THE FUNDAMENTALS OF FORMATION

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ABSTRACT

Paper formation is affected by many operating variables within the control of the papermaker. Each of these variables has a preferred operating range to produce the best results. The key variables discussed are furnish composition, refining, headbox consistency, turbulence on the table, rush/drag, L/b ratio. Furnish and refining are shown to be the most important variables in determining formation. Fiber flocculation is shown to be a significant factor in determining formation. The impact of headbox consistency on flocculation tendency and flocculation times is shown. The beneficial effect of turbulence and hydraulic shear on sheet structure are discussed with relation to turbulence in the forming section. The influence of hydraulic shear when setting the slice jet is also discussed with relation to the relative speed of the jet to the forming fabric and the angle of jet delivery.

Key Words: Formation, Flocculation, Turbulence, Hydraulic Shear

INTRODUCTION

The quality of a paper product and its suitability for the marketplace is frequently determined by its formation. Formation influences the aesthetic properties of a product as, for example, printability, as well as its physical attributes such as strength, density and smoothness. This paper will present some thoughts on the important factors that influence formation and the tools available to the practical papermaker to improve formation. The key factors are presented in their order of importance below.

1. Furnish
2. Refining
3. Headbox Consistency
4. Agitation on the Wire
5. Rush/Drag
6. Setting the Jet

For our discussion, formation will be defined as *the visual appearance of the sheet when held up to the light*. The more scientifically accepted definition is the *coefficient of variation mass distribution of the fibers in the sheet*. For those interested in a detailed discussion, the book written by C.T.J. Dodson(1) is recommended. Both definitions encompass the structure of the sheet and deal with the flocs, their size, distinctness, and distribution. Basically, a well formed sheet will have a uniform fiber distribution with very faint, small flocs evenly distributed throughout the sheet. It can appear flocculated with large distinct flocs, or very uniform with small flocs, or streaky, or bunchy, or open. The list of descriptive adjectives is endless.

More frequently today, formation is evaluated with an instrument. These instruments assess formation by measuring the spacing between floc centers, the diameter of the flocs and their intensity, and the uniformity of their distribution in the sheet. These instruments produce results which frequently can be related to what the eye sees. Instrumentation is preferred over visual inspection for formation evaluation as its reproducibility and lack of prejudice yields more uniform and consistent results. However, a visual system can be effectively used provided a graded set of standards is established for comparison.

There are several different methods used for measuring formation which produce different evaluations of the sheet. Visible light instruments use a very small beam of light passed through the sheet which is usually rotating inside a clear plastic cylinder. The variations in opacity are picked up by a photo cell and analyzed by various methods. Soft x-rays have been used to produce an image based on mass which can be analyzed by an image analyzer or some other photometric device. A very small aperture beta ray gauge may also be used to analyze the mass distribution of the sheet. Recently laser illuminated systems have been used for formation evaluation. Each measurement method provides an evaluation of the sheet with a slightly different bias to the structural aspects of the sheet(2) which makes comparison of results uncertain. The most commonly used instruments in the mill are optical using either white light or a laser beam.

FURNISH

The most important factor in determining formation is the fiber type used in the furnish, i.e., hardwood or softwood, northern, southern, western, South American or Pacific Rim. The more fine, short fibers (hardwood) that can be added to the furnish, the easier it will be to produce good formation. Options of furnish adjustment frequently depend on the product being made and are usually controlled by the final sheet properties and cost.

The geographical source of the fibers has an influence on their ability to form. Northern North American fibers, both hardwood and softwood, tend to be soft, fine, and flexible forming well with little refining. On the other hand southern softwood fibers are thick walled and stiff, do not form as well and require refining to develop their formability. Western softwood fibers, especially Douglas fir, are very long with relatively thin walls and must be refined to shorten them and improve their flexibility to provide good formation.

Examining photomicrographs of softwood fibers from the different geographical areas, clearly shows their different characteristics. Fig. 1 shows northern spruce softwood kraft fibers that are moderately long and slender. Fig. 2 is a photomicrograph Southern pine kraft. The difference in length, width, and wall thickness between the northern and southern fibers is apparent. It is easy to see why formation is more difficult to obtain with southern pine. Western Douglas fir, shown in Fig. 3 has great fiber length and produces a pulp with high tear, but offers a real challenge to achieve good formation.

Fiber length together with fiber fineness provide an indication of the formation potential of a pulp. A way to think about the importance of fiber length and fineness is to consider the number of fibers per gram of pulp. As the number of fibers increases, the probability uniform formation increases. Examination of photomicrographs of hand sheets made with different pulps provides a graphic illustration of the impact of fiber length and coarseness. The hand sheet of southern pine in Fig. 4 shows the impact of the big fibers. Comparing that with the hand sheet made from Northern spruce shown in Fig. 5 demonstrates why it is easier to obtain good formation with northern spruce fibers. To complete the comparison, Fig. 6 depicts a sheet made from eucalyptus fibers with very fine formation. It is easy to understand the worldwide interest in eucalyptus pulps. Not only does eucalyptus grow extremely rapidly, but its fibers have the ability to form very well.

REFINING

The second parameter on the list of factors affecting formation is refining. Unrefined fibers are stiff, straight, and relatively smooth-sided. Refining softens the fibers, "fibrillates" them, creates fiber debris and also promotes fiber collapse which is essential for good formation. A better formed sheet can be made from a refined pulp than from an unrefined one, since the more flexible fibers will conform better and the fiber debris will fill in the sheet. Refining also affects sheet physical properties such as tensile, tear, caliper, stiffness and density The amount that can be applied may be restricted because it will move a sheet property outside the specified limits for the grade. Frequently, however, it is possible to add a little more energy and improve formation without seriously affecting other sheet properties.

The result of refining on some typical fibers is shown in the following figures. Fig. 7 shows typical unrefined northeastern softwood kraft fibers. They are long, relatively thin, and quite straight and smooth-sided. Fig. 8 shows the same softwood after refining. The development of debris is obvious as is the fact that the fiber flexibility has been enhanced. Fig. 9 shows some refined hardwood kraft fibers where the amount of fiber flexing and debris is evident. It is also clear that the fibers are shorter. The one softwood fiber in this figure that should be ignored..

The combination of furnish and refining can be used to good advantage in balancing strength, drainage, and formation. Refining hardwood will improve formation and increase sheet density without adversely affecting drainage. Refining softwood raises tensile and density, improves formation, and decreases tear.

HEADBOX CONSISTENCY

At this point in the consideration of formation fundamentals it is necessary to examine fiber flocs, their properties, and how they behave in the hydraulic turbulence and shear fields that exist in the headbox and on forming sections of the machine. In his book on the sheet forming process Parker(3) points out that four fibers constitute the minimum number required to form a floc with distinct mechanical properties. Therefore, a floc can be as small as four fibers and increase in numbers to quite large amounts. During turbulence decay floc size increases and flocs link together producing a network. During the forming process, as water is removed from the sheet, a network is loosely formed, and then as more water is removed, the network becomes increasingly more rigid. As a result the energy required to rearrange the fiber distribution within the network becomes greater, and ultimately the only way to rearrange the network is to rupture it, destroying the sheet. However, between the headbox and the point where the sheet can no longer be changed numerous opportunities exist to influence the formation and structure of the sheet.

Parker(3) observed that floc size in a hydraulic system is determined primarily by the scale of the turbulence which is fixed by the geometry of the flow channel, and the intensity which is produced by the energy applied to the system. Both the scale and intensity of the system turbulence must be taken into account when considering formation and floc size.

At headbox consistencies, the degree of flocculation depends upon the consistency, the amount of agitation present, and the fiber length. Studies using laser Doppler anemometry(4,5,6) and visual inspection(7) in a special flow apparatus show that in a flowing system there is a distribution of floc sizes not just a single size. These experiments were conducted with fixed geometry so that the scale of the turbulence was fixed, and only the intensity was varied. Under these conditions there is a dynamic equilibrium in which flocs are being created and destroyed all the time with a size distribution dependent on the intensity of the turbulence being generated. When the turbulence intensity is increased, there is a shift in size distribution toward smaller flocs. When the turbulence intensity is decreased such as when the jet leaves the slice and moves toward the wire, there is a shift to larger floc sizes as shown in Fig. 10.

These experiments describe the hydraulic conditions in a headbox. The scale of the turbulence is established by the dimensions and configuration of the headbox, while the intensity is determined by the velocity of the flow through the headbox. Once the flow leaves the headbox and loses its energy supply, the turbulence level is rapidly diminished by viscous damping. The damping diminishes the energy before the slice jet hits the wire and the floc size distribution starts to shift toward larger flocs. It is therefore important that the degree of flocculation in the headbox be reduced to as low a level as possible so that the floc size distribution will remain small in the slice jet, which can be done by increasing the intensity and decreasing the scale of the turbulence in the headbox by good hydraulic design.

An example of the time sensitivity at the slice delivery when the free jet is unagitated, is given in the following example. A Fourdrinier machine running at 1500 fpm (450 mpm) or 25 fps with a typical jet length of 6 inches has a transit time from the slice to impact of 20 milliseconds. A gap former running at 3000 fpm (900 mpm) or 50 feet per second with a jet length of 12 inches will have a time from discharge to impact of 20 milliseconds. Even though this machine is going twice as fast as the first example, the flocculation time is be the same, due to the geometry of the former. Twenty milliseconds is sufficient time for very long fiber stock to begin the reflocculate as will be shown later.

Consistency is another factor which affects flocculation. As consistency increases the fibers become closer together the probability of fiber-fiber contacts increases, reducing flocculation times. Numerous studies have been made on reflocculation times as a function of consistency. These were summarized by Kerekes(8) in Fig. 11. The difference in flocculation times for small changes in consistency are significant. At 0.7% consistency, the reflocculation time is 22 milliseconds, at 0.5% the value is 50 milliseconds, and at 0.3%, it is 110 milliseconds. When these times are compared to those of the free jet travel between leaving the slice and landing on the wire, the importance of headbox consistency is emphasized.

Flocculation is strongly influenced by fiber length. Longer fibers sweep out more volume in their motion and have a greater opportunity to collide with another fiber and start to form a flocs. The long fiber concentration in the furnish is the most critical factor influencing formation. The more dilute the long fiber, the better the formation will be. Research done examining the critical factors affecting formation discovered that for all paper grades when the effective long fiber consistency below 0.3% for good formation was achieved. For example, liner board headbox consistencies are typically about 0.25 to 0.40% which with the essentially 100% long fiber furnish is the consistency needed to get good formation. Fine papers headbox consistencies are usually 0.5 to 0.7% with a long fiber percentage in the furnish of typically 30% which makes the effective long fiber consistency 0.15 to 0.21%. Going much below the 0.3% level does not seem to do much to improve formation.

A method of assessing fiber flocculation tendencies in terms of fiber length, consistency and fiber coarseness was developed by Kerekes(9). His group developed a flocculation index called the crowding factor(N) which defines the number of fibers present within a sphere whose diameter equals the fiber length. The formula for calculating N is given in the following equation.

Equation 1

Crowding Factor Equation

$$N = \frac{5C_m L^2}{\omega}$$

Where: N = Crowding Factor
C_m = Mass consistency, %
L = Fiber length, m
ω = Fiber coarseness, Kg/m

This equation demonstrates the importance of fiber length to flocculation and takes into account the effect of fiber coarseness. It predicts the degree of flocculation in a fiber suspension after agitation has ceased and depicts a final state with time considerations removed. The fiber length and coarseness are determined by the Kajaani FS-100 instrument.

The authors showed that when the Crowding Factor (N) was between 60 and 135, flocculation was almost certain to occur. For values less than 60, the probability of flocculation was small. Table I shows values of N for a few papermaking fibers. calculated from data of Kerekes(9). The C_m used was 0.3%, the recommended long fiber consistency for good formation, to develop a comparison between it and the values of N.

Table I

Values of N for Different Types of Fibers

Fiber Type	Length (mm)	Coarseness (mg/100m)	N
Douglas fir	2.7	25	43.7
Western red cedar	2.5	12.2	76.2
Aspen	0.83	10.8	9.6

Where: C_m = 0.3%

At the consistency of long fiber for good formation of 0.3%, Douglas fir with an N of 43.7 will probably not be flocculated. While the much finer western red cedar of nearly the same fiber length has a value of N of 76.2 indicating that it will floc at this consistency. The finer red cedar will have many more fibers in suspension at the same consistency thus increasing the probability of fiber collisions and floc formation. In the case of aspen(N = 9.6)even with the very low coarseness, the fiber length is so short that flocculation does not occur. Further work by Kerekes(10) has shown that blends of pulps have flocculation tendencies corresponding to the N values calculated for the long fiber based on its concentration in the pulp mixture reenforcing the earlier findings about the effective long fiber concentration and formation.

Crowding factor is useful in evaluating the flocculation tendencies of different pulps and can be used to indicate changes in flocculation tendencies with furnish changes. It does not address the rate of development of flocs or the impact of turbulence or hydraulic shear on flocculation. For these reasons is should not be considered a predictor of formation, but an indicator flocculation tendencies. It can be useful, however, in working on formation problems, since it provides an evaluation of two key formation factors, furnish and refining. For example, if the formation has deteriorated, measurement of crowding factor will indicate whether the furnish or refining has changed in such a way to influence formation. This information can be used to determine whether the change was due to the furnish or other changes on the machine such as headbox consistency, loss of table activity due to worn foils, over use of retention aid, or other such factors.

Reducing headbox consistency to improve formation will increase the flow rate through the headbox. The flow rate should match the rate for which the headbox was designed to avoid formation problems. Flow rates well below design levels will reduce turbulence and allow time for the stock to flocculate producing flocs that are most difficult to break up with a resulting sheet that looks heavily flocculated. Flow rates well above the design values will cause severe flow streaking on the wire, which produces streaks in the sheet. With rectifier roll headboxes, the pond velocity should remain between 0.5 ft/sec (0.15 m/sec) and 1.5 ft/sec (0.45 m/sec). Velocities significantly outside these limits will lead to formation defects.

The effect of exceeding the hydraulic flow limit of a rectifier roll headbox is shown in Fig. 12. In a trial to improve formation by lowering headbox consistency, the hydraulic flow limit of the headbox was exceeded. The result was a streaky sheet with disrupted formation as is clearly visible in this figure. This is a classic demonstration of what happens in all too many mills when the machine gets speeded up, but no one thinks about the limitations of the headbox. The hydraulic limits of the headbox are exceeded and the formation deteriorates.

Hydraulic headboxes do not have rectifier rolls and run "pond" velocities substantially above 5 ft/sec to generate effective turbulence. This turbulence is at a scale that produces good fiber dispersion without flow streaking. Low velocities in high turbulence boxes will cause problems, because the flow will become unstable and formation and CD profile will deteriorate.

AGITATION ON THE WIRE

It was pointed out in the previous discussion of flocculation and floc size distribution that flocculation begins to take place in the slice jet before it has landed on the wire. To redistribute the fibers and break up the forming flocs, energy must be put into the draining stock on the wire. Turbulence and oriented shear, as shown in Fig. 13, are the methods used to supply this energy.

TURBULENCE

Effective turbulence on the wire is as essential to good formation as turbulence in the headbox and jet delivery. Combinations of foil blade angles and vacuum-augmented foil boxes can be used to produce turbulence on the wire. This subject will be discussed in depth in subsequent presentations in this course and so little will be said about it here. The point is that good turbulence must be maintained in the headbox and on the wire to obtain good formation.

Agitation on the wire caused by water removal elements depicted in Fig. 14. The cobble stonelooking surface appearance is caused by the forces being generated by the drainage elements seen as shadows running top to bottom in the picture. Higher levels of agitation can cause spouting which disrupts formation, while levels where no surface agitation is visible will produce poorer formation because the fibers will floc.

ORIENTED HYDRAULIC SHEAR

Oriented hydraulic shear is best exemplified by a ridge of stock going down the wire, passing over a drainage element, and splitting into two smaller ridges with a valley between as shown in Fig. 15. This splitting, referred to as phase shifts, creates a lateral shear which breaks flocs and keeps the fibers dispersed. If the ridges are too large or contain too much energy, they will be disruptive to sheet formation and cause spouting on the wire or streaks in the sheet. If they are of the correct size, spacing, and energy level, and the splitting is properly done, the resulting improvement in formation can be quite remarkable.

Two well accepted methods of creating ridges in the flow are the serrated slice and formation showers(11,12). With the serrated slice, the top slice lip is machined in a wave pattern that generates ridges in the flow. With a formation shower, the water jets from the nozzles create the ridges.

The use of a serrated slice is generally limited to machine speed below 1500 fpm(450 mpm). The size and depth of the machining of a serrated slice are determined by the speed of the machine and the approximate slice flow. The intention of the serration is to produce ridges in the flow of the right size and spacing to phase shift over a drainage element with enough lateral energy to break flocs and rearrange the fibers for better formation. Each phase shift reduces the ridge size and is accompanied by water removal, so that after several splits, the ridges become so small or so much water has been removed that no further splitting can take place.

Although the serrated slice can be beneficial to formation, there are factors which can negate its effect. When the flow out of the headbox is unstable with shifting high velocity streaks and turbulent wakes from the rectifier rolls, the effect of the serrated slice ridges is overpowered and little or no formation improvement is obtained.

Formation showers provide the second method of producing ridges in the flow. They produce a series of fine closely spaced jets that generate ridges in the stock flow. These ridges are split as they go over the drainage elements as with the serrated slice ridges. A formation shower can also be used close to the slice instead of a serrated slice.

The position and design of the shower are critical to successful operation. To produce good ridges, the shower jets must be of small size and coherent, i.e., they must be a solid stream and not broken up into droplets. If the jets break into droplets, splashing will occur and poor ridge formation will result. The spacing of the shower nozzles is also critical because it determines the width of the ridges. If they are too close or too far apart, they will not produce the desired type of ridges; and they will not last many phase shifts before they die out. On heavier weight sheets several showers can be used to produces a really beneficial effect.

SLICE JET RUSH/DRAG

The purpose of the slice is to deliver a uniform jet of water and stock onto a moving wire at a set velocity. Differences between the jet velocity and the wire velocity will produce relative movement between the stock and the wire, which can improve or disrupt formation depending on the magnitude and direction of the difference. The classic work done by Schroder and Swenson(13) clearly showed that formation is quite sensitive to J/W ratios, and for practical purposes this ratio should stay between 0.90 and 1.10. They further showed that for the papers they were making the best formation was obtained at very close to a J/W of 1.0.

Higher STFI units indicate poorer formation. For both operating speeds the optimum formation comes at J/W ratios between 0.95 and 1.05. The reason for the slight hump in the curve at J/W 1.0 was not explained by the authors. The current theory is that at 1.0 the shear between the bottom of the jet and the wire is at a minimum, which creates the possibility for a slight deterioration in formation due to this reduced shear.

Their original data indicated that formation is more sensitive to J/W as the speed increases, and at least for these runs the formation got better as the speed increased. However, when their data are plotted using the difference in speed between jet and wire, the curves take on essentially the same shape as shown in Fig. 16. The effect of machine speed is still apparent with the higher speed producing better formation. The conclusion is that the difference between jet speed and wire speed is the determining factor in formation control and not J/W ratio. .

The visual effect on formation of changing the Rush/Drag on formation is shown in Fig. 17. The machine which normally runs at theoretical head, R/D of 0 increased the head above this level, and the formation deteriorated. Notice the crowding or bunching of the fibers typical of rushing the jet on the wire.

An example of the influence of changing the R/D on a Fourdrinier machine with a hydraulic headbox is shown in Fig. 18. In this study a hand held M/K formation tester was used while the adjustments were made. With this instrument the lower the number the better the formation. The shape of the curve shows the sensitivity of formation to R/D changes. The steepness of this curve emphasizes the importance of making the adjustments in small increments so that the optimum point is not missed. The best formation was at R/D +24 and not the expected 0. This difference indicates the error in the spouting velocity equation used to calculate the static head.

The response of formation to changes in R/D with a twin wire gap former is quite different as shown in Fig. 19. There is less influence of R/D on formation with the curve showing a slight dip at a positive R/D.

SETTING THE SLICE JET

Setting the jet on the wire of a fourdrinier or in the gap of a gap former is the result of the relative position of the slice lip and the apron and controlling the point of impact on the fabric relative to the forming board on a fourdrinier or the gap of a twin wire former.

The jet angle is controlled by the relative position of the slice and the apron, L/b. The L/b ratio, which is the ratio of the projection of the lower slice lip beyond the upper lip(L) to the slice opening(b) is very important in determining how the slice jet will land on the wire. Fig. 20 shows a sketch of this geometry. A low L/b of 0.5 means a steep jet angle into the wire and is referred to as pressure forming while an L/b of 0.8 or greater means a relatively flat jet and is called velocity forming.

In pressure forming, water is driven through the wire at the slice discharge and the sheet is set quickly. With a headbox that has poor delivery, removing the water early tends to minimize this effect flow defects which become amplified as they go down the wire. Pressure forming frequently causes a breast roll discharge; and if there is not sufficient space around the breast roll to handle the water, the bottom of the sheet will be disrupted. This kind of forming can lead to sheet sealing from too rapid drainage causing water removal and formation problems. At low L/b ratios a small change in either L or b will change the jet angle significantly but not the point of impingement, so the forming board/jet impingement relationship changes very little.

Pressure forming produces two separate sheets on the wire. The first one is established at the point of impingement of the jet where one third or more of the sheet is formed. The second sheet, formed on top of this has quite a different character because it is formed later. The paper produced in this way is usually very sensitive to moisture and humidity changes and will have curl problems. This type of forming is one of the sources of diagonal curl which is so critical for Xerox-type copy papers and in liner board where it causes twist warp.

During velocity forming, when L/b is greater than 0.8, the jet angle is low and travels more nearly parallel to the wire and is the normally preferred method of delivery. The jet should be delivered to the wire at a low angle and land just before the leading edge of the forming board. With this arrangement, the bottom of the slice jet and the film of air traveling with it are removed by the leading edge of the forming board as shown in Fig. 21. This is the desired effect since the bottom of the jet tends to flow backwards when it hits the wire and would have poorer formation if allowed to stay with the sheet. In addition the layer of air traveling with the bottom of the jet must be eliminated at the forming board so that it will not disrupt the bottom side of the sheet and produce a streaky appearance.

When velocity forming, a small change in either L or b will change the point of impingement and can disrupt formation by landing the jet directly on the forming board. Adjustments to the L/b ratio should be made in small increments to avoid missing the optimum point and to allow adjustments to the forming board when necessary

SUMMARY

Making good formation on a machine involves working with many factors. This paper has presented the fundamental parameters relating to formation control and discussed the operating applications most usually used. In approximate order of importance the key parameters are:

1. Furnish
2. Refining
3. Headbox Consistency
4. Agitation on the Wire
5. Rush/Drag
6. Setting the Jet

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Fig.1 Northern Spruce

Fig.2 Southern Pine

Fig.3 Douglas Fir

Fig.4 Southern Pine Sheet

Fig.5 Northern Spruce Sheet

Fig.6 Eucalyptus Sheet

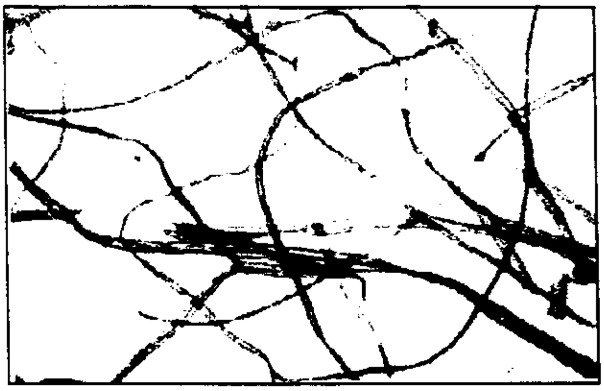

Fig.7 Unrefined Northern Softwood Kraft

Fig.8 Refined Northern Softwood Kraft

Fig.9 Refined Hardwood Kraft

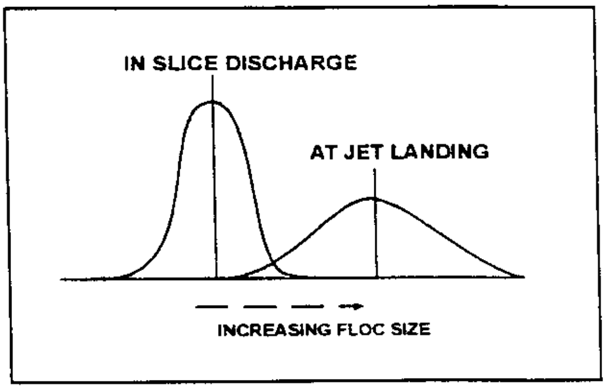

Fig.10 Floc Size Distribution Change

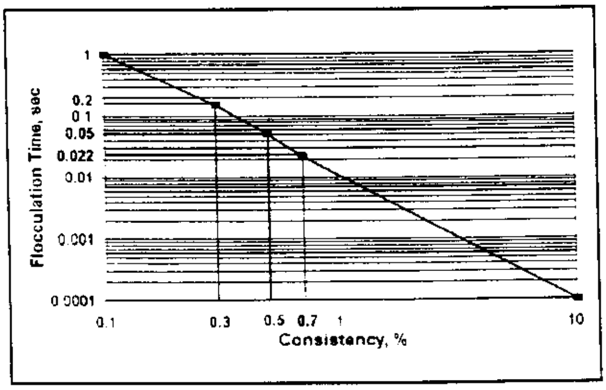

Fig.11 Effect of Consistency on Reflocculation Time

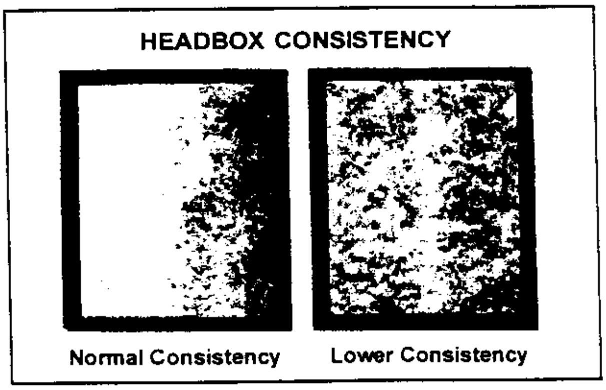

Fig.12 Effect of Too Low Headbox Consistency

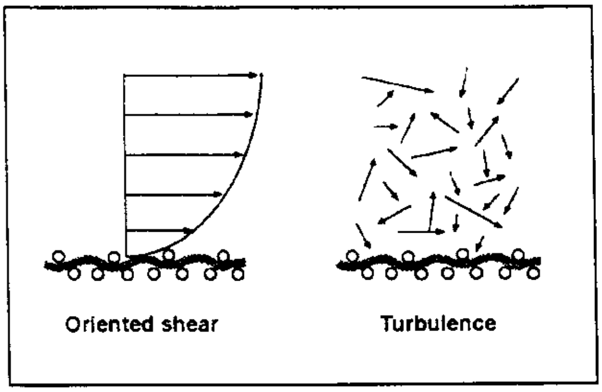

Fig.13 Comparison of oriented shear and turbulence

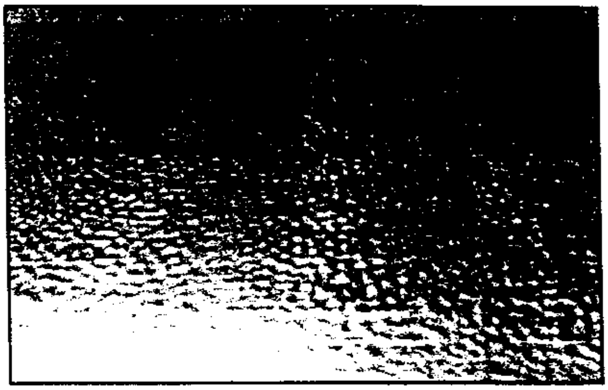

Fig.14 Good turbulent agitation

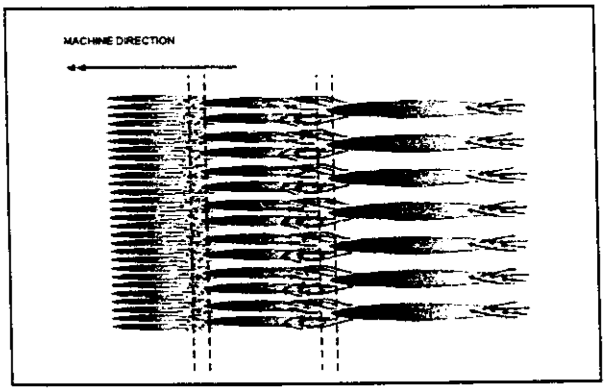

Fig.15 Flow action as viewed from above

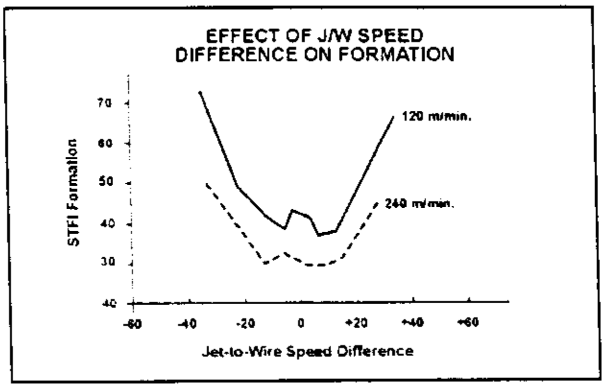

Fig.16 Effect of jet-to-wire speed difference on formation

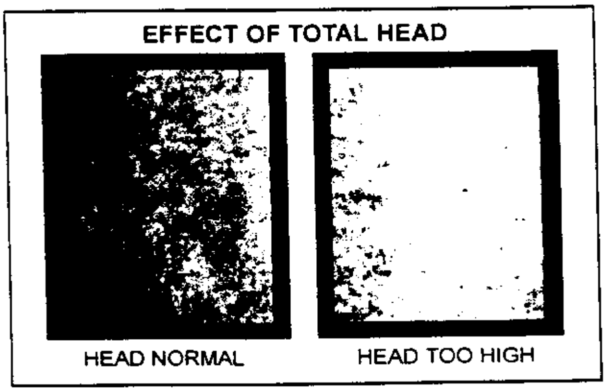

Fig.17 Effect of total head on formation

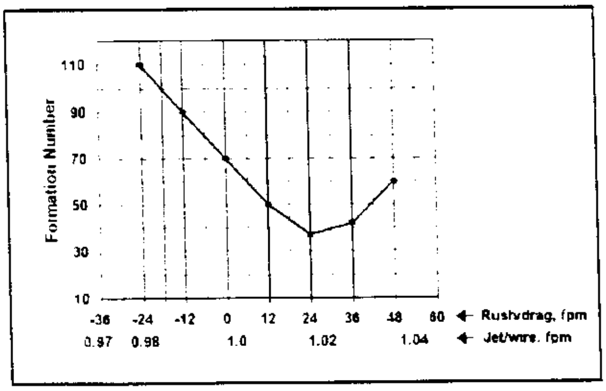

Fig.18 Fourdrinier formation vs. rush/drag

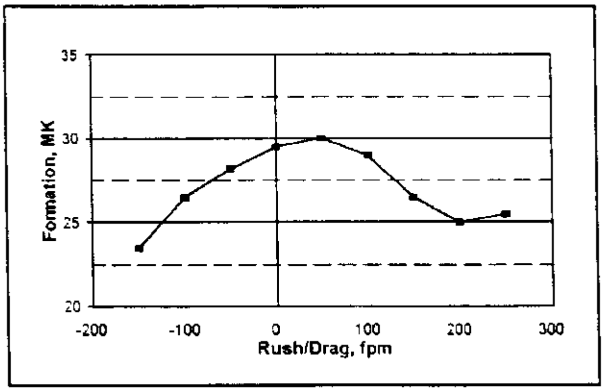

Fig.19 Effect of rush/drag on formation gap formers

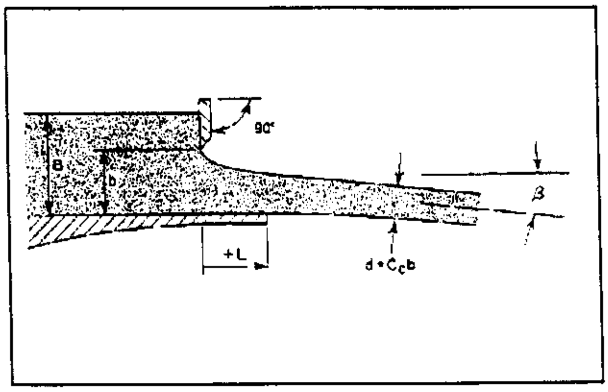

Fig.20 Slice geometry

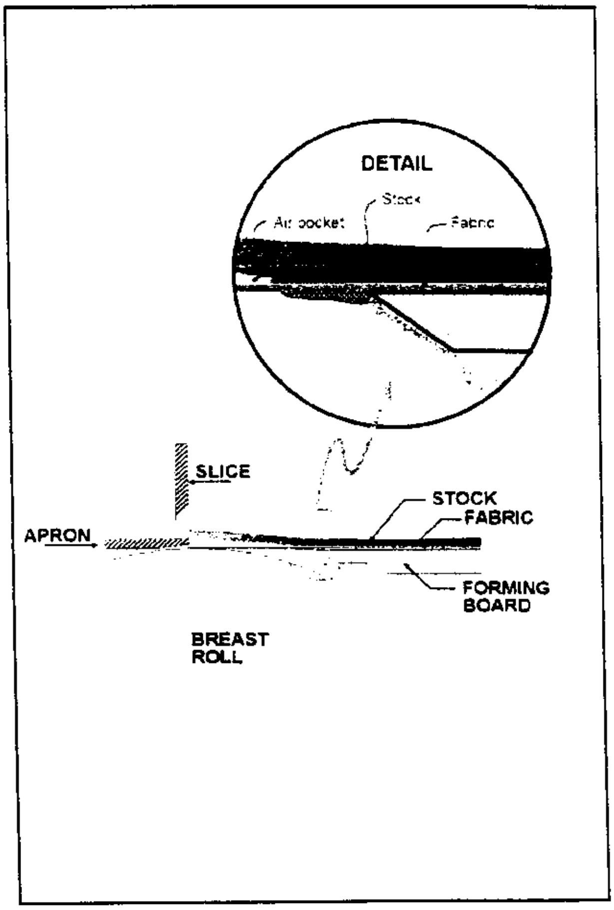

Fig.21 Slice jet impingement