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Final Report

A PRELIMINARY STUDY OF THE INSTABILITY OF THE STOCK ON THE WIRE OF A FOURDRINIER PAPER MACHINE

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INTRODUCTION

Two of the several types of disturbances observed* in the flow of the stock on the wire screen of a Fourdrinier paper machine occur (1) immediately downstream from the slice and (2) downstream from the top of the first few table rolls. Longitudinal ridges or surface waves form at the lip of the slice and extend some distance downstream. In addition, slender columns of stock, commonly referred to as spouts, form a few inches downstream from the top of the first few table rolls. These occurrences are interrelated and probably affect the even distribution of the fibers in suspension, which in turn affects adversely the quality of the manufactured paper.[2] Also, as the speed of a machine is increased, spouting becomes sufficiently extreme that it limits the maximum feasible speed of some installations.[2]

These instabilities can be studied either analytically or experimentally. Observations of jet formation made at The University of Michigan and elsewhere,[3] indicate that the initial disturbances at the slice are due to eddies in the flow. The large downward acceleration at the table roll then presumably results in a marked differential motion and spouting in accordance with a theory presented by Taylor. Both of these occurrences are affected by the presence of fibers;[2,3] however, the demonstration of the causes and effects can be achieved with water in the absence of wood fibers. In this way simple equipment can be utilized in a fluid mechanics laboratory with a minimum of elaboration and expense.

This study was sponsored by the Fluid Mechanics Subcommittee of the Technical Association of the Pulp and Paper Industry as Research Project No. 92. It is part of an extensive program of related basic research sponsored by this subcommittee and it was initiated as a preliminary study to investigate the characteristics of flow at high Froude numbers as they occur in the formation of paper.

DISTURBANCES IMMEDIATELY DOWNSTREAM FROM THE SLICE

The formation of longitudinal ridges immediately downstream from

*An extensive review of the factors affecting formation is given in Ref. 1.

the slice can be attributed to disturbances generated in the head box or at the lip of the slice. Such disturbances may result from well-defined vortices extending to the free surface of the stock, from eddies forming because of the presence of a distributor roll, or from other irregularities in the flow. These vortices and eddies, upon their emergence from the slice and superposition of a high longitudinal velocity, take the form of vortex tubes. Because the depth of flow is relatively small, of the order of one inch, they frequently manifest themselves as surface disturbances. The flow downstream from the slice is characterized by a Froude number of the order of magnitude of ten to twenty. It is known that, in the case of flow with such a large Froude number, surface disturbances are carried downstream very rapidly and take the form of waves. The pattern of development of these waves is a function of the magnitude of the Froude number. The aforementioned longitudinal ridges can be clearly seen in Fig. 1, plate I, in the area left of the first table roll.

Also, small surface distrubances originate at the slice, particularly with low-speed paper machines. These are attributed primarily to lip geometry or to discontinuities on the metal surface and are of a smaller order of magnitude.

The transformation of random vortices and eddies into longitudinal vortex tubes, as a longitudinal velocity is superimposed, is a common occurrence in the lower atmosphere. It has been observed by micrometeorologists that vortices originating from the ground level orient themselves in the direction of the prevailing wind, taking the shape of a horseshoe-like vortex tube. Also, in the case of a thin layer of liquid heated from below and subjected to a mild temperature gradient, the pattern of flow assumes the form of three-dimensional vortices of a hexagonal shape, commonly referred to as Benard[4] cells. Upon superposition of a horizontal-velocity field, these cells transform into vortex tubes oriented in the direction of the velocity.

To verify the aforementioned explanation of the origin and formation of the longitudinal ridges, a preliminary and qualitative experimental investigation using water instead of paper stock was conducted. A flume with a sluice gate was used in such a way as to produce a flow of water in the flume at a Froude number of about eight. The flume was 8 inches wide, 18 feet long, and the maximum head available in the head box was about 15 inches. The sluice gate (corresponding to the slice) was opened 0.75 inch and the average velocity of efflux was approximately 9 fps. The Froude number, defined as the ratio of the average velocity to the square root of the product of the gravitational acceleration and the depth, was calculated using the velocity and the depth of flow at the vena contracta.

Under tranquil conditions in the head box the surface of the water in the flume was relatively undisturbed, except for the small disturbances caused by minute discontinuities of the edge of the gate. Upon the introduction of a vortex in the head box, created by a single stroke of a paddle crosswise to the direction of flow, a single longitudinal ridge appeared downstream from the sluice gate and traveled across the channel. The two occurrences were clearly coordinated, the time lag of several seconds between the creation of the vortex in the head box and its appearance as a longitudinal ridge downstream from the sluice gate corresponding to the time for the fluid and the disturbance to move from one point to the other. Subsequently, a lattice of approximately the same solidity as that of a distributor roll was placed in the stilling chamber a few inches upstream from the sluice gate. In this case there were several longitudinal ridges which corresponded to the several eddies shed from the lattice.

These preliminary observations indicate the possibility of studying this particular form of disturbances by means of simple laboratory equipment with water replacing paper stock. Although the absence of fibers will limit the practical application of the results of such experiments, a better understanding of the fundamental principles underlying this phenomenon will help in devising means for its elimination, either by removing the causes that lead to its appearance or by superposition[3] of disturbances of a smaller scale that will help in breaking up and dissipating the longitudinal ridges. The latter is probably more desirable because turbulence is the mechanism that maintains the fibers in suspension and prevents their flocculation. Also, such a study may be a necessary preliminary to the experimental investigation of spouting because the formation of spouts probably depends on initial disturbances such as longitudinal ridges.

DISTURBANCES IMMEDIATELY DOWNSTREAM FROM THE TOP OF TABLE ROLLS

About two inches downstream from the top of the first few table rolls spouts begin to form as a manifestation of unstable flow conditions of the stock. The size of these spouts increases with increasing speeds of the paper machine, and at sufficiently high speeds the stock appears to leave the wire. In Fig. 2, plate II, this phenomenon can be clearly seen.

Spouting is a consequence of the large downward acceleration of the stock which occurs immediately downstream from the center of a table roll and the initial disturbances, such as those manifested as longitudinal ridges. Taylor[5] investigated theoretically an initially disturbed, free surface of a layer of fluid which is subjected to a sudden downward acceleration. Lewis[6] studied the same phenomenon experimentally and showed that spouts could be formed in this way. Taylor obtained the following expression for the amplification of an initial disturbance on the free surface of a layer of fluid which is accelerated downward:

$$\frac{\eta}{\eta_o} = \cosh \sqrt{\frac{4\pi s(g_1-g)}{\lambda g_1}} \qquad (1)$$

in which

η_o = the amplitude of the initial disturbance,
s = the distance that the fluid layer is moved downward,
λ = the wavelength of the initial disturbance,
g_1 = the induced downward acceleration, and
g = the gravitational acceleration.

Lewis found Eq. 1 to be valid for values of the radical up to about one. Thereafter, the observed and computed amplifications diverge, the predicted values being considerably too large.

In a paper machine the downward acceleration of the stock throughout its thickness due to suction and to the partial wrapping of the wire screen around the table roll can be estimated from the relationship,

$$g_1 = \frac{U^2}{R} \quad . \qquad (2)$$

If U = 2,000 fpm and R = 7 inches, the downward acceleration is approximately 60 g. Also, if it is assumed that the wire is depressed 0.1 inch before it leaves the roll, and if the wavelength of the disturbance is taken as 1 inch, the amplification of the initial disturbance, from Eq. 1, is approximately 1.7. This means that the height of the longitudinal ridges will be almost doubled, and spouting will take place. Of course, this increase in height takes place at the instant that the stock first experiences the downward acceleration at the first table roll. Subsequently, the height of the spouts will continue to increase after receiving this strong impulse.

In an actual paper machine the presence of air bubbles may accentuate spouting. Wrist,[2] using moving pictures, observed that the presence of bubbles causes a well-defined depression, and at a machine speed of 1,500 fpm the spouts were originating from the bottom of the bubble craters. Possibly the initial disturbance caused by the bubbles in this instance was larger than that represented by the longitudinal ridges.

The symmetry and periodic appearance of the spouts can be easily observed in Fig. 2, plate II. Taylor[7] and C. A. Lee[3] attributes the regularity in the transverse direction to Taylor vortices forming under the wire screen at the suction side of the table rolls and the longitudinal spacing to vibrations of the wire screen.

The above explanation of the origin of spouting is strengthened by other studies associated with this phenomenon. The magnitude of the suction at the table roll that gives rise to the downward acceleration has been determined theoretically by Taylor[7] and substantiated experimentally by Wrist.[2] The partial wrapping of the wire screen around the table rolls has been discussed extensively by Wrist.[2] The tightening of the wire screen or the reducing of the suction by peripheral slots in the table roll, each causing a reduction of the downward acceleration, has also been found to reduce spouting. Elimination or reduction of the size of the longitudinal ridges (initial disturbances) in experimental paper machines has had the same effect.

Although corroborative evidence of the foregoing explanation does exist, the instability immediately downstream from the first few table rolls is far from completely understood. Additional investigations should be undertaken to obtain data and information which will definitely establish the interrelationship of the primary variables affecting spouting. With the quantitative results and the added understanding which such studies would provide, perhaps positive steps can be taken to alleviate or eliminate this source of trouble in the manufacture of good quality paper.

This phenomenon can be studied experimentally using water in place of pulp because the inertial characteristics of the flow rather than the viscous properties of the fluid are predominant. A standard flume can be arranged to simulate the slice and the table of a paper machine. Calibrated artificial disturbances in the head box of the flume can provide the initial disturbances in the free surface. A depressed section of the flume floor, possibly with suction and drainage, can provide the necessary downward acceleration of the fluid layer. Alternatively, a rotating cylinder can be installed to duplicate even more closely the occurrence on the Fourdrinier wire. The resulting amplification of a small initial disturbance could be determined for the variety of conditions found in paper machines. Subsequently, the results should be confirmed through tests on a paper machine operating with paper stock. The latter tests would presumably be conducted in an industrial laboratory.

CONCLUSIONS

From this preliminary investigation of the flow of paper stock on a Fourdrinier wire of a paper machine, the primary causes of instability can be described as follows:

a. The superposition of a comparatively high longitudinal velocity downstream from the slice on eddies and vorticies forming in the head box transform these into vortex tubes. These vortex tubes appear as surface disturbances in the form of ridges and depressions which are greatly elongated in the direction of flow.

b. Initial disturbances, caused as described in (a) or otherwise (as from bubble entrainment), give rise to spouting as the stock experiences a large downward acceleration. The acceleration is created by the suction and partial wrapping of the wire screen at the table roll immediately downstream from the top of the first few table rolls. The disturbance can result in an extreme differential acceleration, as shown by Taylor.

These phenomena can be studied with simplified laboratory equipment, using water instead of pulp. From idealized studies a detailed understanding of the occurrences may assist materially in eliminating or reducing the disturbance to the flow.

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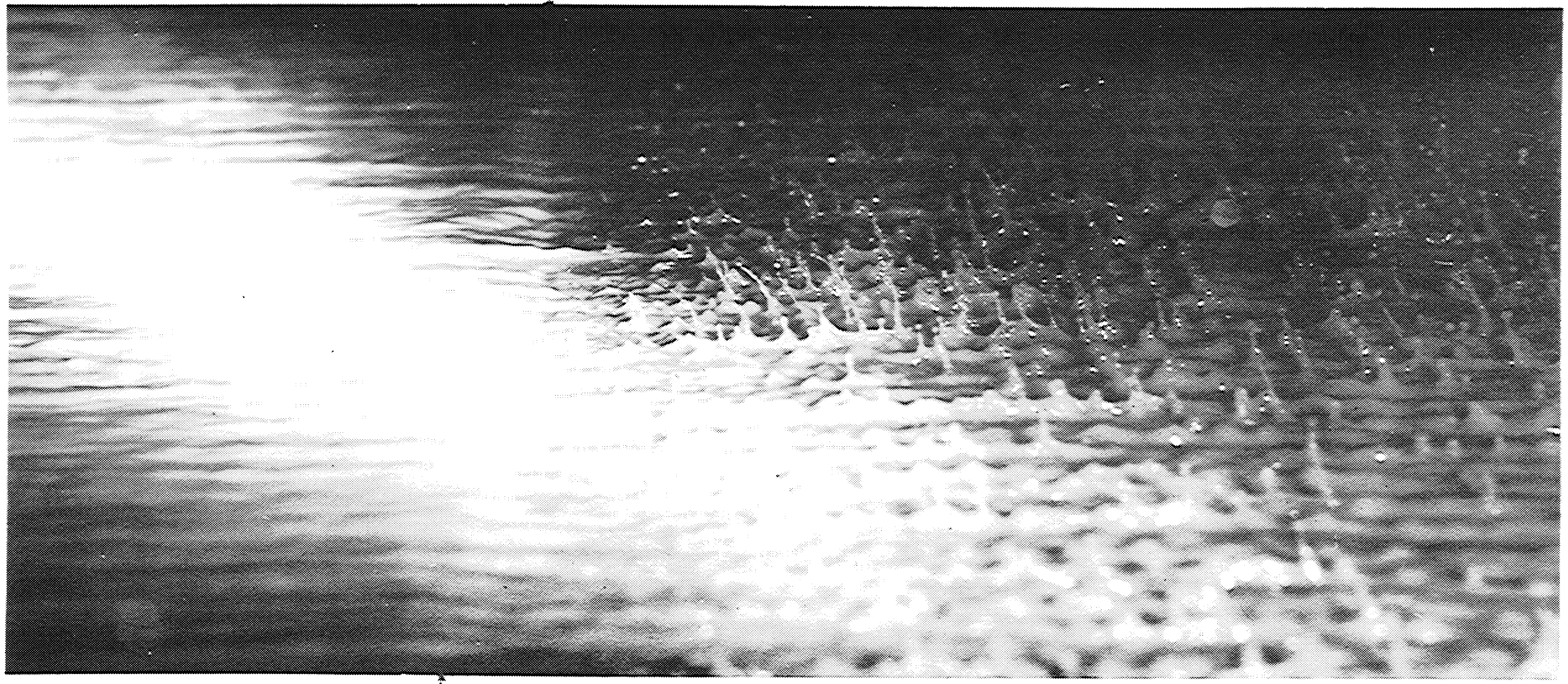

Fig. 1, plate I. Free-stock surface at first table roll on a Fourdrinier wire. Machine speed 1470 fpm, camera shutter speed 1 microsecond. Courtesy of the Fluid Mechanics Laboratory of Kimberly-Clark Corporation.

Fig. 2, plate II. Free-stock surface at second table roll on a Fourdrinier wire. Machine speed 1470 fpm, camera shutter speed 1 microsecond. Courtesy of the Fluid Mechanics Laboratory of Kimberly-Clark Corporation.