INTRODUCTION

Many fluid-mechanics problems exist in the pulp-and paper-making process. Those of greatest consequence center in the paper machine itself and have a great effect on paper quality as well as the production potential of the machine. Once started, a machine will run continuously for days making rolls of paper from a fiber slurry that has an original consistency of from 0.1 to 1 per cent by weight. Machines differ greatly in design, but have several common functional parts: (a) the filtration of a wet fiber web on a moving fine-mesh screen, (b) mechanical pressing for additional water removal while on, or between, carrying felts, and (c) final drying by means of steam heated dryers. Each of the many elements on the machine must function with a high degree of safety to insure that the process does not break down.

The end objective of fluid-mechanics research is to improve the paper quality at a given production rate or to realize greater production at a given quality level. The overall results must, of course, fit into a favorable economic picture. The translation from basic laboratory work to final production application transcends a large number of variables that cannot be evaluated with a good degree of certainty. This has two principal effects on research work. Considerable expense for pilot-plant equipment is justified. It is desirable that such pilot-plant equipment, and model components, be full scale in cross section and in operating speed. Fortunately, the prototype dimensions are such that duplication of cross-sectional scale is quite practical; widths are reduced considerably.

The normal process-development procedure is from laboratory theory and model work, to pilot-plant trials, then to prototype application. The quantity of work done in each phase is a balance between the increased precision that might be obtained and the risk in going to the next stage. It should be pointed out that the sequence of laboratory work, pilot-plant studies, and production application is based on the assumption that the overall objectives and problems in a development are well defined. This is not always true. In some instances, considerable time must be spent on prototype observations and pilot-plant trials, before a constructive overall program can be established.

Perhaps the best way, to demonstrate the need for pilot plant components,
is to discuss briefly some of the more significant development difficulties and then present a specific problem example.

The greatest technical problem lies in the poor knowledge of flow of fiber suspensions. Some references exist for specialized flow conditions, but progress is slow because of the difficulty of making hydraulic measurements. The fibers hang up and agglomerate on the leading edges of measuring elements and small-scale flow-control devices. Visual observations are usually not feasible because of the opacity of the slurries. The problem is complicated further by the tremendous variation in the natural and synthetic fiber furnishes and the mixtures in which they are used.

The fibers also enter into the dynamics of the filtration process. In this case the wire screen, with its partially deposited layer of fibers, is an essential boundary geometry of any flow analysis. Though the drainage relationships for such a boundary are complicated, sufficient data are available for approximate analytical treatments [1,2]. The problem differs from the more common porous-flow situations in a number of respects. The web is compressible so that the resistance of a given pad is a function of the total driving force with the concentration of fiber per unit volume increasing throughout its thickness. In a strict sense, the compaction is not instantaneous, nor is it completely reversible. Work to date has been with relatively thick pads; this has yet to be extended to lighter webs where the screen has some effect and a sizable portion of the fiber fines are not retained in the web.

A very important consideration, which is not altogether technical, is how the target of improved paper quality is defined. Uniformity of quality and uniformity of paper weight apply universally to all kinds of paper. Beyond these, each paper can, and usually does, have its own balance of desired qualities that are considered to be of greatest value to the ultimate user. The intangibles of product design, as well as technical problems in process development, strengthen the need for pilot plant equipment.

A last overall consideration has to do with how improvements are applied to production machines. A very large part of increases in paper production is achieved by minimum rebuilds to increase the output of existing machines. Due to differences in vintage, machines are seldom duplicates. Thus, there is a uniqueness factor for each machine that must be considered in all stages from problem definition to possible compromises in final application.

THE "Wet End" OF A FOURDRINIER-TYPE PAPER MACHINE

The particular example to be presented is "spouting," or "stock jump," which can occur on high-speed Fourdrinier-type paper machines. In the light of the previous discussion, it should be pointed out that spouting is not a
universal problem on all machines of this type nor is its problem aspect well understood. Thus, the following work was done primarily to help achieve a problem definition and point to possible ways of controlling the phenomena.

A typical headbox, or inlet, and Fourdrinier section of a book-paper or newsprint machine is shown in Fig. 1 in its simplest form. The widths of modern book-paper machines run to about 20 feet, of newsprint machines to about 30 feet. The length of the flat part of the moving wire, or Fourdrinier section, might be up to 65 feet. Speeds of newsprint machines go to over 2,000 fpm; speeds for better grade papers are less than this.

The inlet is a pressurized box that delivers a thin jet (about one half inch deep) of dilute pulp slurry across the machine width. The inlet pressure is controlled within narrow limits so that the slurry velocity is substantially the same as the velocity of the endless wire-screen that is rotating around the Fourdrinier section. The function of the Fourdrinier section is to de-water the slurry from its original consistency of 0.5 to 0.8 per cent to a consistency of about 18 per cent. At 18-per-cent solids the fiber web has enough strength to support its own weight over a span of a few inches. Following the Fourdrinier, the web is transferred to the press, or felt, section where endless felts carry and protect the web while it is mechanically pressed to consistencies of 35 per cent or so. Steam-heated drum driers complete the drying of the paper.

Machines differ in detail but have three general functional areas on the Fourdrinier. The slurry is very free draining when it first lands on the wire screen and no deliberate effort is made to remove a great deal of water. The slurry is allowed a stilling length and the members under the wire are primarily to support the wire and remove free water that has drained to the underside of the wire. The longer middle section of the Fourdrinier consists of "table" rolls that pump water out of the sheet; high vacuums
Fig. 2 (a). Spouting After First Solid Table Roll on 19-Inch-Wide Experimental Unit. Speed of 1500 fpm. Headbox Consistency 0.58 per cent. (One Microsecond.)

Fig. 2 (b). Different Approach-Flow Conditions.
exist in the leaving nips of the solid rolls. The water removal capacity of
the rolls diminishes as the slurry thickens and a section of slotted stationary
vacuum boxes is necessary for the last length of the wire. The slurry loses
its wet appearance and becomes non-reflective before leaving the vacuum
box area.

Spouting on the Fourdrinier

Figure 2 shows spouting which is occurring after the first solid table
roll. This is normally the inception point although it can occur where the
slurry jet hits the wire. Unless grooved rolls are very lightly grooved, they
will not cause spouting; on the other hand they remove much less water than
solid rolls. The differences between Figs. 2(a) and 2(b), which show similar
set-ups except for the approach flow, explain in part the inconclusive nature
of past work or opinions on the mechanism of spouting.

Many photographs of the phenomena exhibit an inversion pattern of
the surface depth. Spouts rise from what were previously low streaks, or
spots, in the flow approaching the roll. This pattern is easiest to distinguish
when the flow has a predominance of ridges such as shown in Fig. 3.

The suggested mechanism for spouting is shown schematically in Fig.
4. The region of roll wrap causes a growth in the magnitude of nonuni­
formities; for the sake of simplicity we will again consider them to be pri­
marily of the ridge type. The most appropriate reference for fluid being
accelerated away from its free surface is some work by Lewis and Taylor

Fig. 3. Photograph of Ridges Rising from Low Streaks (3000 Frames per
Second), Viewed from Above.
[3,4]. They find that the growth of disturbances due to the downward acceleration of the fluid is given by

\[ \frac{\eta}{\eta_0} = \cosh \sqrt{\frac{4\pi^2 s (g_1 - g)}{\lambda g_1 \frac{(\rho_2 - \rho_1)}{(\rho_1 + \rho_2)}}} \]

in which
- \( \eta_0 \) = amplitude of initial disturbance
- \( \lambda \) = wave length of initial disturbance
- \( s \) = downward displacement of the fluid
- \( g \) = acceleration of gravity
- \( g_1 \) = induced acceleration
- \( \rho_1 \) = density of upper fluid
- \( \rho_2 \) = density of lower fluid

In the present case, the magnitude of the acceleration ratio is not significant because the acceleration of gravity is small in comparison to \( g_1 \). Densities \( \rho_1 \) and \( \rho_2 \) are fixed with \( \rho_1 \) being negligible. On the basis of this equation, the total downward displacement and the original scale of the disturbance are the only items over which some control might be achieved. As an overall consideration, it is not possible for this region to cause any slurry to rise above its original horizontal trajectory.

If the free surface approaching the point of wire release from the roll were completely smooth, there would be no mechanism for spouting. The impingement of irregularities of flow onto the released wire results in lateral velocity components that in turn collide and cause the spouts, or in simple terms, splash. The inception of spouting could be expected to depend on the angle of impingement, the velocity of the slurry, and the character of the approach flow that has now been modified by the preceding region. The geometry of the wire, which should be indicative of the impingement angle, can be described by considering a free body of the wire over the leaving nip. The upward components of the wire tension forces must be
balanced against the pressure integration beneath the wire plus the changes in vertical momentum of the slurry. Taylor [5] has published a theoretical basis for determining the pressure distribution in a leaving nip:

$$\text{max. nip vacuum} = \frac{1}{2} \rho V^2$$

$$\text{nip length} \propto \frac{k_p R V}{\mu} \quad \text{(at this value nip vacuum is max.)}$$

$$q = \frac{1}{2} (0.590) \frac{k^2}{\mu^2} R p^2 + V^3$$

in which the previously undefined variables are

- $V$ = velocity
- $k$ = drainage coefficient with a length dimension (higher $k$ means more free draining)
- $R$ = roll radius
- $\mu$ = dynamic viscosity
- $q$ = drainage rate

Taylor's work has been substantiated by Burkhard and Wrist's experimental measurements in a practical sense, even though there are some questionable assumptions in the theoretical treatment [6]. The relationship of Taylor's theory with impingement angle indicates that spout inception would be fostered by increasing speed, increasing roll diameter, decreasing drainage resistance, or decreasing wire tension. The last of these, wire tension effect on spouting, is quite well established.

The theories of the growth of nonuniformity and subsequent splash are both related to the amount of wire deflection. The possible variables that might be controlled to diminish wrap would also diminish the amount of water removal and lengthen the Fourdrinier. The following tests were undertaken to verify possible means of control and to explore the mechanics of the two related fluid deflections.

**Pilot-Plant Fourdrinier Tests**

The principal group of tests were made on a 19 inches wide, experimental Fourdrinier section. The section was too short to make finished samples of paper at the sheet weights of present interest. The web slurry from the wire was remixed with the filtrate and recirculated to the headbox. The recirculation of the long fraction of the fibers with the fine solids that pass through the wire prevented the selective building of fines that is characteristic of a continuous process. It was felt that this did not seriously affect the relative results of the tests. Tension of the wire was held constant by means of a weighted stretch roll.

The general test layout is shown in Fig. 5. The catch pan was located
slightly upstream of the maximum elevation that the airborne slurry would achieve at speeds of 1500 to 2000 fpm.

A wire was completely sealed with four coats of Hypalon to check the limiting condition of infinite drainage resistance. The coating was quite flexible and did not materially stiffen the wire. No indication of spouting was observed with the wire running on a flat table. Hosing of large quantities of water into the entering and leaving nips had no noticeable effect on this stable flow condition. The solid table roll was then raised one inch which resulted in an artificial roll wrap of approximately two degrees. Comparison of these two conditions is shown in Figs. 6(a) and 6(b). Note that the wrap condition, which corresponds to only the downward acceleration over a normal roll, causes disturbance growth but no signs of an inversion. The scale and character of these nonuniformities are shown in Fig. 7(a); Figure 7(b) shows normal spouts at approximately the same scale. Some of the higher areas went off in almost a normal trajectory elevation. The immobility of the headbox structure made it impractical to maintain similar approach flow conditions on a more steeply sloped wire so further increments of wrap were not tested.

A normal wire was then installed with the table again in its flat position. Runs were made at constant speeds with inlet consistency as the controlled variable. The determinations of airborne slurry resulted in the curves shown in Fig. 8. The four-inch increments of the catch-pan opening were
too coarse to give a significant distribution of the airborne fractions. No measurable slurry was obtained in even the second opening until the 500-cubic-centimeters-per-second level was reached. 100 cubic centimeters per second is equal to approximately 0.25 per cent of the headbox discharge. Each increment of 0.1-per-cent increase in inlet consistency had a quieting effect on the jump equivalent to about 100-feet-per-minute drop in speed.

The effect of roll diameter was investigated by replacing the 13-inch roll with a 5-inch one. The 5-inch roll gave no measurable jump within the speed range previously investigated with consistencies to less than half a per cent. The slurry immediately downstream of the roll was observed to be quite "wild," however.
SMALL-SCALE MODEL TESTS

It was not possible to isolate the impingement aspect of spouts on the test Fourdrinier. This was done in a qualitative way by utilizing a simple jet-deflection flow section shown in Fig. 9. The top profile piece was selected on the basis of its simplicity as well as the fact that it is somewhat representative of the flow approaching the end of the roll wrap. The one-inch spacing of the teeth was of the same order of magnitude as some of the ridges observed in the earlier trials. The section was made quite close-coupled to minimize possible boundary-layer and edge effects. No separation was observed in the contraction, although some disturbance may have resulted from the three-dimensional flaring of the curve.

(a) GROWTH OF NONUNIFORMITIES WITH SEALED WIRE. WIRE WRAP ON ROLL—TWO DEGREES.

FIG. 7. COMPARISON OF SPOUTING CHARACTER APPROXIMATELY 18 INCHES DOWNSTREAM FROM TABLE ROLL.

The splash of the jet with an impingement angle of $6^\circ50'$ is shown in Figs. 10(a) and 10(b). (This angle is of the proper order of magnitude for our wrap considerations.) Several measurements were made for this condition. The quantity of water rising in the spouts was determined by
holding a scoop down to the bottom of the spout at a point 1 inch from the end of the lucite section. The results are shown in Fig. 11. Spout (b) was less symmetrical than the others. The rise angle of the spouts was determined from photographs. This angle was 9°37' relative to the six-inch bottom piece at 1500 fpm and 10°33' at 2500 fpm.

Downward deflection of the jet is shown in Fig. 12. At any downward angle the deflection of the top of the ridges was quite minor.

**Energy Dissipation in Spouting**

An important consideration in spouting is the possible energy loss that may result from the mechanism. The tests on the 6-inch flow section, with

![Fig. 7 (b) Normal-Type Spouts.](image)

its simplified ridges, suggested a mechanism of energy exchange without an immediate consideration of internal losses in the slurry. A net loss in forward momentum of the slurry can occur even if the internal losses over the roll and through the splash are negligible. The energy, hence velocity, of the fluid can be constant, but the impingement of the ridges will result in part of the flow having significant lateral velocity components. The net loss in machine-direction momentum could be computed if the flow after impingement could be described in detail. The Fourdrinier wire must
then supply the energy necessary to bring the slurry back up to wire speed.

Momentum losses can be computed from practical measurements, if one more step is taken. The quantity and upward velocity of the airborne slurry is the same as the lateral velocity pattern if the lateral flows collide with no internal losses, negligible surface tension restraint, and in a symmetrical manner. The rise angles in the 6-inch flow section indicate that the rising fluid has lost 1.7 per cent of its horizontal velocity component at 2500 feet per minute. The horsepower necessary to bring the airborne portion back to wire speed would be 0.005 HP per foot of width at 1500 fpm and 0.022 HP at 2500 fpm (this assumes all of the fluid is rising at the same angle). Values for the pilot plant test can be computed by using
the maximum elevation of the spout trajectories. At the 600-cubic-centimeter-per-second airborne-slurry level and 2000-fpm screen speed, a portion of the slurry had risen 6 inches and lost 1.5 per cent of its horizontal velocity.

**INTERPRETATION OF RESULTS**

The regions of nonuniformity growth and splash will be discussed separately before considering their composite. The tests to attempt a separation of the two occurrences were directed primarily at spouting after solid table rolls, but they are of more general application to instability on the Fourdrinier. For example, the rebound aspect can occur as an isolated case, if the jet from the headbox strikes the wire at too steep an angle.

Growth of nonuniformities in a region of downward acceleration is perhaps an understatement. Some of the higher nonuniformities had very little downward deflection when observed on the sealed wire test with 2° of artificial wrap. Normal roll wrap at these speeds would be about three times this value [6]. This was also substantiated through the observations on the 6-inch flow section. The limited degree of flow deflection explains the second pressure peak of Burkhard and Wrist's pressure profile measurements [6] through a roll nip. As the fluid becomes more loosely associated with the bottom surface, it causes less vacuum due to centrifugal force. An isolated splash could be obtained only in the 6-inch flow section. By necessity the approach flow was an idealized pattern being somewhat representative of true scale only in two dimensions. The rise angles of the splash and the fractions of air-borne water were found to be quite constant in the 1500- to 2500-fpm range for a given impingement angle. This indicates that internal losses, surface tension, and gravity are of relatively minor importance. This conclusion should not be extrapolated to slurry on the wire.
without further studies. Fiber content in the fluid could cause a damping effect on the splash. Investigation of this aspect would have required additional refinements to the 6-inch flow section and measuring means. A comparison of the surface smoothness between the two cases showed appreciable differences; the approach flow in the 6-inch section had a very fine scale surface roughness.

It is difficult to give any experimental proof that the airborne fraction of the liquid has a lower velocity component in the horizontal direction than the rest of the flow. The original argument was that the maximum efficiency of the splash would be one of constant energy. Since this occurred with a change in direction, part of the momentum in the direction of the flow has been lost. (This is not quite like the case of a jet impinging on a flat surface since some force is created at the curvature point.)

The backward lean of spouts and splash nonuniformities would support the velocity picture if one could say that each came from the same source. This is probably true but was not verified in detail. Air drag would
also retard the air-borne liquid. Rough estimates of air drag indicated significant, but not major effects.

A lengthy discussion of energy dissipation, or exchange, due to splash would be nebulous. The values presented here could greatly underestimate true magnitudes because of the assumptions that were necessary to facilitate calculations. The only quantity that can be given a specific significance is the loss in machine-direction velocity of the airborne liquid. This portion of the slurry will exert a drag when it returns to the wire—a drag that can be compared with the control tolerance on the slurry discharging from the headbox. The control limits on the discharge from the headbox may be as low as \( \pm \frac{1}{2} \) per cent for better grade papers; if the difference between slurry and wire speed is greater than this the paper suffers in quality. A good share of the airborne slurry is out of these control limits and could affect paper quality for this reason.

Movies and still photographs of flow over solid table rolls exhibited the distinct regions of nonuniformity growth and subsequent splash quite well. It was more apparent in low areas than for higher ridges. Higher ridges would frequently carry farther downstream from the roll; this might be
expected because of the limited downward deflection of ridges. Air bubbles in the slurry are excellent inception points for spouts, but their population was not sufficient to have any significance in these tests. None of the observations indicated that the surface condition was being governed by flow in the entering or leaving nips right under the wire [5].

The tests of different roll sizes, drainage resistance, and headbox consistency behaved as predicted: that is, conditions that gave more water removal were also more conducive to spouting. Unfortunately, this does not allow much latitude in reducing spouting on present machines.

Roll diameters and wire tensions are dictated by structural considerations. The slurry composition and the wire resistance are dictated primarily by product design; so these items, with their effect on drainage resistance, cannot be used as a control means. The problem is one of compromising the necessary water removal against inception or magnitude of spouting. The amount of water to be removed can be diminished by increasing the fiber consistency in the headbox slurry, but this has adverse effects on paper quality after a certain level is reached.
Work to establish the relationship of approach flow to spouting could result in significant design improvements. Many machine limitations that are attributed to spouting could be due to the fact that a poor flow condition from the headbox is being exaggerated by spouting or is, perhaps, causing it. A technical background of this aspect would do much to determine where and how much money should be spent to upgrade a machine.

On a longer-range basis, it would be well to consider the general aspects of free-surface stabilities rather than just the solid table rolls. Other types of drainage elements have higher incipient spouting speeds, but all result in some degree of wire deflection.

The course of the previous discussion emphasized most of the general problems presented in the introduction. The phenomenon of spouting, which can be described quite simply, was shown to involve many unknown relationships. A precise knowledge of each would require a great deal more research work. A minor number of pilot plant tests made it possible to define these areas and also produced a framework of knowledge that was adequate for suggesting several development programs.

The translation of the problem to paper quality was not supported by
specific results because of limitations to the pilot-plant Fourdrinier length. Furthermore, such evaluation would be quite specialized and beyond the intent of this paper.

CONCLUSIONS

Pilot-plant equipment, which is essentially full scale in cross section and speed is highly desirable for paper-making process development. The problem of spouting on the Fourdrinier demonstrated how such equipment defines technical problems for laboratory study and at the same time facilitates a semi-empirical approach to development work.

Spouting was found to be best described as a splash resulting from non-uniform flow impinging on the wire. Inception of spouting was found to be largely dependent on geometric conditions. Additional work is needed to verify whether internal resistance, surface tension, and gravity restraint are negligible at higher machine speeds.

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REFERENCES

Discussion

John McNown commented that the speaker had pointed out clearly that one of the major problems in attempting a model study is often the inability to understand all of its complexities. Effort must first be directed toward demonstrating what the various aspects of the problem are before proceeding to model some of them. The production of a wide, high-Froude-number, uniform jet is in itself difficult.

Girrard Calehuff asked if the possibility of deleterious effects from the landing of the drops had been considered. The speaker said that this possibility led to the attempt to compute the loss in velocity. As it gets toward the end of the wire the jump becomes a little more severe and formation falls off. In one instance it was necessary to reduce the tension on the wire screen.

W. D. Baines said that the photographs illustrate what paper makers mean when they say they are making paper of raindrops not pulp. It is quite a spectacular display to see the spouts jumping and the droplets traveling several feet before landing and leaving a weakened spot in the paper. He stated that the spouts are rich in the fine part of the stock and that the heavier and bigger fibers do not seem to get into the spout. He asked if this could be explained in terms of the speaker’s hypothesis. He added that the hypothesis that the spouts are caused by centrifugal acceleration has several defects as the speaker pointed out. The speaker replied to the question about the fines in the drops by saying that he could not explain it. He added that there is an instability underneath the wires which are curving and, if there is very little stock on the wire, the instability underneath shows up on top.

Alfred Nissan asked two questions: first, are there any beneficial effects from the drops which may compensate for their deleterious effects, as Reynolds theorized that rain calmed the sea by dissipation of energy and momentum; and second, does there seem to be a periodicity in the ridges before they break into spouts, a periodicity which may be related to the curving of the wire screen? The speaker replied that these were things that were not looked into. He added that the inlet used is one-half scale and is more or less standard for the machine. The questioner commented that, if it were the inlet condition, one would expect a random distribution unless there was a uniform distribution from the paper rolls which would give another periodic disturbance. The speaker said that this had not been checked.