compression. This type of dewatering follows the same basic rules as those in wet pressing, which means that the pressure applied is divided between hydraulic and mechanical pressure in the web. The amplitude of pressure applicable is limited by the allowable amount of wire mark embossed into the web surface.

The last part of dewatering in the wire section is performed by air suction. Water removal during this phase is a displacement process in which water is exchanged for air. This process differs considerably from a filtration or a thickening processes. The sheet dryness after the couch is therefore not a simple function of the flow resistance of the web.

It should be advantageous for final web dryness to keep the sheet mechanically compressed during air suction. Also, as little water as possible should be left in the wire, since much of that water may follow the web at the point of separation of wire and web.

Britt and Unbehend (81) found in laboratory experiments that different stocks often behaved quite differently during initial dewatering (up to the *dry line*) and during the final vacuum dewatering. There is no general correlation between initial and final dewatering rates, which makes it difficult to predict the overall dewatering characteristics for a specific paper pulp.

7. Mix dewatering

When the mix suspension is dewatered in the wire section of a paper machine, the actual process differs highly from the idealised conditions in laboratory sheet formers. Since the fibre consistency in real forming may be at least an order of magnitude higher than that in laboratory sheet forming, measures have to be undertaken to improve the mass formation of the paper produced. These measures are: *drainage, oriented fluid shear* and *turbulence* (2), see *Fig. 19.*

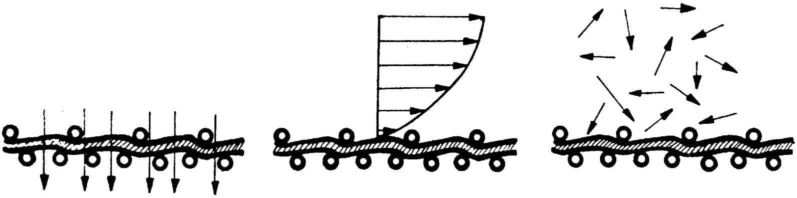

Fig. 19: Drainage, Oriented fluid shear and Turbulence (2).

As mentioned in section 6.2, drainage has a self-healing effect on grammage variations. Oriented shear is originally generated by a velocity difference between mix jet and wire, and may also be generated by shaking of a fourdrinier wire and by gradients in the fluid pressure applied in twin-wire formers. Oriented shear will move free fibres in a fibre suspension relative to one another, and may also disrupt fibre flocs. Oriented shear will affect the orientation of fibres and fibre segments, and will therefore have a strong effect on the anisotropy of the sheet properties.

Turbulent velocity fluctuations may occur in the mix jet from the headbox, and may also be generated in the wire section. The scale of the turbulence is vital for its interaction with the fibres in a suspension. Only eddies up to the same order of size as the fibre flocs will have a disrupting effect, while larger eddies will mainly superimpose floc motion. On a fourdrinier wire, turbulence can be generated by vertical movements of the wire as it passes over dewatering elements. In twin-wire forming, turbulence can be generated by pressure fluctuations between the wires.

The degree to which these effects occur in a given drainage section and the degree to which they are relevant to reach desired product qualities is still mainly unknown, and much more research is needed to extend the knowledge within the area.

In this chapter, basic process aspects in the wire section will be discussed, starting with forming wires and followed by fourdrinier forming, twin wire forming and multi-ply forming.

7.1. Forming wires

Helle recently presented an overview of the development of forming wires during this century (82).

Earlier, forming wires were made of bronze, they were single layered and of two shed design. Neither the material nor the design was a good choice for maintaining a long wire running time combined with high paper quality on high speed paper machines. When wires of polymeric materials were developed in the 1970's, the bronze wires therefore quickly disappeared from the market.

7.1.1. Wire surfaces

For good wire wear resistance, it is an advantage to have as much CD yarn material as possible facing the stationary wire support. This means that the machine direction threads, which take the main mechanical load, are subject to less mechanical abrasion, which in turn increases wire life. The influence of wire design parameters on the amount of material available for wear has been described in a theoretical model by Batty (83).

The wire side of a paper replicates the forming wire to some extent. A predomination of paper side MD nuckles, which is the case for a single layered wire with a predominance of CD nuckles on the bottom side, leads to increased deflection of fibres into the wire openings, "blinding" and reduced dewatering capacity (84). The preferential machine direction orientation of fibres on the wire side of the paper is one reason for this effect. Beran (85) introduced a "Fiber Support Index" to quantify the top surface quality of a wire.

The surface of the wires is also important for the generation of wire mark, which can be analysed using optical techniques (86).

It is thus obvious that a single layered forming wire cannot be optimised for both running time and paper quality. The introduction of polymeric materials made it possible, however, to design double layered wires, on which the top and bottom sides are more independent. Recently the use of "shute support" on double layered wires, which extra threads on the paper side of the wire has improved the support for the fibres during dewatering. Further, multi-layered wires have been introduced, which in principle consist of a fine top wire for paper support combined with a coarse bottom wire for runnability. Multi-layered wires are now introduced for most paper grades (87).

Good mechanical wire properties are important. This is accentuated because the dewatering pressure in twin-wire formers is generated by wire tension, and a uniform tension profile across the whole machine width is essential for a good cross machine grammage profile.

7.1.2. Dewatering properties

The traditional criteria for evaluating the drainage efficiency of forming wires were:

the relative vertically projected open area

the air or water flow resistance.

The relative open area concept ignored the fact that modern wires exhibit a highly three dimensional structure, in which the openness varies considerably in the thickness direction of the wire.

A better way of characterizing the openness is therefore to describe the distribution of material and voids in the thickness direction of the wire (88), see *Fig 20* . The influence of MD and CD threads can then be separately quantified.

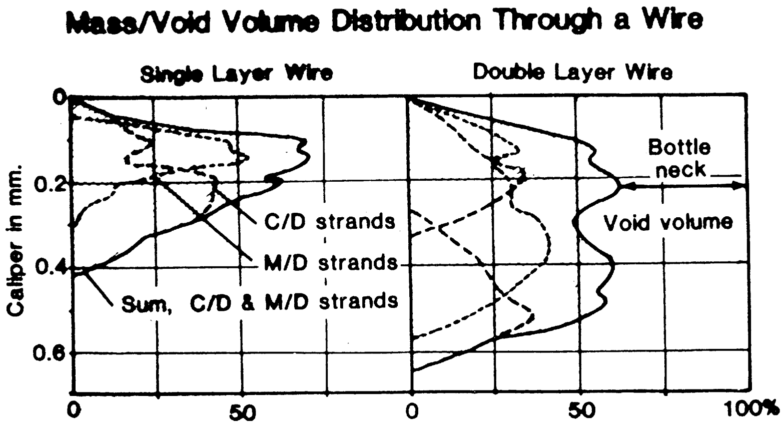

Fig 20 Mass / void volume distribution through wires (88)
Left: Single layer wire Right: Multi-layer wire

The wire design is also important for the level of retention of fibre material, but the size of the wire openings makes it extremely hard to filter out fines and filler, see *Fig. 21* (88).

Johnson (89) studied the deposition of air-suspended fibres onto different types of wires in a 32 times scaled up experiment. He found an improved retention going from a single layered to a double layered wire design. He also found that drainage was strongly influenced by the degree of sheet support for the first layer of fibre web.

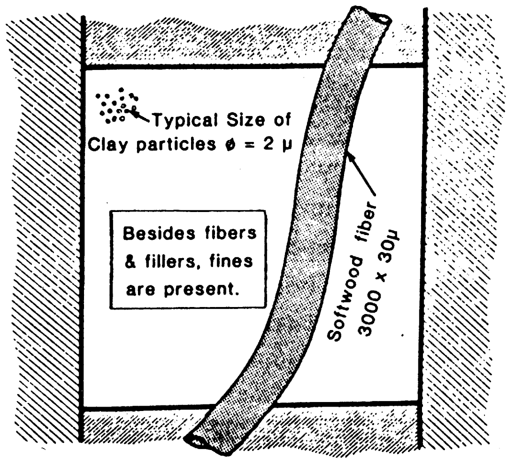

Fig. 21: Size of wire mesh "window" is 200µ x 200µ (88).

Fibre carry back is a term which refers to fibres which do not follow the wet sheet on its removal, but which are instead left on the wire surface and thus return to the forming zone. These fibres disturb sheet dewatering, by locally increasing the dewatering resistance of the forming wire, and cause a deterioration in mass formation. In twin-wire forming, the geometrical and mechanical properties of forming wires have a marked influence on the amount of fibre carry back (90).

7.2. Fourdrinier dewatering

The history of fourdrinier dewatering was recently presented in an interesting paper by Hansen (91). Classical fourdrinier dewatering has been described in some detail in references (1), (2) and (3).

7.2.1. Initial dewatering

The setting of the jet onto the wire and its initial dewatering is extremely important for both the dewatering capacity and the product quality. The jet should ideally hit the wire immediately in front of a supporting forming board.If the jet hits the wire much ahead of this board,too rapid dewatering will result in a deteriorated mass formation , whereas air will be trapped and disturb forming if the jet hits the wire on top of the forming board.

Wahren has theoretically analysed the situation when a jet hits a wire. He postulates that the ideal situation occurs when that part of the jet which remains on the wire will move horizontally as a result of the impulse exchange when part of the jet is deflected downwards (92). The influence of jet angle, jet thickness, horizontal and vertical distance from headbox to forming board, front angle of forming board and fraction of jet deflected downwards is analysed.

Österberg applies a laboratory former to study the initial part of the dewatering process (93).

7.2.2. Jet velocity pulsations

Pressure pulsations in the mix feed flow generate jet velocity pulsations when hydraulic headboxes are used. In fourdrinier forming applications, these velocity pulsations can result in serious grammage variations. Grammage variations up to ten times as large as the jet velocity variations have been observed.

One explanation for this amplification is the generation of standing waves on a fourdrinier wire (94).Maximum amplification will occur when maximum wave amplitude coincides with the dry line. The distance from headbox to dry line then corresponds to one fourth of the total wavelength of the standing wave, and the frequence is then normally in the range 10-20 Hz.

Another explanation of the amplified grammage variations could be the forward and backward movement of the position at which the jet hits the wire (95).

In twin wire forming, jet velocity pulsations do not generally cause serious problems. Since the jet is immediately enclosed between two wires, amplification due to standing wave generation is avoided.

7.2.3. Improvement of mass formation

To improve mass formation, horizontal shaking of the wire has been very useful, especially at low speeds. Recently it has however also been applied at speeds as high as 600-700 m/min.

A dandy roll, applied on the wire at a position where the average consistency is aound 2.5% improves mass formation by introducing shear in the suspension. A better effect would be achieved if the dandy roll were applied at even lower consistencies, but then severe downstream spouting cannot be avoided. This is because the dandy roll is not a dewatering element. and the suspension consistency is therefore approximately the same on the upstream and the downstream sides of the roll.

A new dandy roll application has been presented by Kallmes and Langdok, who used the roll for dewatering (96). They led the fourdrinier wire upwards on the downstream side of the dandy roll and also introduced a return roll, see *Fig 22* Having watched a demonstration run of this principle on the IPC experimental wet end, I am still amazed at the way water clung to the inside of the roll, allowing axial removal at “9:00 o´clock”.

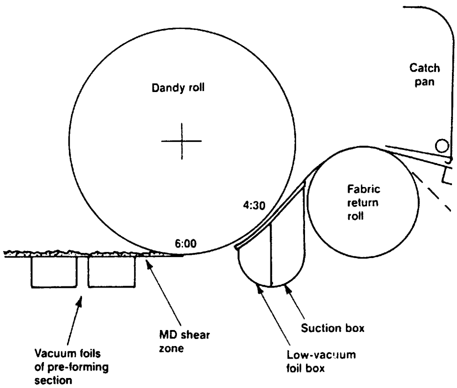

Fig. 22 Scheme of M/K Dandy Roll Former (96).

Mainly because of cleaning problems, dandy rolls have not been used on high speed machines. As far as the effect of mass formation improvement is concerned, the twin wire former can be interpreted as being a development from the dandy roll, since it can be run with low ingoing fibre consistency and still yield a sufficiently high outlet consistency. Many fourdrinier machines, especially those manufacturing printing grades, have been modernized to *hybrid formers* (see section 7.3.3) by the introduction of “extended dandy rolls” in the form of top wires.

7.2.5. Dewatering devices.

Originally, all dewatering relied on gravity effects, and supporting rolls were introduced only to keep the wire horizontal while causing a minimum of friction drag. Today, dewatering devices are applied to fourdrinier wires with the object both of creating dewatering effects and also of providing means for controlling the degree of fibre flocculation in the sheet formed.

Table rolls

The basic principle for table roll dewatering was understood during the 1950’s, and was described in work of Wrist (97), Taylor (98,99) and Bergström (100).

At a table roll, a suction pressure peak is generated in the downstream expansion zone between wire and roll. This causes a local downward deflection of the wire immediately after the roll, and a corresponding upward movement of the wire then has to occur before the next dewatering element is reached. The vertical motions of the wire generate turbulence in the suspension on the wire, which may to some degree improve final mass formation.

Pires, Springer and Kumar developed a computer program for the evaluation of drainage on a fourdrinier wire supplied with table rolls and vacuum boxes. They used the equation for table roll drainage developed by Taylor and determined the specific filtration resistance experimentally using their DVRT-tester (76), see section 6.

The amplitude of the table roll suction pressure is proportional to the square of the wire speed. There is an upper speed limit for the application of table rolls of approximately 500 m/min, above which the vertical wire movement is so intense that the high degree of turbulence generated disturbs the final mass formation.

A modified table roll which has recently been introduced is the *Sonic Roll* (101). It can be described as a gear wheel of wire section width, with each tooth broken at regular intervals along its length. During rotation, each tooth causes a local upward lift of the wire, and the amplitude of the wire movement is determined by tooth width and separation. For very slow machines it has been found useful to drive the Sonic Roll at an excess speed, which makes it possible to shake the wire at its resonant frequency (102).

Foils

Foils were introduced during the 1960's (1), and took over as the standard dewatering element at speeds where table rolls could no longer be used. Just as in the case of table rolls, the maximum amplitude of the suction pulse is proportional to the square of wire speed - in fact it equals the dynamic pressure of the mix on the wire. However, by choosing a very small angle between foil surface and wire, as low as even below one degree, a suitable suction pressure can be achieved even at high wire speed.

Usually several foil elements are used in combination, and to increase the overall dewatering effect they are mounted in vacuum boxes.

The overall optimization of the individual foiles angles and separation distances is a complex procedure. Schmid (103) performed an experimental study, and evaluated the turbulence level introduced by watching the surface of the suspension on the wire using a strobe light. The amplitude of surface disturbances was graded as "activity" in numbers from 1 (smooth surface) to 10 (severe stock jump). Among other things he found that an increase in foil angle along the wire gave an optimum combination of dewatering capacity and sheet mass formation.

Step foils

One disadvantage with conventional foils is that a complete element has to be replaced if the dewatering pulse is to be changed. This makes optimization of sheet mass formation through suitable activity in the mix on the wire rather complex.

The *Step foil* is a design in which the mix activity can be controlled by vacuum (104). The distance between the foil element and the wire undergoes a step increase, see *Fig. 23*, and the vacuum level in the foils box determines the extent to which the wire is deflected into the step. An increased vacuum level causes a larger vertical wire deflection, and thus create a greater activity in the mix on the wire.

Cadieux (104) performed a study on a pilot fourdrinier machine using step foils for the main part of the dewatering, and on the basis of the results he set up a mathematical model to describe dewatering. The equation is an expansion of the Kozeny-Carman equation, and the difference between a "static" laboratory sheet former and dynamic fourdrinier dewatering is taken account of by a *Fourdrinier Factor*. Of all the 17 independent variables tested, those found to be most significant were fibre compressibility, the first zone of the drainage element pressure pulse, drainage element position along the wire and headbox jet configuration.

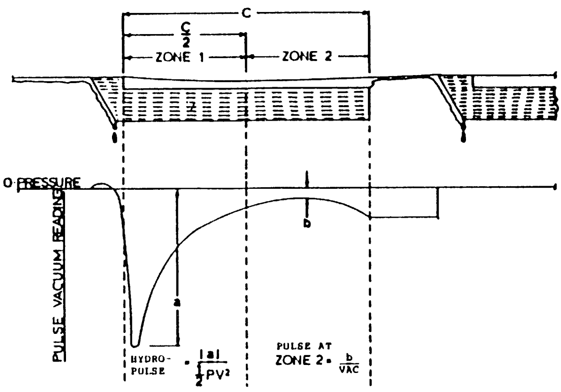

Fig. 23: The Step Foil (104).

Iso-flo foil

Iso-flo foils are horizontal support blades mounted in a vacuum box. Every second blade is slightly lowered, and thus the wire is be subject to vertical movements when running over the box with vacuum applied. The degree of activity on the wire is then controlled by the vertical distance between the blades.

Cascade foil

A cascade foil consists of several gently sloping sections with horizontal connections. A single cascade foil can have a capacity of several millimetres of dewatering, without the application of vacuum. Contrary to ordinary foils, the cascade foil does not introduce any activity in the fibre suspension on the wire. The reason for this is that the vertical wire movements are stabilized by the introduction of the neutral zones between the dewatering zones (105).

Flexi-Former

A dewatering device which acts from the top of the mix suspension on the wire is the Flexi-Former (106). A flexible (or stiff) blade is pressed against the mix, and dewatering occurs by the pressure generated in the suspension between a stationary upper surface and the moving wire. See further description in section 7.3.1.

7.3. Twin-wire dewatering

Principles for twin-wire forming were patented as early as during the last century, but not until the 1950's were machines developed which could be used for practical paper/board making. The new developments avoided the simultaneous mechanical guiding of both wires within the forming zone, a task impossible to perform with the required accuracy. The secret to success was always to let one of the two wires automatically adjust to the wire separation required by the prevailing forming conditions.

David Webster's (107) privately developed twin-wire former for paper production and Brian Attwood's (108) "Inverform" design, developed for board production at St Anne's Board Mill, were the first two designs of practical value.

The Webster patent for the *roll former* principle was acquired by Börje Wahlström of KMW, where the basic development continued and commercial equipment was produced. The roll former concept was also studied at PPRIC (109) and equipment was manufactured in co-operation with Dominion Engineering Works (110).

Twin-wire *blade formers* with stationary dewatering elements were developed by Beloit [4](111) and Black Clawson (112).

In pure twin wire formers, the mix jet is delivered directly into the gap

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[4]An earlier development by Times Inc. was taken over by Beloit.

between the two wires, whence the name *gap former* [5].

In a *hybrid former*, a fourdrinier section precedes the twin-wire nip. Valmet´s twin-wire formers have mostly been of the hybrid former principle (113), and during the early 1980's, Malashenko of Dominion Engineering suggested a *top wire* forming unit (114) to update fourdrinier machines to hybrid twin-wire formers.

The basic advantage of twin-wire formers compared to fourdrinier machines is the closed forming zone with the possibility of two sided dewatering. Two sided dewatering means high dewatering capacity and the possibility of symmetrical dewatering. A closed forming zone prevents fibre movement by surface waves, and makes it possible to introduce comparatively large amounts of dispersing energy without the risk of free surface instabilities.

In twin-wire formers, two webs are formed, each of half the total grammage. This means that a lower retention level can be expected in comparison with fourdrinier forming, since retention increases with web grammage.

An overview of different twin-wire formers available in 1987 was published by Thorp (115).

7.3.1. Roll formers

During the 1960's, paper scientists tried to describe theoretically the interrelationship between twin-wire forming conditions and dewatering pressure. The energy equation (Bernoulli equation) was applied, and the mix jet followed into a predefined space between the forming wires. This was an unsuccessful approach, since the primary variable in reality is the fluid pressure generated by a tensioned, curved wire, and the Bernoulli equation does not appply when outer forces are present.

In a twin-wire roll former, a mix jet is injected into the nip between two wires wrapping a rotating roll. The outer wire is given a tension T, and using classical mechanics the fluid pressure p generated in the mix to support the wire is given by the equation

$$p = T/R \qquad (9)$$

where R is the local radius of curvature of the wire.

During most of the dewatering phase, the roll radius is an acceptable approximation for R, since the separation between the outer wire and the roll surface is small relative to the roll radius. Dewatering can take place through both the outer and inner wires. The latter water is kept in the open roll surface and released when the inner wire has been removed from the roll, see *Fig. 24*.

During the initial phase of dewatering, the radius of wire curvature cannot be approximated by the roll radius, since the wire approaches the forming zone

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[5] Introduced by Antti Lehtinen, Valmet.

along a straight path, R = ∞. There is a gradual decrease of outer wire radius from infinity to roll radius, and a corresponding build up of dewatering pressure.

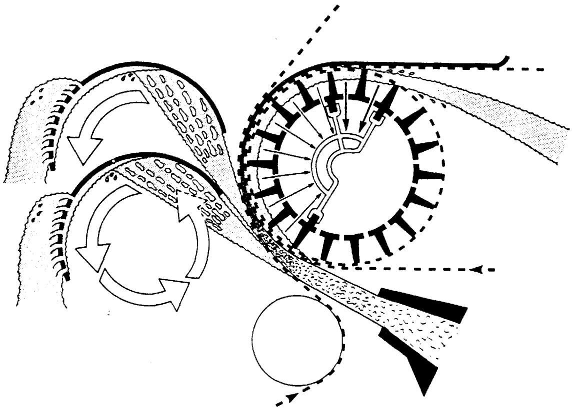

Fig. 24: Twin-wire roll former with two sided dewatering.

The dewatering pressure has been measured in roll formers with one-sided dewatering, with a pressure sensor mounted in the surface of a solid forming roll (116, 117). An example of a pressure curve is shown in *Fig. 25*:

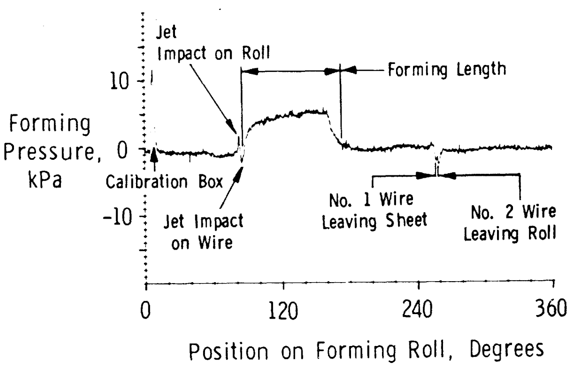

Fig. 25: Dewatering pressure in a one-sided, twin-wire roll former (117).

Ingemarsson developed a model for the initial phase of roll former dewatering, (118).

Jet/wire speed ratio

On a fourdrinier machine, minimum fibre orientation anisotropy is achieved at a jet/wire speed ratio of unity, which corresponds to equal velocities of jet and wire.

In a twin-wire gap former, a jet/wire speed ratio in excess of unity has to be used for minimum anisotropy. This is because the jet is decelerated when entering the pressure zone between the wires, and not until after this initial deceleration should jet speed equal wire speed for minimum fibre alignment.

The following equation for the jet/wire speed ratio required for minimum anisotropy can be derived using the Bernoulli equation. It applies to a twin-wire former with wire radius of curvature R, wire tension T, suspension density ρ, jet velocity u_j and wire velocity u_w :

$$\frac{u_j}{u_w} = \sqrt{1 + \frac{T}{R}\frac{2}{\rho u_w^2}} \qquad (10)$$

It follows from eq. (10) that the jet/wire speed ratio for minimum fibre orientation anisotropy increases with decreasing machine speed, and this is exemplified in *Table 3* :

Table 3: Jet/wire speed ratio for minimum fibre orientation anisotropy with T=6 kN/m and R = 0.7m.

Wire speed m/min	100	200	400	1000	2000
Jet/wire speed ratio	2.68	1.59	1.18	1.030	1.008

On entering the forming gap, the jet decelerates and then has to undergo a relative thickness increase equal to the jet/wire speed ratio given in the table.

Too high an expansion is not possible while maintaining stable flow conditions, and therefore a roll former cannot be run at speeds below approx. 200 m/min.

Centrifugal effects

If a fluid element of radial extension h and density ρ moves with velocity u along a path with a radius of curvature R, a centrifugal pressure p_c develops according to the equation:

$$p_c = \rho h \frac{u^2}{R} \tag{11}$$

It is often claimed that the dewatering pressure in a roll former is generated by centrifugal forces. This is however entirely incorrect, and centrifugal forces in fact only tend to decrease inwards dewatering (107). To counteract this effect, and thus still get symmetrical dewatering, roll formers are supplied with vacuum zones to increase inwards dewatering, see fig. 24.

The ratio between centrifugal pressure p_c and wire generated pressure p_w can be described by the following equation (119)

$$\frac{p_c}{p_w} = \frac{\rho h u^2}{T} \tag{12}$$

If the centrifugal pressure were to exceed the wire pressure, unstable conditions would result. This means that there is a practical upper limit for the p_c/p_w-ratio of unity. From eq. (12) it is clear that these conditions are reached independently of the local radius of wire curvature R. Corresponding values for fibre suspension radial thickness h and machine speed u are shown in *Fig. 26* (119).

Machine speeds in excess of those indicated in fig. 26 would result in unstable forming conditions.

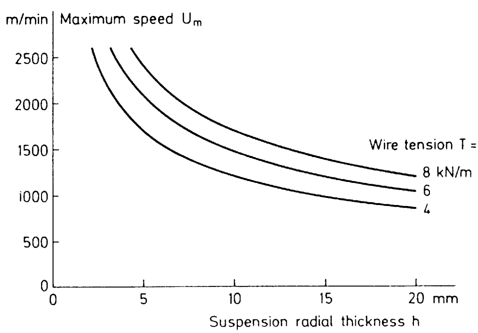

Fig. 26: Maximum wire speed u_m as a function of the suspension radial thickness h and wire tension T according to eq. (12)

One-sided dewatering

Twin wire roll formers are generally equipped with "open" forming rolls, allowing two sided dewatering, see fig.24. One exception is in tissue manufacture. For cost reasons, a solid forming roll is then used, and thus only one-sided dewatering. This is possible since neither the two-sidedness of the sheet nor the dewatering capacity is a limiting factor.

Another device for one-sided dewatering is the Flexi-Former (106), which has also been applied to industrial forming of tissue. During dewatering, the fibre suspension is sheared between a stationary upper surface and the running wire. Under these extreme shear conditions, mass formation is better than that achieved with fourdrinier dewatering. When a flexible plate is used, the dewatering pressure is controlled by the vacuum below the wire, the frictional drag forces along the plate, wire tension and jet/wire speed ratio. An example is given in *Fig. 27.*

It is also possible to use a stiff, curved plate. Vacuum is then unnecessary, and the local dewatering pressure is determined by the local radius along the backing plate. This principle has been used in high consistency forming, see section 7.4.

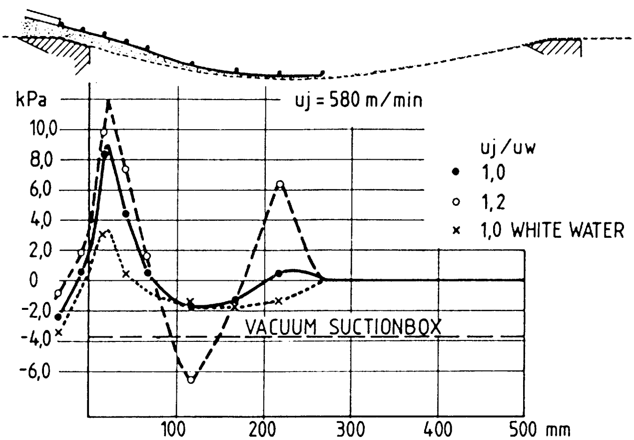

Fig. 27:Pressure distribution in Flexi-Former at 580 m/min (106)

Jet/wire speed ratio:	————	*1.0*
	-------------	*1.2*
	....	*1.0 (white water only)*

7.3.2. Blade formers

As late as during the Internationl Water Removal Conference in London,1975, the basic principle for a blade former was explained as being due to the same mechanism as that in roll forming (120). The dewatering pressure over a Bel Baie forming shoe was calculated according to eq. (9), and the radius of mounting for the blade tips was inserted instead of the radius R of wire curvature. The radius was one order of magnitude larger than that of a roll former. The hypothetically lower dewatering pressure was suggested to be the main reason for the improved mass formation obtainable in a blade former.

The pulsating nature of dewatering in blade formers was however emphasized by Norman (107), the deflection of the wires over the individual blades being the basis for the generation of the dewatering forces F according to the equation:

$$F = 2T \sin \alpha/2 \tag{13}$$

where T is the wire tension and α wire deflection angle over a blade tip. It was suggested that the pulsating nature of the dewatering pressure creates internal shear in the fibre suspension between the wires, and thus improves the mass formation of the sheet produced.

This basic principle has later been generally accepted. The shape of the pressure pulse generated by the blade force F depends on several factors, such as wire speed, wire separation and wire stiffness. No attempts to describe the detailed pressure event mathematically has been made as yet.

Measurement of the shape of the pressure pulses has been undertaken by Beloit, using a static pressure probe extending from within the headbox into the fibre suspension between the wires. Examples of pressure measurements are shown in *Figs. 28* and *29*, (121).

There is a general tendency that, compared with roll formers with uniform dewatering pressure, blade formers with pulsating dewatering pressure produce sheets with superior mass formation but with lower retention of fines and filler.

The fibre orientation anisotropy cannot be manipulated to the same degree using the speed difference between jet and wire as variable in a blade former as in a roll former. This is because the pressure pulses along the forming zone all affect fibre orientation, and only the conditions in the very beginning of the forming zone can be controlled by the jet speed. As a rule, a blade former gives a higher minimum anisotropy than a roll former.

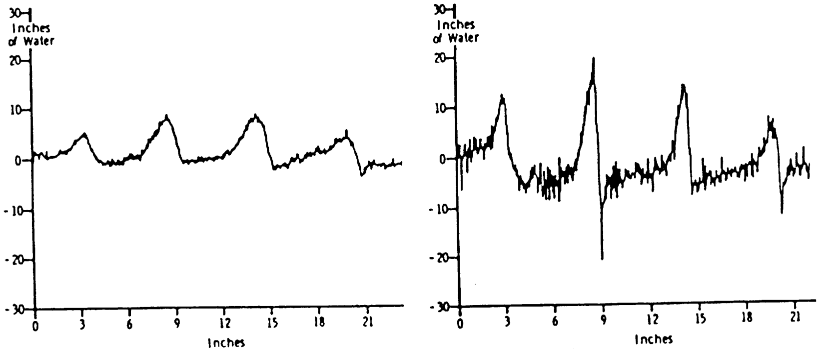

Fig. 28: *Pressure pulses, Bel Baie blades. 48 g/m², T = 4.4 kN/m*
Left: 460 m/min. Right: 920 m/min.

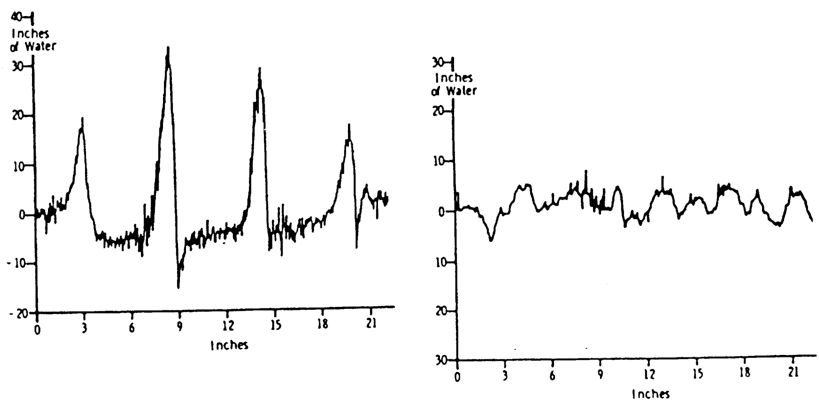

Fig. 29: *Pressure pulses, Bel Baie, 48 g/m², 920 m/min, T = 7 kN/m*
Left: Standard blades Right: Vacuum shoe

Constant and pulsating dewatering

Recently combinations of roll dewatering and blade dewatering have also been utilized.

In a blade former, the application of a forming roll during the later part of the dewatering adds an even pressure that improves retention without any loss in mass formation (122).

Starting with partial dewatering in a roll former, one thin web is formed on each wire. If pressure pulses from deflector blades are subsequently applied, shear forces can be introduced which may disperse the fibre suspension between the webs. In a roll former, the introduction of blades after the roll has been found to improve the mass formation, and operating experience with this design is now documented (123).

Controlled pressure pulses

One drawback with all the twin-wire formers described above is that the only on-line variable available to control dewatering conditions is wire tension. By changing the wire tension. the amplitude of the complete pressure event can be controlled. It is however not possible to adjust local dewatering pressure according to specific requirements.
Recently a new method has been introduced, by which it is possible to change the individual forces on stationary dewatering blades (124), see *Fig. 30.*

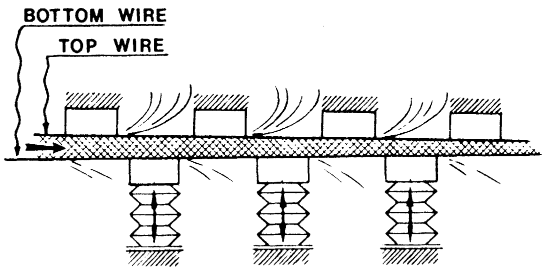

Fig. 30.: Principle of flexible twin-wire dewatering system (124).

This means that there is freedom to set the desired dewatering pressure profile. The new principle has been applied in boardmaking. It seems also to have a large potential for high-speed papermaking.

7.3.3. Hybrid forming

The hybrid former consists of a fourdrinier section for initial dewatering, and a twin-wire section for final dewatering. For each of these parts, the principles discussed above apply.

The twin-wire part of the hybrid former has one limitation compared with an ordinary gap former: Since the fibre suspension is transported into the nip by the bottom wire, the jet/wire speed ratio in the twin-wire nip is always equal to unity. This causes some fibre alignment, and the minimum fibre orientation anisotropy is therefore higher than that for a fourdrinier, or a roll former wet end.

7.4. High consistency forming

As mentioned in section 5.5., forming at 3-4% consistency differs from conventional forming in that the fibres form a network already inside the headbox. Dewatering in high consistency forming is, by definition, therefore a thickening process. The resulting sheet density of a high consistency sheet is therefore lower than that of a conventional sheet formed under filtration conditions.

It has been shown, for sheets made in a special high consistency laboratory sheet former, that the z-direction strength is more than doubled compared to that of standard laboratory sheets, while the strength losses in the plane of the sheet are only about 5% (79).It was also found that ply bond between two high consistency sheets was about twice as high as that for the corresponding conventional sheets. This meant that the ply bond for high consistency sheets was about the same as the z-direction strength of a conventional sheet.

The development of high consistency forming is mainly a matter of headbox development. Some improvement in mass formation can however be achieved by using dandy rolls or by dewatering in a twin-wire nip (125, 126). Application of the Flexi-Former techniques to high consistency dewatering can improve strength properties (127).

High consistency techniques have so far been industrially applied to form the centre ply in board products, see further section 7.5.

7.5. Multi-ply forming

Multi-ply forming has traditionally been the dominating process for higher grammage products, such as board, where single ply forming would involve dewatering limitations. Multi-ply forming then also automatically offers the possibility of choosing different raw materials in the different plies.

Cyinder vats were the dominant equipment used for multi-ply board manufacturing until the 1960's. Increased demands on the evenness of product quality then opened up the field for different combinations of fourdriniers and/or twin-wire arrangements.A recent summary of multi-ply forming concepts has been made by White (128).

Lately, increased interest has also been paied to the manufacturing of low grammage products, such as tissue and fine paper, using stratified headboxes. In this overview, the term *simultaneous forming* will be used when all plies are delivered from one headbox, while *separate forming* indicates the use of several headboxes. These terms are preferred to the previously used terms multilayer and multiply respectively, which do not seem to be clear enough.

For the forming principles of a single ply in a multi-ply product, reference is made to the preceeding discussions within that area. In addition, ply bond between the differeent plies has to be considered, a property which is often critically low in multi-ply products.

Ply bond is influenced by the amount of fine material at the interface between two plies, and is therefore highly influenced by the forming methods used. As an example, the low fines content on the wire side of a fourdrinier sheet can be critical if this side is facing another ply in a multi-ply design. The problem is often accentuated if mechanical pulp is used as raw material in more than one ply.

There are four basic ways of forming a two-ply product:

I Two plies are formed separately, and couched together.

II A second ply is formed on top of a first ply, and dewatering is made away from the first ply.

III A second ply is formed on top of a first ply, and dewatering is made through the first ply.

IV Both plies are formed simultaneously from a stratified headbox.

Generally, ply bond between the two plies will successively increase along this list of forming principles.

As mentioned in section 7.3, twin-wire forming at very low machine speeds generally causes instability problems. However, the application of controlled pressure pulses.in a twin-wire forming unit, permits the forming of a high grammage ply even at speeds below 100 m/min (129).

High consistency forming of the centre ply in a board product results in a more bulky sheet and higher z-direction strength as well as ply bond compared to conventional forming. Therefore, the greatest potential for high consistency forming is as the centre ply in board products, since the positive effects then include product properties as well as investment costs (130).

7.5.1. Simultaneous forming

In comparison with single-ply forming, multi-ply forming using a stratified headbox offers the possibility to produce low grammage sheets with optimized surface properties as well as centre ply characteristics. It has found a widespread use in tissue manufacturing (131, 62). Simultaneous forming has also been applied to printing papers (63), and has been used since over ten years on a Swedish linerboard machine.

The advantage of simultaneous compared to separate multi-ply forming of low grammage products lies in reduced investment costs and improved runnability. The basic problem with simultaneous forming is that the different plies tend to mix to some degree, so that *layer purity* may suffer. Layer purity can be defined from *Fig. 31.*

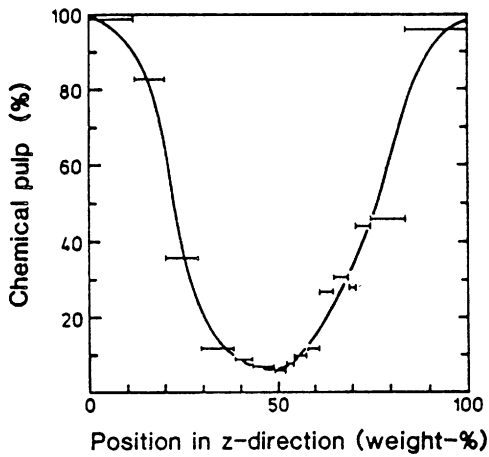

Fig 31: Fibre distribution in a roll formed FEX sheet with chemical pulp in the surfaces and CTMP in the centre (132).

Perfect layer purity would mean that the surface layers contain 100% and the centre-ply of the sheet 0% chemical pulp respectively. In fig. 31, the centre of the sheet contains approx. 10% chemical pulp, which can be interpreted as a comparatively high layer purity.

In simultaneous forming it is usually not possible to completely separate the white waters from the different furnishes. A common white water system can mean considerable reductions in investment costs. It is then necessary to achieve high retention levels, to minimize the deterioration of layer purity through the white water system. Terland made a theoretical investigation of the influence of the degree of white water separation, retention level and amount of broke on layer purity in three-ply simultaneous forming (133).

Terland also pointed out that even if layer purity is high, layer mass formation may be unacceptable (132), which is illustrated in *Fig 32*:

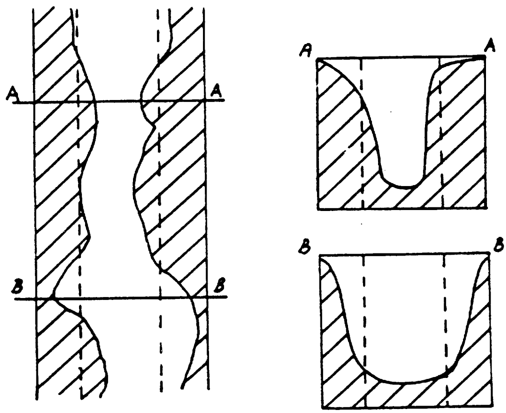

Fig 32: Stratified sheet with with high layer purity, right, but bad layer mass formation, left (132).

As already mentioned in section 5.4, there are two basic types of stratified headboxes which can be used for simultaneous, multi-ply forming. Following either of these headboxes, the twin wire dewatering can be performed with constant or with pulsating dewatering pressure, or with a combination thereof. Probably controlled pressure pulses will be a useful dewatering arrangement in this context. The combination of headbox principle and dewatering pressure event required to achieve specified levels of layer purity and layer mass formation is an important field for future investigations.

8. Product properties.

The vast literature relating forming conditions to product properties cannot be covered in this overview. Only two specific areas will be briefly discussed in this section, firstly the relationship between mass formation and strength and secondly fibre orientation anisotropy as a result of process conditions.

A recent literature review on paper quality aspects of twin-wire formed paper in comparison to fourdrinier formed paper has been prepared by Sinkey and Wahren (134).

8.1. Mass formation and mechanical properties.

It is well known that higher dilution of a fibre suspension before drainage results in better mass formation as well as higher paper strength. This can be explained by the self healing effect of dewatering on fibre distribution mentioned in section 6.2.

Corte made experiments using a modified laboratory sheet former, by increasing the height of the suspension tank so that the initial fibre consistency could be decreased one order of magnitude from the standard value of 0.02%. Also in this range he found improved product properties with increased dilution (135).

Terland and Fellers (136) studied the effect of forming consistency on sheet properties in twin-wire roll forming. They found a considerable influence on tensile index and elongation to rupture, see *Fig. 33,* as well as burst, but negligible effects on tensile stiffness and tear index.

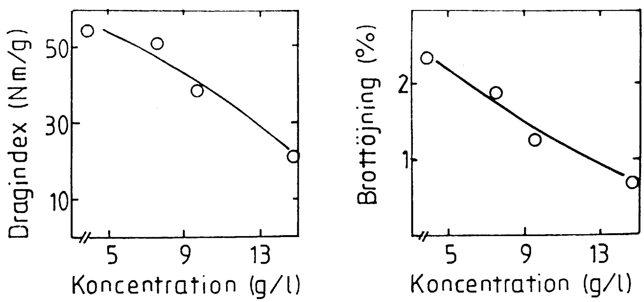

Fig 33.: Influence of forming consistency in the FEX roll former unit on tensile index (left) and elongation to rupture (right) (136).

It has been claimed that multi-ply forming results in improved product properties when compared to a single ply product. Terland and Fellers (137) showed that this may be a matter of forming consistency. Single-ply and two-ply products were formed on the FEX machine, and using the same forming consistency there was no significant difference between the product properties. However, two-ply forming made it possible to decrease the forming consistency in each layer compared to single ply forming, with a resulting improvement in sheet mass formation as well as in mechanical properties.

It has been demonstrated in several investigations that twin-wire blade forming yields better mass formation than roll forming and thereby also better mechanical properties, see e.g. (136). Further esults by Reiner demonstrated that in a linerboard blade former, an improvement in mass formation as a result of an increased blade pressure pulse had a negative effect on the burst value.

It has further been demonstrated that an improved mass formation through eccessive retention aid addition has no effect on the strength properties of the product (136).

It can thus be concluded that mass formation is not unambiguously related to paper strength. The effect on product strength of an improved mass formation is therefore determined by the what type of change in forming consitions generated the improvement.

Finally it should be pointed out that paper strength is not determined exclusively by forming consistency, but also by other variables such as the degree of refining of the furnish. In a practical application with given dewatering capacity, an optimization of the degree of refining and the forming consistency has to be performed. This is demonstrated in *Fig. 34*, in which also the different response to forming consistency for long fibre and short fibre pulps respectively is demonstrated (Hallgren and Lindström 71).

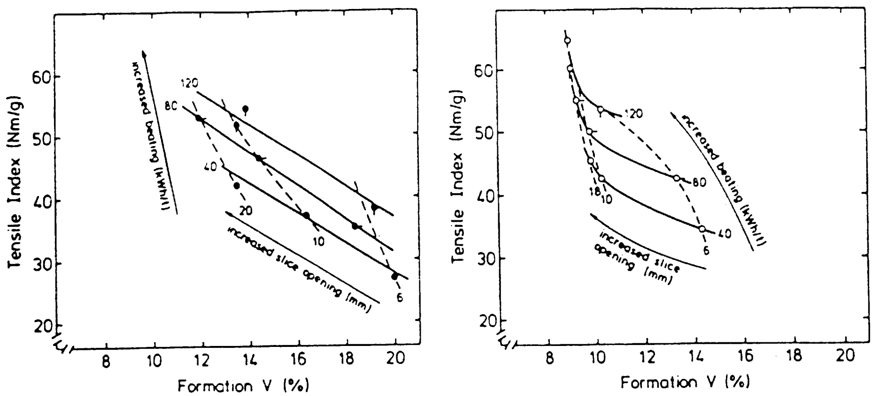

Fig. 34: The effect of forming consistency and refining on the tensile index-mass formation relationship in the FEX roll former unit. Left: Softwood. Right: Hardwood (71).

8.2. Fibre orientation anisotropy

Lately, the concern about variations in fibre orientation and about fibre orientation skewness has increased, partly because of increased product demands and partly because of improved ways of detecting such conditions.

Anisotropic fibre orientation was noticed in the mix jet leaving the headbox already by Moss and Bryant (55), as mentioned in section 5.3.1. The higher the contraction in the headbox nozzle, the greater the fibre orientation.

The first investigation of the distribution of fibre orientation in the z-direction of a sheet was performed by Danielsen and Steenberg (139), who used polar diagrams to describe the degree of orientation, see *Fig 35*.

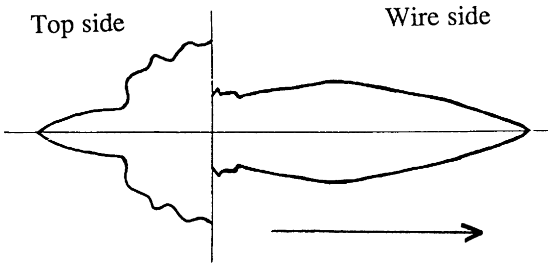

Fig. 35: A polar diagram of fibre orientation in paper (139)
Left: Top side of paper, Right: Wire side of paper.

During dewatering, longitudinal shear at the interface between wire/web and mix suspension introduces a "combing" effect that tends to increase the fibre orientation. The orientation is stronger on the wire side of a sheet, since this side is formed first and a relative motion between wire/web and mix gradually decreases as the dewatering process proceeds.

It is well documented that in fourdrinier forming, a difference between jet and wire velocities affects fibre orientation as well as mass formation.When the velocity difference deviates from zero by small amounts, mass formation improves. This could be caused by the breaking up of fibre flocs through shear, but more likely be a result of the supply of extra fibres for local low grammage areas through the relative movement of fibre suspension in the plane of the sheet.

At larger velocity differences, fibre orientation will increase, but disturbing effects will cause mass formation to deteriorate.

A recent study of the influence of jet to wire velocity difference on sheet properties was made by Bubik and Kleppe (140). They demonstrated that the degree of anisotropy is affected by the forming consistency, see *Fig. 36*. This can be explained by the orientation effects in the headbox nozzle. The higher the forming consistency, the smaller the slice opening, the larger the nozzle contraction and thus the greater the orientation effects.

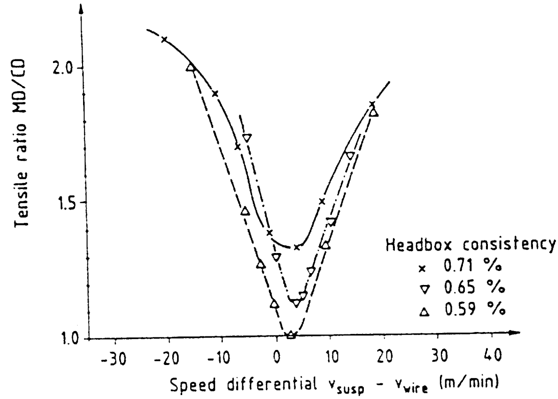

Fig. 36: Influence of the difference of the of jet and wire velocity on tensile ratio MD/CD at different forming consistencies (140).

In a twin-wire roll former, the influence of jet to wire velocity difference is similar to that of the fourdrinier machine. It should be pointed out, however, that the relevant jet velocity is that after the initial deceleration in the twin-wire nip, see e.g. eq. (10).

In a twin-wire blade former, the possibilities to control fibre orientation with the jet to wire velocity difference is limited [6]. The reason for this is the pulsating nature of the dewatering pressure. Since local shear in the fibre suspension is inevitably introduced by every pressure pulse, the local shear intduced by the initial jet velocity is relatively seen less important than in the roll former case.

Niskanen (141) has studied the effect on fibre orientation of velocity differences between jet and wire, and later during this symposium his experimental investigation and a theoretical model will be presented.

Hasuike et. al. (142) studied the correlation between local distribution of fibre orientation and local grammage using X-ray techniques. They found that fibre orientation in the heavy areas was more isotropic compared to that in the low grammage areas, see *Fig. 37*. This is natural if the heavy areas are mainly built up from fibre flocs.

[6] Unpublished FEX results.

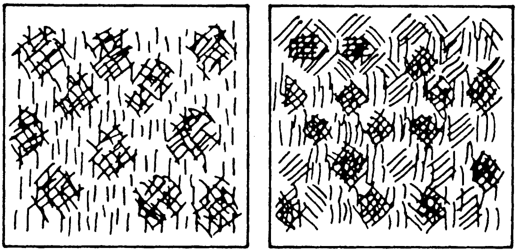

Fig. 37: Fibre orientation in high grammage and low grammage areas respectively (142).

It should be pointed out that when the anisotropic properties of a sheet are discussed, besides the effect of headbox and dewatering also the increase in anisotropy in the free draw after the press section and the final increase in anisotropy by tension during drying have to be taken into consideration.

8.2.1. Skew fibre orientation

So far, symmetric fibre orientation with respect to the machine direction has been assumed in this overview. Skew fibre orientation often occurs, and can be caused by a headbox jet velocity vector not in line with the machine direction or by sideways flow generated in the wire sction.

Holik and Weisshuhn (143) demonstrated that even with an angular deviation between jet and machine directions as small as a half degree, a considerable cross flov velocity arises on a modern high speed paper machine. The sum of this cross flow velocity component and the difference between machine speed and jet MD-speed form a velocity vector representing the relative suspension movement on the wire.

Holik and Weisshuhn pointed out that local variations in the angle of this relative velocity is largest when the MD-component is low, and that the angle of skewness will even change sign with a change from excess jet velocity to deficit jet velocity, see *Fig. 38*. They further exemplified the impact of imperfections in headbox design on jet skewness.

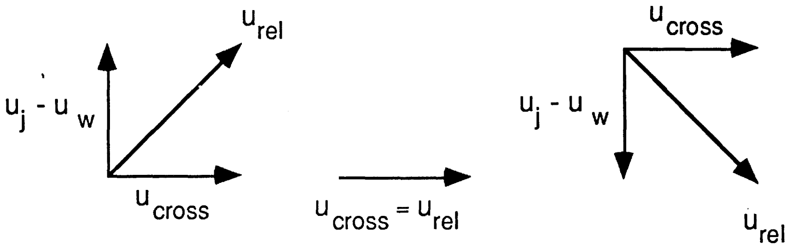

Fig. 38: The relative velocity u_{rel} as a function of the difference between jet and wire speeds, u_j - u_w and cross flow u_{cross}.

Left: $u_j - u_w > 0$, Centere: $u_j - u_w = 0$, Right: $u_j - u_w > 0$

As already mentioned, Westmayer (61) has calculated the effect of headbox nozzle shape on the amount of sideways flow caused by a local change of slice opening. A low angle headbox nozzle can be over four times as sensitive as a headbox with vertical front wall in this respect.

To completely avoid sideways flow from a headbox, the cross machine distribution must be perfect and the slice opening constant across the whole machine width, see further section 5.3.2.

9. Acknowledgements

The author is indebted to Dr Anthony Bristow for the linguistic revision of the material.

Ping, Anna-Karin, Olof and Brian volounteered to spend the Saturday evening and Sunday night immediately before my flight to Cambridge, preparing the 350 copies of this overview required at the symposium. This help is gratefully acknowledged.

Finally, I would like to thank the responsible persons within FRC for not striking out this contribution when deadlines were not met, and instead allowing its presentation in this third volume of the proceedings.

10. References

I "Formation and Structure of Paper" Trans of the 2nd Fundamental Research Symposium in Oxford, 1961. Francis Bolam, Ed. Techn Sec. British Paper and Board Makers Assoc., London (1962).

II "Consolidation of the paper web" Trans. of the Symposium held at Cambridge, 1965. Francis Bolam, Ed. Techn Sec. British Paper and Board Makers Assoc., London (1966).

III "The Fundamental Properties of Paper Related to its Uses", Trans. of the Symposium held at Cambridge , 1973. Francis Bolam, Ed. Techn. Sect. BPBIF, London (1976).

IV "Fibre - Water Interactions in Paper-Making". Trans. of the Symposium held at Oxford, 1977. FRC Ed. Techn.Div. BPBIF, London (1978).

V "The Role of Fundamental Research in Paper Making". Trans. of the Symposium held at Cambridge, 1981. James Brander, Ed. Mech.Eng. Publ.Ltd., London (1983).

VI "Papermaking Raw Materials". Trans. of the 8th Fundamental Research Symposium held at Oxford, 1985. Vaughan Punton, Ed. Mech. Eng. Publ. Ltd., London (1985).

VII "Fundamentals of Papermaking". Trans. of the 9th Fundamental Research Symposium held at Cambridge, 1989. C. Baker and W. Punton Ed. Mech.Eng.Publ.Ltd., London (1989).

1 Wrist, P.: Dynamics of Sheet Formation on the Fourdrinier Machine. In Ref I, 839.

2 Parker, J.: The Sheet-Forming Process, TAPPI STAP no 9 (1972)..

3 Radvan, B.: Forming. Papermaking Science, Elsevier, 176 (1976).

4 Lindström, T.: Some fundamental chemical aspects on paper forming. In Ref VII, 309.

5 Wahren, D.: Proposed definitions of some basic papermaking terms. Sv. Papperstidn. 70 (21), 725 (1967).

6 Corte, H.: Über die Verteilung der Massendichte in Papier. Das Papier 24 (5), 261 (1970).

7 Burkhard,G., Wrist,P.E. and Mounce,G.R.: A Formation Meter Which Graphically Records Paper Formation. Pulp and Paper Mag. of Canada 61 (6), T139 (1960).

8 Daunais, R. and Garner, R.: The NUI formation tester - an evaluation, modification and comparison with other techniques. Int. Paper Physics Conf., 43 (1987).

9 Kallmes, O. and Ayer, J.: Light scanning system provides qualitative formation measurement. Int. Paper Physics Conf., 209 (1987).

10 Papworth, S.: The application of image analysis to evaluate optical properties of paper. 6th Scand. Conf. on Image Analysis, 808 (1989).

11 Norman, B. and Wahren, D.: Mass distribution and sheet properties. In Ref III, 7.

12 Komppa,A. and Ebeling,K.: Correlation between the Areal Mass and Optical Densities of Paper In Ref V, 603.

13 Norman, B. and Wahren, D.: The measurement of mass distribution in paper sheets using a beta radiographic method. Sv. Papperstidn 77 (11), 397 (1974).

14 Cresson, T.: The Sensing, Analysis and Simulation of Paper Formation. Thesis, Syracuse, New York (1988).

15 Paper Structure and Properties. Anthony Bristow and Petter Kolseth Ed., Marcel Dekker, New York (1986).

16 Kajanto, Komppa,Ritala: How formation should be measured and characterized. Nordic Pulp and Paper Research Journal, 4 (3) (1989).

17 Yuhara, T., Hasuike, M. and Murakami, K.: Application of Image Process Technique for Analysis of Sheet Structure of Paper. Japan Tappi 61 (1), 85 (1986).

18 Tomimasu, H., Luner, P. and Hanna, R.: Rapid imaging of mass distribution in paper by electron beams. In Ref VII, 159.

19 Norman, B and Axell, O.: A Method for Measurement of Chalk Distribution in Paper Sheets. In Ref. VI, 577.

20 Taylor, G.I.: The Spectrum of Turbulence. Proc. Roy. Soc. Lond., A 164, 476 (1938).

21 Norman, B. and Wahren, D.: A comprehensive method for the description of mass distribution in sheets and flocculation and turbulence in suspnsions. Sv. Papperstidn. 75 (), 807 (1972).

22 Haglund, L, Norman, B. and Wahren, D.: "Mass Distribution in Random Sheets. Theoretical Evaluation and Comparison with Real Sheets. Sv. Papperstidn.77 (10), 362 (1974).

23 Taylor, G.I.: Statistical theory of turbulence. Proc.Royal.Soc. London. A151, 421 (1935).

24 Jordan, B.D. and Nguyen, N.G.: Specific perimeter. A graininess parameter for formation and print-mottle textures" Paperi ja Puu 68 (6-7): 476, 1986.

25 Duffy, G., Ek, R., Möller, K. and Norman, B.: Hydrodynamics of papermaking fibres in water suspensions. In Ref IV, 195.

26 Kerekes, R., Soszynski, R. and Tam Doo, P.: The Flocculation of Pulp Fibres. In ref VI, 265.

27 Kerekes, R.: Pulp flocculation in decaying turbulence: A literature review.Journ. of Pulp and Paper Sci. 9 (3), TR 86 (1983).

28 Wahren, D.: Fibre Network Structures in Papermaking Operations. The Cutting Edge Conf., Inst of Paper Chemistry, 112 (1979).

29 Steenberg, B, Thalén, N. and Wahren, D.: Formation and properties of fibre networks. In Ref II, 177.

30 Wahren, D. and Meyer, R.: On the Elastic Properties of Three-Dimensional Fibre Networks. Sv Papperstidning, 67 (10), 432 (1964).

31 Soszynski, R. and Kerekes, R.: Elastic interlocking of nylon fibres suspended in liquid. Part 1. Nature of cohesion among fibres. Nordic Pulp & Paper Research Journal, 3 (4), 172 (1988)

32 Jacquelin, G.: Prepared contribution. In Ref. II, 299.

33 Soszynski, R. and Kerekes, R.: Elastic interlocking of nylon fibres suspended in liquid. Part 2. Process of interlcking. Nordic Pulp & Paper Research Journal, 3 (4), 180 (1988).

34 Riitala, R. and Huiku, M.: Scaling, percolation and network theories: new insights into papermaking. In Ref VII, 195.

35 Onabe F. and Sakurai, K.: Applications of flow visualisation technique in wet end chemsitry. In ref VII, 219.

36 Wagle, D., Lee, C. and Broadkey, R.: Further coments on a visual study of pulp floc dispersion mechanisms. Tapi J. 71 (8), 137 (1988).

37 Steen, M.: The application of refractive index matching for two-phase flow measurements in turbulent fiber suspensions by laser doppler anemometry. Nordic Pulp & Paper Res. Journ. 4 (4), (1989).

38 Steen, M.: On turbulence structure in vertical pipe flow of fiber suspensions. Nordic Pulp & Paper Res Journ. 4 (4), (1989).

39 Norman, B. and Tegengren Å.: Mixing of thich stock and white water. XXIII Eucepa Conf., 51 (1988).

40 Norman, B., Wedin, P-O., Grundström, K-J. and Hagen, N.: Visualization of flow in a high consistency screen. TAPPI Eng. Conf., 585 (1986).

41 Goldenburg, P., Fredriksson, B. and Leblanc, P.: The Beloit S-screen - a new concept for high consistency screening. New Available Technique, SPCI, 1063 (1987).

42 Carlsson, Bengt and Gistrén, Henrik.: A new design for high consistency cleaning. Graduate work, Royal Inst. of Techn. (1989)

43 Röding, S., and Norman, B.: FEX the STFI experimental paper machine - design of white water system. Tappi Eng. Conf., 449 (1985).

44 Waller, M.: Recent developments in headboxes. Tappi J. 70 (1), 33 (1987).

45 Trufitt, A.: Design aspects of manifold type flowspreaders. TAPPI Pulp and Paper Technology Series, 32 (1975).

46 Syrjälä, S., Saarenrinne, P. and Karvinen, R.: Fluid dynamics of tapered manifold flow spreader. TAPPI Engineering Conference, 233 (1988).

47 Bubik, A. and Christ, A.: Step diffuser - the hydraulics of Escher Wyss headboxes. Tappi Eng. Conf., A 149 (1976).

48 Lin, J.: A numericla study of turbulent flow through a circular step diffuser. TAPPI Eng. Conf., 21 (1988).

49 Mardon, J.: Discussion. In Ref. I, 889 (1961).

50 Reiner, L., and Wahren, D.: The Characterization of Flow from the Headbox of a Paper Machine. Svensk Papperstidn, 74 (8), 225 (1971).

51 Parker, J. and Hergert, R.: Simultaneous convergence - a new concept in headbox design. Tappi 51 (10), 425 (1968).

52 Sanford L.: Characteristics of flow from a two-dimensional nozzle with multiple-tube inlet. Tappi Eng. Conf., A 159 (1976).

53 Wolf, K. and Egelhof, D.: The W-type High-Turbulence Headbox - its development concept and basic arrangement. Paper Techn. 15 (2), 77 (1974).

54 Ilmoniemi, E., Aroviita, L. and Yli-Kokko, E.: The role of headbox turbulence generators in grammage uniformity. Appita 39 (1), 36 (1986).

55 Moss, L and Bryant,E.: Photographic study of the Motion of Fibres and Water in Flowing Fiber Suspensions. Paper Trade J., 106 (April 14) Tappi Section, 226 (1938).

56 Jones, G. and Ginnow, R.: Modeling headbox performance with computational fluid mechanics. TAPPI Eng. Conf., 15 (1988).

57 Appel, D. and Yu, Y.: Free-streamline analysis of flow from nozzles, flow through side inlets and flow past corners. Studies in Engineering Mechanics, No 17, Center for Research in Engineering Science, University of Kansas, Lawrence (1963).

58 For the results in ref. (57), see alternatively: TAPPI TIS 014-2,3,4.

59 Kerekes, R. and Koller, E.: Equations for calculating headbox jet contraction and angle of outflow. Tappi 64 (1), 95 (1981), with correction in 64 (4), 104 (1981).

60 Karlsson, H. and Eriksson, L.: Controllability of Paper Making. In Ref VII.

61 Westermeyer, W.N.: Modellierung der Strömung in der Stoffauflaufdüse und auf dem Langsieb im Hinblick auf das Flächengewichts-Querprofil der Papierbahn. Das Papier 41 (11), 591 (1987)

62 Linkletter, M.: Tissue layering. PIRA Conf.: New Technologies in Multiply & Multilayer Structures, paper 6 (1987).

63 Stenberg, G.: A new headbox for multilayered printing paper. Tappi J. 70 (9), 49 (1987).

64 Swedish pat. 355.615

65 Swedish pat. 385.029

66 Swedish pat. 412.078

67 Nomura, T., Wada, K. and Shimizu, T.: High consistency sheet forming. 1: Research and development of headboxes.Tappi J. 72 (1), 115 (1989).

68 Radvan, B., Dodson, D. and Sköld, C.G.: Detection and cause of the layered structure of paper. In Ref II, 189.

69 Mohlin, U.-B.: Mechanical pulp properties - the importance of fines retention. Sv. Papperstidn. 80 (3), 84 (1977).

70 Sauret, G., Trinh, H. and Lefebvre, G.: Experiments to reproduce multi-ply boards in the laboratory (in German) Das Papier 23 (1), 8 (1969)

71 Hallgren, H. and Lindström, T.: The influence of stock preparation on paper forming efficiency. XXIII EUCEPA Conf., 35 (1988).

72 Corte, H. and Kallmes, O.: Statistical geometry of a fibrous netwok. In Ref I, 13.

73 Gorres, J., Cresson, T. and Luner, P.: Sheet formation from flocculated structures. Journ of Pulp and Paper Science 15 (2), J55 (1989).

74 Steen, M.: A concept for fibre flocculation in turbulent flow. In Ref VII, 251.

75 Ingmanson, W.L. and Andrews, B.D.: High-Velocity Water Flow Through Fiber Mats. Tappi 46 (3), 150 (1963).

76 Pires, E., Springer, A. and Kumar, V.:Computational model for water drainage in fourdinier paper machines. Tappi J. 71 (4), 133 (1988).

77 Britt, K.: Mechanisms of Retention During Paper Formation. Tappi 56 (10), 47 (1973).

78 Wahlström, B. and O´Blenes, G.: The Drainage of Pulps at Paper-Making Rates and Consistencies Using a New Drainage Tester. Pulp and Paper Mag of Canada, 63 (8), T405 (1962).

79 Grundström, K.-J., Hartog, S., Norman, B. and Reiner, L.: Basic principles of high consistency forming and the mechanical properties of felted structures. Int. Paper Physics Conf., II 8 (1975).

80 Britt, K., Unbehend, J. and Shridharan, R.: Observations on water removal in papermaking. Tappi J. 69 (7), 76 (1986).

81 Britt, W. and Unbehend,J.: Water removal during paper formation. Tappi. J. 68 (4), 105 (1985).

82 Torbjörn Helle: Paper forming wires over 75 years. 75th Annual Meeting, Technical Section CPPA, B 285 (1989)

83 Batty, R.: A mathematical model to aid in the design of paper machine forming fabrics. Journ of Pulp and Paper Sci. 9 (1), T25.(1983).

84 Helle, T. The influence of wire structure on sheet forming. Paper Techn & Ind. 21 (4), 123 (1980).

85 Beran, R.: The evaluation and selection of forming fabrics. Tappi J. 62 (4), 39 (1979).

86 Helle, T.: Analysis of wire mark in printing paper. Journ of Pulp & Paper Science 14 (4), 91 (1988).

87 Lewyta, J.: Recent developments in paper machine clothing: forming fabrics. Tappi J. 70 (2), 39 (1987).

88 Helle, T.: On the evaluation of the forming characteristics of papermaking wires, International Water Removal Symposium, 93 (1982).

89 Johnson, D.: Retention & drainage of forming wires. International Water Removal Symposium, 67 (1982).

90 Nordiskafilt. Unpublished FEX results (1986).

91 Hansen, V.: Draining and forming through the years. 75th Annual Meeting, Technical Section CPPA, B 63 (1989).

92 Wahren, D.: Fourdrinier jet geometry. Nordic Pulp and Paper Res. Journ. 3 (special issue), 29 (1988).

93 Österberg, L.: Initial dewatering. The Ekman Days (abstract only) (1988).

94 Parker, J. and Epton J.: Wet end barring. Tappi 60 (10), 90 (1977).

95 Moen, C.: Basis weight barring. Tappi 60 (10), 116 (1977).

96 Kallmes, O. and Langdok, R.: Initial operation trials of a dandy roll former. Tappi J. 71 (4), 74 (1988).

97 Wrist, P.: The Papermaking Process as a Filtration Problem. Pulp Paper Mag Can. 55 (6), 115 (1954).

98 Taylor, G.I.: Drainage at a Table Roll. Pulp Paper Mag Can 57 (3), 267 (1956).

99 Taylor, G.I.: Drainage at a Table Roll and a Foil. Pulp Paper Mag Can 59 (C), 172 (1956).

100 Bergström, J.: Table Roll Drainage. Sv Papperstidn 60 (1), 1 (1957).

101 Kufferath, W., Kallmes, O. and Steffen, H.-R.: Die Sonic Roll, Das Papier, 42 (10A), V141 (1988).

102 Kallmes, O., Marinari, G. and Perez, M.: Forming a sheet on a fabric vibrating at or near its resonant frequency. Tappi Papermakers Conference, 153 (1989).

103 Schmid,W.: Stroboskopische Untersuchungen in der Blattbildungszone. Wochenblatt für Papierfabrikation, 109 (11/12), 371 (1981).

104 Cadieux, S.: A mathematical drainage model for Fourdrinier paper machines. Journ of Pulp & Paper Sci. 9 (4), TR 111 (1983).

105 Kufferath, W., Kallmes, O. and Steffen, R.: The Cascade-Foil. Das Papier 41 (10A), V136 (1987).

106 Reiner, L.: The Flexforming concept. Journ Pulp & Paper Sci. 10 (2), J30 (1984).

107 Norman, B.: Principles of twin-wire forming. Sv. Pappersteidning, 82 (11), 330 (1979).

108 Attwood, B. and Lawrence, L.: Inverform - An account of the experimental work during the development of a new method of paper and paperboard manufacture. Paper Techn. 1 (5), T195 (1960).

109 de Montigny, R., Pye, I. and Hedley, T.: The Papriformer (1) - the machine and its performance. Pulp Paper Mag.Can. 68 (10), T482 (1967)

110 Atkinson, W. and Malashenko, A.: Commercial development of the Papriformer. Tappi, 54 (9), 1464 (1971).

111 Gustavsson, D. and Dennis, L.: The "Bel-Baie" twin wire former. Tappi, 53 (3), 483 (1970).

112 Stewart, R. and Howarth, J.: Verti-Forma versus fourdrinier. Pulp Paper 5 (13), 70 (1971).

113 Mauranen, P. and Hujala, J.: Valmets former for paper machine rebuilds and new paper machines. CPPA Ann. Mtg., B 195 (1983).

114 Malashenko, A., Deperis, G. and Lindström, R.: Dominion Dynaformer. 68th CPPA Ann Meeting, A139 (1982).

115 Thorp, B.: Fundamental and commercial overview of twin wire and multiple wire forming. Tappi Twin Wire seminar, 1 (1989)

116 Stenberg, G.: The KMW - Papriformer. KMW Sales Conference, Karlstad (1971).

117 Hergert, R. and Sanford, L.: Pressure measurements in the forming zone of a twin-wire tissue machine. International Water Removal Symposium, 47 (1982)

118 Ingemarsson, G.: Mathematical modelling to explain roll former behaviour. International Water Removal Symposium, 73 (1982)

119 Norman, B.: On the mechanisms of dewatering in twin-wire and press sections. Nordic Pulp & Paper Res Journ, 3 (special issue), 39 (1987)

120 Gustavsson, D.: Water removal from the Bel-Baie former. International Water Removal Symposium, I:234 (1975).

121 Nash, J.: Twin wire forming development. Tappi Twin Wire Seminar, 79 (1989)

122 Hergert, R. and Harwood, J.: Retention, drainage and formation on high speed formers. Tappi Papermakers Conf., 271 (1988).

123 Odell, M.: Drainage Mechanism of a Roll and Blade Former. Tappi Eng. Conf. (1989).

124 Baumann, W.-D.: Duoformer D - A new approach to top wire forming. Tappi Twin Wire Seminar, 115 (1989).

125 Blomquist, B.: Alform-Technologies for Multilayer Board. XXIII EUCEPA Conf., 187 (1988).

126 Nomura, T., Wada, K. and Shimizu, T.: High consistency sheet forming. 2: Pilot plant tests. Tappi J. 72(4), 171 (1989).

127 Reiner, L.: Flexforming (abstract only), The Ekman days (1988).

128 White, C.: The concept of multiply & multilayer paper & board products. PIRA Conf.: New Technologies in Multiply & Multilayer Structures, paper 3 (1987).

129 Meinecke, A.: The Duoformer (D) - Concept and Operating Results. XXIII EUCEPA Conf., 97 (1988).

130 Blomquist, B.: Alform-Technologies for Multilayer Board. XXIII EUCEPA Conf., 97 (1988).

131 Andersson, I.: How tissue production & sheet properties can be effected by multilayer forming. PIRA Conf.: New Technologies in Multiply & Multilayer Structures, paper 7 (1987).

132 Terland, O., Lindström, T. and Norman, B.: Forming on the FEX machine. PIRA Conf.: New Technologies in Multiply & Multilayer Structures, paper 20 (1987).

133 Terland, O.: Calculation of layer purity in simultaneous multi-ply forming as a function of degree of white water separation, retention level and broke amount. (In Swedish). STFI (1985).

134 Sinkey, J. and Wahren, D.: Quality comparisons of twin-wire and fourdrinier papers. Tappi J. 69 (8), 110 (1986).

135 Corte, H.: Personal communication (1974).

136 Terland, O. and Fellers, C.: The influence of mass formation on the mechanical properties of paper (in Swedish). STFI Report, (1986).

137 Terland, O. and Fellers, C.: Potential advantage of multi layering of paper (in Swedish). STFI Report, (1986).

138 Reiner, L.: The influence of blade former settings on the burst value of linerboard. Unpublished results, SCA, (1977).

139 Danielsen, R. and Steenberg, B.: Quantitative Determination of Fibre Orientation in Paper. Svensk Papperstidn 50 (13), 301 (1947).

140 Bubik, A. and Kleppe, P.: Multiply sheet formation for sackkraft & linerboard grades. PIRA Conf.: New Technologies in Multiply & Multilayer Structures, paper 9 (1987).

141 Niskanen, K.: Distribution of fibre orientation in paper. In Ref VII, 275.

142 Hasuike, M., Johansson, P.-Å., Fellers, C. and Terland, O.: Fibre orientation and its relation to paper formation studied by image analysis. Int. Paper Physics Conf., 185 (1987).

143 Holik, H. and Weisshuhn, E.: Influence of headbox flow conditions on paper properties and their constancy. Tappi Eng. Conf., 469 (1987).

Transcription of Discussion

OVERVIEW OF THE PHYSICS OF FORMING

B. Norman (Review Paper)

Dr. C. Dunning, James River

I wonder if you can comment on how rapidly flocs form in the headbox. Let's presume for a moment that we have some means of destroying any flocculation at the entrance to the headbox. How rapidly would flocs form between the tube bank and the slice opening?

Prof. B. Norman

I know you can find figures in the literature on this subject, however I am reluctant to rely on them. For instance, Otto Kallmes presented a Table with figures showing how quickly flocs will reform at different consistency levels. In that paper he referred to Douglas Wahren. When I discussed this with Douglas, he did not agree with the interpretation put on his figures. His results were very specific and generalisations are not necessarily valid. Consistency level, degree of turbulence and geometry as a whole are variables which must be considered in reflocculation. Generally, there is adequate time for reflocculation. If you destroy the flocs at an early stage they can definitely re-appear later on. To break down fibre flocs you have to introduce turbulent energy and when that energy decays flocs re-form. This area will be explored further in tomorrow's papers.

Dr. H. Paulapuro, Finnish Pulp & Paper Research Institute

You did not mention retention at all in your review. We know that retention is related to the chemistry of the papermaking process but there are many physical effects also. Is there any specific reason why you did not mention this?

Prof. B. Norman

In this presentation I did not have the time, it is mentioned in the paper. It is impossible to make a good review without mentioning paper chemistry. One has to be careful when discussing retention as it must first be defined. In this paper what is referred to as first pass retention is a function of the ratio between the recirculated white water consistency and the headbox consistency. This is the term used in 99% of mills. This is useful only when considering one system where the white water distribution is kept constant. If you try to compare different machines it will be invalid because the only thing that is considered is what is going through the short circulation. There are examples of newsprint mills where half the fines in the thick stock are recirculated via the long recirculation system.It is not therefore correct to have a retention value which only considers what is going round in the short recirculation system. The major problem with the long circulation is one of time to equilibrium. We have simulated this and were also able to do measurements on a papermill together with IVL in Sweden. We changed the refining in a liner mill and wanted to see how long it would take the extra dissolved material to reach equilibrium. It took 48 hours for the long circulation. I am merely pointing out the complexities of the system and its bearing on retention. Details of retention will be covered in the Chemical Section later this week.

Dr. H. Paulapuro

May I continue with another question - could I have your opinion on the application of high consistency forming to low basis weight grades eg. below 100 g/m2.

Prof. B. Norman

If you design a new process it is much cheaper to choose a high consistency solution. Many components are not required at all and others are much smaller. HC forming will give some advantage for the product. Thus the advantage of using this technique in a board product comes from both capital cost reduction and product improvement. It is hoped that HC application will continue to lower grammages but the drive is not then as great as for board products. I think a more relevant question is on stratified production of low grammage papers. This is more important than high consistency forming of them.

Dr. G.A. Baum, James River

You implied that modern high speed headboxes with a jet to wire velocity ratio near to one could lead to instabilities in terms of the fibre orientation distribution. Could you comment on the contribution of automatic slice adjustments to that problem?

Prof. B. Norman

In devices with automatic slice flow adjustment you have to consider the influence of cross flow on the skewness of anisotropy, which has not been done so far. You cannot just control the grammage profile to what you want.

Dr. A. Ibraham, Papyrus, USA

I would like to understand more about your comments on contraction in the nozzle. If I understand you correctly are you in favour of reducing turbulence by increasing the contraction coefficient?

Prof. B. Norman

A higher nozzle contraction will mean a lower degree of relative turbulence which is an advantage in paper forming. It is particularly advantageous to have a perfect jet when you are considering twin wire forming.

Dr. A. Ibraham

In that case we are going to meet high L/b ratio. The jet is going to travel further down through the wire and it is going to flocculate further as shown by Kerekes. I am really against that concept. High L/b and low angle is not good for formation.

Prof. B. Norman

I am referring to the contraction within the headbox nozzle not the impact onto the wire. It is a function of flow velocity entering the nozzle and flow velocity leaving the nozzle. What you refer to is a separate topic.

Dr. M.B. Lyne, International Paper, USA

In your talk you were describing the sources of variation in orientation angle across the papermachine. Would you care to offer an explanation or a model for variations in orientation angle in the Z direction during forming? The difference in fibre orientation angle between the top and wire side of a sheet is an important factor in the complex curl of paper sheets.

Prof. B. Norman

The jet to web speed difference in a given CD position will gradually decrease as dewatering proceeds. The original cross flow component in the same CD position will, by definition, move sideways during dewatering, and thus successively influence other CD positions.

Dr. M. MacGregor, KTH (Voith), Sweden

Is the non-uniform shrinkage which occurs during drying and the need to have uniform basis weight possible to optimise, or does it lead to a compromise situation?

Prof. B. Norman

It is theoretically impossible to have both uniform orientation and grammage in the cross direction if you have non uniform cross machine shrinkage.There is a paper later this week which says how you can restrain the paper to avoid shrinkage in the cross direction during drying

Dr. M. MacGregor

If basis weight control is by flow redirection, then I agree - which it is in most cases.

Prof. B. Norman

Unless you control local consistency in the headbox which is a theoretical solution. When you control grammage with slice opening the aforementioned problems are always present.

Dr. M. MacGregor

So in general the papermaker does not realise that he is giving up many things to achieve a nice flat reel.

Dr. T. Uesaka, PPRIC, Canada

In one of your slides you mentioned the tensile ratio between MD and CD as a function of jet speed and wire speed ratio - I understand this relationship looks very unique when we keep the contraction ratio constant. I am wondering if we increase the wire speed by keeping the jet speed and wire speed difference constant what will happen to that relationship. We have already experienced in many high speed machines that we have a difficulty in controlling the tensile ratio by changing the jet speed/wire speed difference in contrast to the older Fourdrinier machines.

Prof. B. Norman

What do you mean by high speed machine? Is it a Bel-Baie?

Dr. T. Uesaka

Yes, in the case of Bel-Baie for example.

Prof. B. Norman

This is another project we are working on. In the case of the Bel-Baie you haven't the same degree of control as you have on a Fourdrinier or Roll-former because all the pressure pulses during dewatering will effect the fibre orientation. You can only control the jet conditions as it enters between the two wires.

Dr. R. Ritala, Finnish Pulp & Paper Research Institute

I would like to ask about fibre flocculation. The Wahren-Meyer formula has been derived so that we have three contact points on the average for each fibre. Why should this have any significance as it is on average, I can understand why we need three points to build flocs but why do we need three points on the average?

Prof. B. Norman

I refer you to Dr. Wahren.

Dr. R. Ritala

I would like to offer an alternative explanation. There is a coincidence in that the threshold to have a connected network of fibres (That can be shown to be at a consistency which is simply the inverse of the fibre aspect ratio) in fact fits the data in your Fig.3 a bit better in the region from 80 - 200 in the aspect ratio.

Prof. B. Norman

Yesterday you mentioned this new reference from a physics paper to me. This will be interesting to see. It would simplify things if the sediment consistency is equal to the fibre diameter divided by the fibre length.