# The effects of retention aids, drainage conditions, and pretreatment of slurry on high-vacuum dewatering: a laboratory study

**Kari O. Räisänen, Hannu Paulapuro, and Seppo J. Karrila**

*ABSTRACT: After the initial drainage by gravity and foils on the paper machine wire section, water is removed by suction. A certain pressure difference across the web is reached, depending on the volume of airflow and the resistance of the wet-web wire system. Most of the resistance comes from the web. The objective of this study was to determine the importance of chemical addition and shearing conditions prior to drainage for the air permeability of the sheet. In addition, more knowledge was sought on the dynamics of vacuum-assisted water removal. The study was done with a specially designed laboratory-scale drainage tester called the moving belt drainage tester. Different chemical additions, shear forces, and shear times prior to forming were used in order to change the structure of the formed sheet. The filler content was also varied. After the initial drainage, very short, strong suction pulses were applied, and the solids content of and airflow through the sheet were measured. The effect of different suction pulse rates on water removal was examined.*

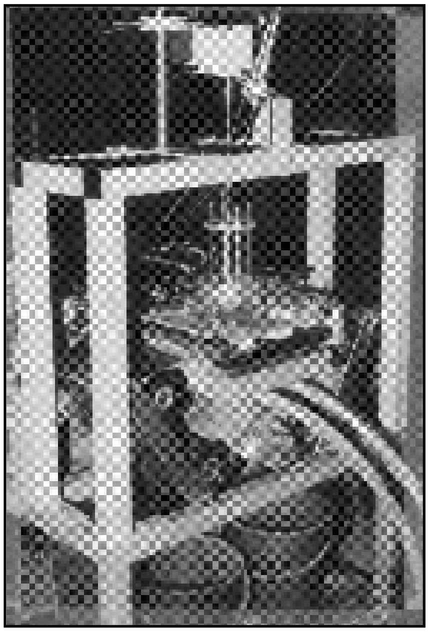
*KEYWORDS: Air permeability, dispersions, drainage, fiber mats, fillers, gas permeability, pretreatment, retention aids, separation, shear stress, slurry, test methods, vacuum, water removal, wet webs.*

Water removal by suction is believed to be caused by compression and airflow pulling water along. The compression is effected by the air flowing though the web. The vacuum generated depends on the structure of the fiber mat and the volumetric flow of air. The looser and more permeable the fiber mat, the higher volumetric flow rate required to maintain the desired vacuum level. It is not clear whether it is the volume of air pulled through, the speed of the airflow in the pores, or the mechanical compression of the web due to the pressure difference that is the main cause of dewatering. There are some indications *(1)* that the airflow has only a minor effect. In the experiments of Ref. 1, the airflow through the sheet was totally prevented, and the only force imposed on the sheet during vacuum application was mechanical compression; the final solids content remained practically the same as with air flowing through the sheet. However, because the pressure difference is in practice created by airflow (typically controlled by volumetric pumps), which consumes electrical energy, it is essential to know which factors are the most prevalent. These factors are examined in the following discussion.

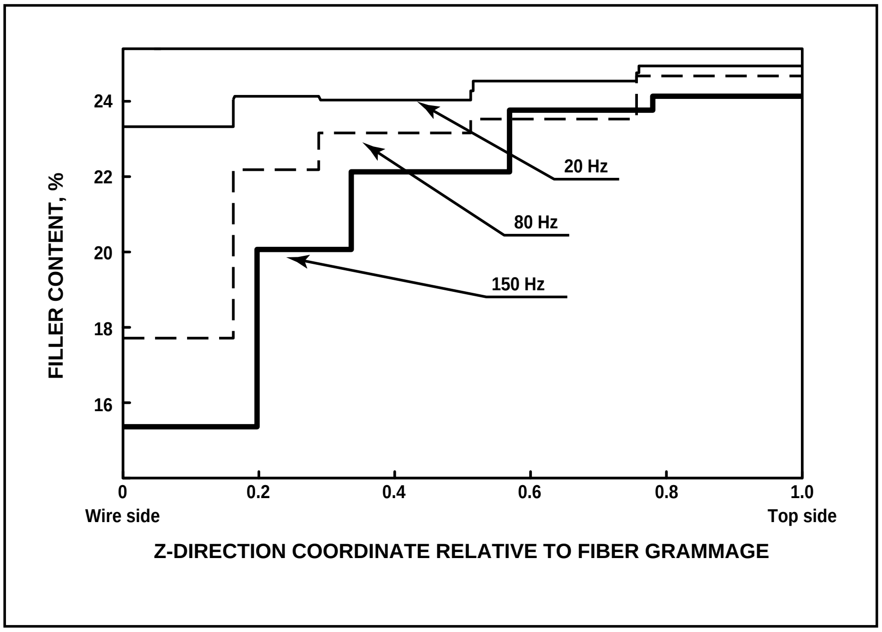
It is well known that flocculation of fibers, fines, and filler material affects the air permeability of the web and the sheet formation. The flocculation of fibers, sometimes called macroflocculation, is harmful for the small-scale material distribution in the web, i.e., its formation.

**Räisänen is a research scientist and Paulapuro is a professor at the Helsinki University of Technology, Laboratory of Paper Technology, Vuorimiehentie 1A, 02150 ESPOO, Finland. Karrila is a senior scientist at the Finnish Pulp and Paper Research Institute, P.O. Box 70, 02151 ESPOO, Finland.**

**1.** The moving belt drainage tester



**2.** Distribution profiles of fillers at different pulse rates, slowly increasing vacuum and ash contents within each slice




**I.** Effect of formation on air permeability and solids content of the sheet

| *Condition* | *Solids content, %* | *Formation, $g^{1/2}/m$* | *Airflow through the sheet, L/min* | *Vacuum, kPa* |
|---|---|---|---|---|
| 70 g/m$^2$ | | | | |
| No retention aids | 10.6 | 0.51 | 13.0 | 12 |
| PAM* 0.015% | 10.5 | 0.53 | 12.5 | 12 |
| PAM 0.03% | 10.6 | 0.81 | 16.5 | 12 |
| 100 g/m$^2$ | | | | |
| No retention aids | 11.2 | 0.54 | 2.5 | 12 |
| PAM 0.015% | 11.2 | 0.63 | 1.7 | 12 |
| PAM 0.03% | 11.1 | 1.02 | 5.5 | 12 |

* Ployacrylamide

When the small-scale material distribution becomes more uneven, causing poorer formation, the probability of large pores in the web increases, and air flows more easily through the sheet. This causes a relatively low pressure differential over the web and poor water removal. On the other hand, an improvement in the small-scale material distribution, i.e., formation, improves dewatering by suction *(2).*

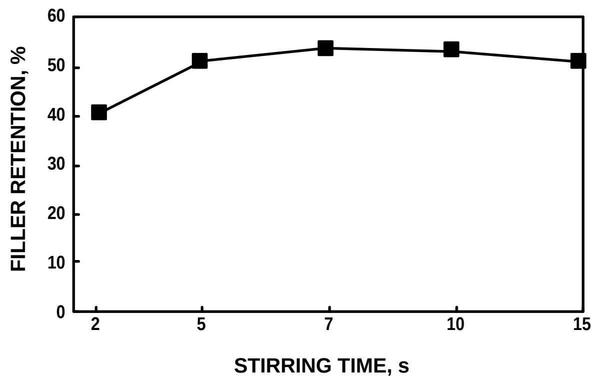
The mechanisms by which flocculation affects dewatering are well known but not quantitatively documented. Furthermore, we evaluated the effect of keeping the pressure difference constant and evaluating dewatering performance. These results are discussed later in the paper.

Different levels of dewatering are attained depending on the suction profile used. So far it has been nearly impossible to simulate the dynamic dewatering phenomena of a paper machine in laboratory conditions. The greatest shortcoming has been the lack of a high-vacuum pulsation rate, typical of any paper machine, requiring very short suction pulses. For example, on a machine running at 1500 m/min, the web is affected by suction pulses with durations of only a few milliseconds.

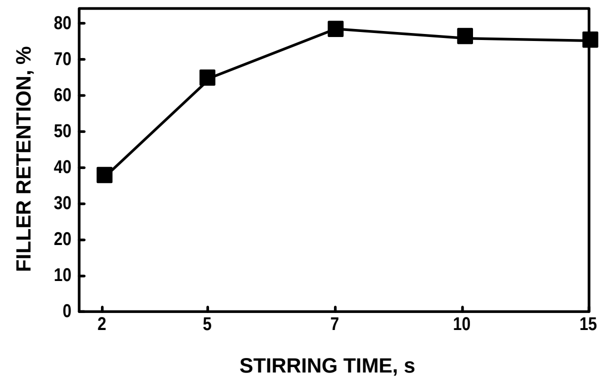
## The moving belt drainage tester

The moving belt drainage tester (MBDT) (**Fig. 1**) was first introduced at the TAPPI 1992 Papermakers Conference *(3).* Its essential features are a very high vacuum pulsation rate (up to hundreds of pulses per second), short individual suction pulses (2 ms or less), a computer-controlled adjustable suction profile, and the scraping of the underside of the wire. During its operation, the pressure differential over and airflow through the formed sheet are measured. Computer-controlled addition and mixing of retention aids is also provided. The *z*-direction filler distribution was studied to determine whether it is possible to influence the sheet structure by changing the pulse frequency. The results presented in **Fig. 2** show that a sufficient pulse frequency is needed to produce a *z*-direction sheet structure that is similar in filler distribution to that obtained on a fourdrinier. This result suggests that the MBDT is capable of imitating the mechanical effects in fourdrinier forming that determine the *z*-direction distribution in the sheet. The computer control enables accurate timing of the chemical injection and

**3.** Filler retention at various stirring times with the MBDT




**4.** Filler retention at various stirring times with the RPA *(5)*




regulation of the mixing and shear forces prior to forming, both important for relevant simulation.

## Experiments and results

All the experiments of this study, unless otherwise noted, were made with a 50/50 mixture of a bleached hardwood/softwood kraft, beaten to a Schopper-Riegler value of 30. The sheet grammage was 80 g/m$^2$. Note that the furnish composition and grammage are typical of woodfree fine paper. The vacuum pulse rate was 75 pulses/s, unless otherwise noted.

### The influence of retention aid dosage on the solids content and formation of the sheet

The aim of these experiments was to observe the effect of formation on the airflow through the sheet and its final solids content, under a constant pressure difference. Different amounts of retention aid were added. The forming and dewatering conditions were kept constant. Calcium carbonate (40% with a particle size less than 2 μm and 99% less than 9 μm) was the filler, and the retention aid was long-chain, middle-charged cationic polyacrylamide. The wet sheet was weighed, dried, and then reweighed to determine the solids content. The formation was measured by an Ambertec beta formation meter. Refer to **Table I** for the parameters and test results.

According to this table, poor formation correlates with increased airflow though the sheet. Despite the increased airflow, the solids contents were about same. This indicates that only the pressure difference is essential for water removal. In this experiment, the vacuum level was only 12 kPa.

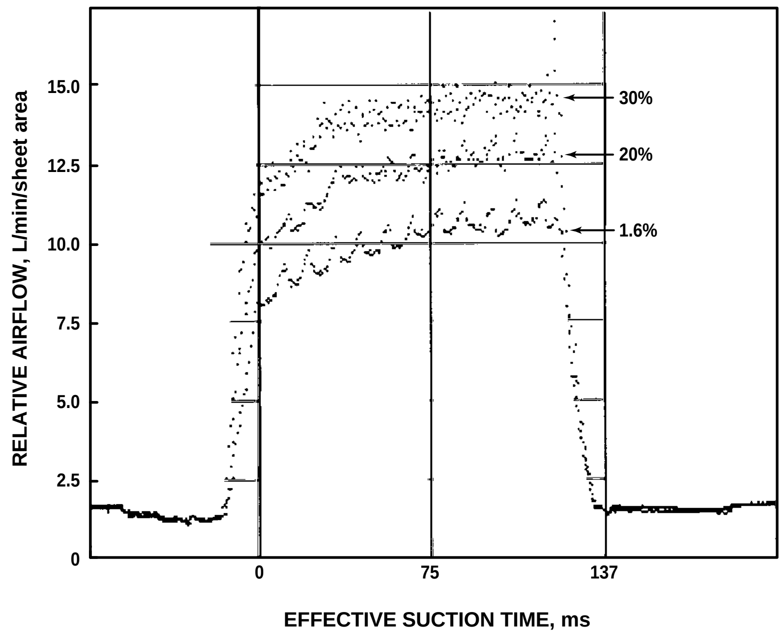
**II.** Effects of stirring time on retention, drainage, and airflow through the sheet

| *Stirring time, s* | *Filler retention, %* | *Solids content, %* | *Contents of filler in the sheet, %* |
|---|---|---|---|
| 2 | 40.9 | 22.0 | 12.2 |
| 5 | 50.8 | 21.9 | 15.2 |
| 7 | 53.4 | 22.3 | 16.0 |
| 10 | 53.0 | 22.3 | 15.9 |
| 15 | 50.7 | 22.8 | 15.2 |

### The effects of shear forces and their application time on retention and vacuum-assisted drainage

The point at which retention aids are injected into the process strongly affects the performance of the chemicals. Depending on the addition point, the chemicals and pulp slurry are subjected to different types of shear forces, and the resulting retention varies. We evaluated differences in dewatering by varying the stirring time prior to drainage. The retention aid was added after homogenization of the pulp slurry. After the addition, the slurry was stirred at 800 rpm for 2–15 seconds. From the beginning of the drainage to the dry

**5.** Airflow through the wet sheet containing different percentages of filler content




**III.** Effects of filler content on air permeability and solids content after the high vacuum

| *Filler content, %* | *Air permeability, L/min/sheet area* | *Fiber specific solids content,%* |
|---|---|---|
| 1.6 | 11.0 | 24.3 |
| 20 | 12.5 | 22.3 |
| 30 | 15.0 | 21.2 |

line, the vacuum was slowly increased to 5 kPa; after that it was raised rapidly to 40 kPa. The filler retention, solids content, and airflow through the formed sheet were measured. Refer to **Table II** for the parameters and the results.

The solids contents are fiber specific; the weight of fillers is subtracted from the total sheet weight. This is done because the filler does not bind the water in the same way as the fibers. If the filler weights were not subtracted, the solids contents would indicate the changes in filler retention rather than changes in dewatering.

**Figure 3** shows the effects of the stirring time on retention. With the shortest stirring time, there is insufficient time for mixing, and the retention remains poor. When increasing the stirring time, the optimum level is attained, and after that the shear forces begin to destroy the polymer bridges between the filler particles; this is reflected in the decreasing retention. The result concurs with the flocculation theory of the long-chain, middle-charged cationic acrylamides *(4).*

**Figure 4** shows a similar retention curve made by a modified dynamic drainage jar tester called the retention process analyzer (RPA) *(5).* The differential between the lowest and highest retention value is greater with the RPA than with the MBDT. This is probably due to the sheet forming that takes place in the MBDT but not in the RPA.

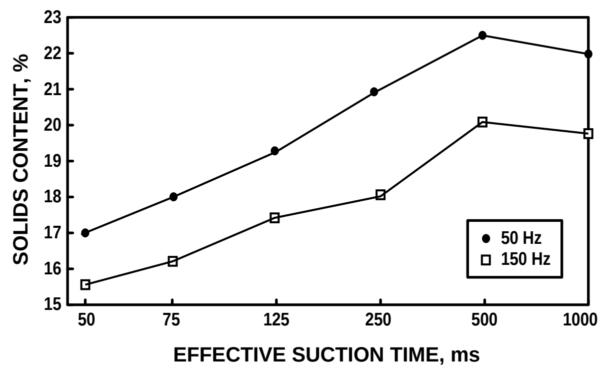
## The effects of filler content on air permeability and vacuum-assisted water removal

Tanaka *et al. (6)* have discussed the effects of retention on *z*-direction distributions. They found that more uniform fines and filler distributions result in better retention. They also provide data concerning the dewatering and air permeability of test sheets that contained different amounts of filler. However, it is difficult to draw any definite conclusions based on these results. In general, little data are available on the effect of fillers on wire-section dewatering. Springer *(7)* has shown that fillers increase the specific filtration resistance value. In this work, the experiments were made using a tester that was incapable of generating the required high suction pulse rates. The results may have been different if rapidly pulsating vacuum had been available for tests.

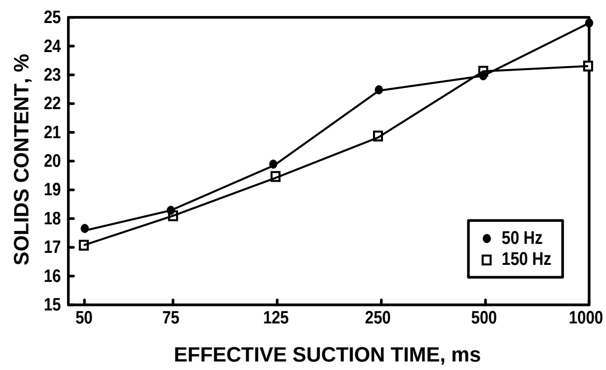
To further explore high-vacuum dewatering and the effects of fillers on the air permeability of the wet sheet, experiments were made with different amounts of filler: 1.6, 20, and 30%. The amount in the sheet was controlled by overdosage and by adding retention aids, and the grammage was kept constant. For this reason, the amount of fibers was decreased when increasing the filler content. After gentle initial dewatering, a vacuum of 40 kPa was applied. During the test, the airflow through the sheet was measured, and at the end of the test, the solids content was measured. The results are shown in **Table III**.

**Figure 5** shows the airflow curves for these three filler levels. In this figure, the highest content is combined with the highest airflow and the smallest fiber-specific solids content. The increased permeability achieved while increasing the filler content can be explained by the

**6.** Dewatering curves for 20 kPa of suction




**7.** Dewatering curves for 30 kPa of suction




**IV.** Effect of pulse frequency on solids content and retention

| *Pulse frequency, Hz* | *Pulse time, ms* | *Time between pulses, ms* | *Total time, ms* | *Solids content in the end, %* | *Retention, %* |
|---|---|---|---|---|---|
| 80 | 1.6 | 12.5 | 500 | 23.5 | 57.4 |
| 120 | 1.0 | 8.3 | 500 | 24.1 | 52.7 |
| 150 | 0.8 | 6.7 | 500 | 24.8 | 45.7 |

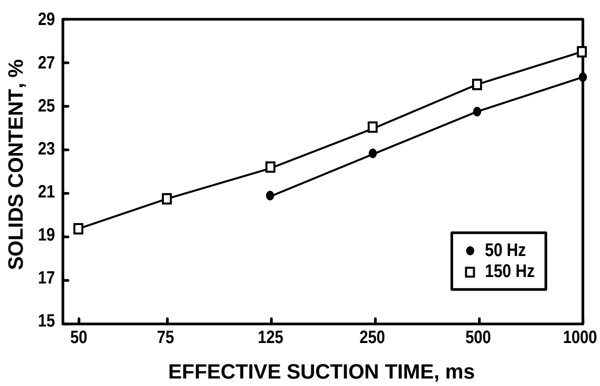
looser fiber network. The filler used evidently fills the pores in the network and penetrates between the fibers, thus increasing the permeability of the sheet.

## The effect of the suction pulse frequency on the retention and solids content

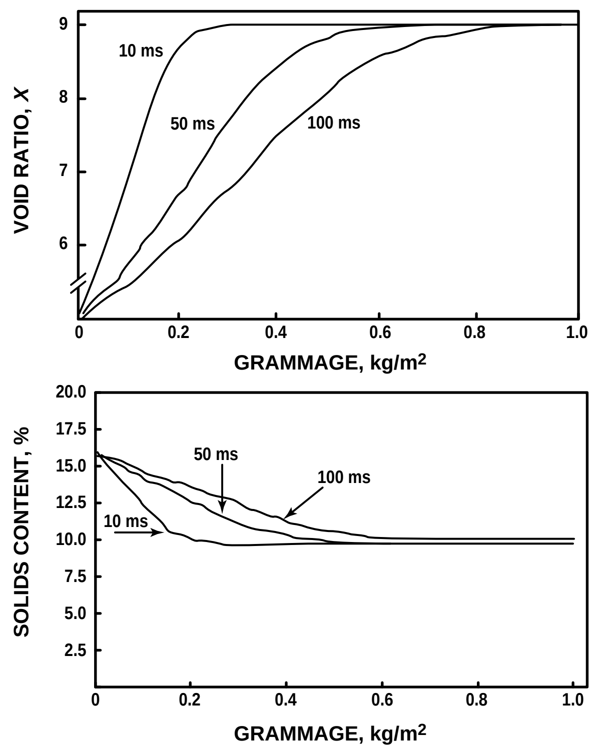
On a paper machine, the strong pulsation caused by the foils helps water removal and hinders retention. The stronger the pulsation, the looser and more open the web structure. The difference between continuous or slowly pulsating suction and rapidly pulsating suction evidently originates from the differences in the degree of compaction of the fiber mat. Continuous suction compacts the fiber mat, particularly the layer closest to the wire. This enables more effective entrapment of fines and fillers, and retention improves compared to the looser network structure caused by the pulsating vacuum.

The suction pulse frequency and the duration of the pulses are easy to vary with the MBDT. Conventional dewatering testers are incapable of producing equally short suction pulses with high frequencies. The test in which the duration of single pulses was varied *(1)* indicated such effects, but at that time the vacuum used was fairly low, and the pulsation frequency was constant. Therefore, we evaluated whether the previously mentioned effects of pulsation on retention and dewatering can be observed. In this test series, three pulse frequencies were used: 80, 120, and 150 pulses/s. The durations of each pulse and the time between them became shorter with increasing pulse frequency. After gentle sheet forming with low

**8.** Dewatering curves for 40 kPa of suction




**9.** The propagation of a compression pulse. Void ratio (upper) and solids content (lower) at 10, 50, and 100 ms after the beginning of the pulse. Suction strength is 30 kPa.




vacuum, a vacuum of 40 kPa was applied. The total suction time is constant, and thus the effects of different suction profiles can be compared. After each test run, both the final solids content and filler retention were measured. They are shown in **Table IV** along with the test variables.

According to this table, the higher the pulse frequency, the poorer the retention and the higher the solids content. These results agree well with the observations on a paper machine. The exact mechanisms of increasing the pulse frequency and the roles of the pulse length and the time between the two pulses, however, are unknown. A rule of thumb *(4)* for the vacuum levels and suction box covers is that, in wet suction boxes, the width of the slots should be about twice the width used in the dry end. The experiments in Ref. 3 and those presented above were done to shed more light on this phenomenon, but they provided an insufficient basis for clearly defining themechanism and the effects of pulse variables. New experiments were conducted to further study these factors.

In the new experiments two suction pulse durations (0.8 and 2.4 ms) were used. Because the suction pulse duration was varied by changing the belt speed while the width of the suction slits and the gap between them were kept constant, the pulse frequency and time between pulses also changed. Three different suction levels (20, 30, and 40 kPa) were used, and dewatering curves for each were determined. **Figures 6–8** show the dewatering curves, i.e., the solids contents as a function of vacuum duration. When comparing the curves, for lower vacuum levels, the longer suction pulses give better dewatering. At the highest vacuum level, the short suction pulse produces a higher solids content. These findings suggest that for each suction level there is an optimal pulse duration. With the MBDT, the optimal combinations can be determined for a given pulp.

## An approximate model for the dynamics of water removal during a suction pulse

In this section, we present a rough mathematical model, capable of qualitatively explaining some of the phenomena observed.

**Assumptions.** We assume that water removal takes place in water-saturated patches of the wet web. Therefore, we only consider single-phase incompressible flow in a compressible porous matrix. The compressible porous matrix is considered a continuum. We shall only inspect one-dimensional deformations and flows.

**Mathematical model.** In a recent publication *(8)*, a model for wet pressing was proposed. The equation (slightly modified) is as follows:

$$\frac{\partial X}{\partial t} = \frac{-1}{\mu W^2 S_S^2} \frac{\partial}{\partial y}\left[ K(X)\, P_m'(X) \frac{\partial X}{\partial y} \right] \quad (1)$$

Here $y \in [0,1]$ is the coordinate (based on accumulated fiber grammage) in the thickness direction, $X$ is the void ratio, $t$ represents time, $P_m$ is the mechanical pressure, and $K$ is a dimensionless permeability. The remaining symbols represent constants: $\mu$ is the viscosity, $W$ represents the grammage, and $S_S$ is the specific surface.

The model is similar in form to the nonlinear heat conduction equation:

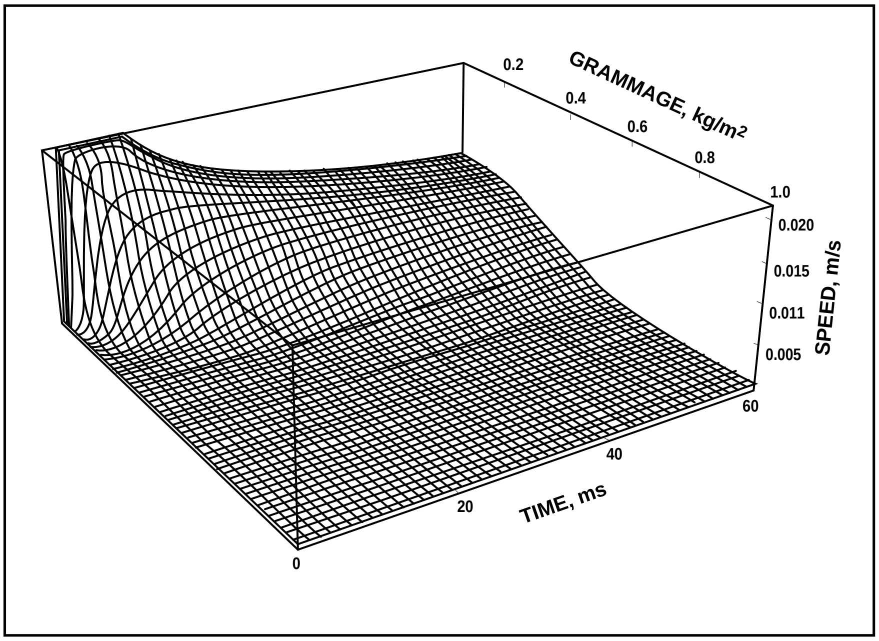
$$\frac{\partial X}{\partial t} = C \frac{\partial}{\partial y}\left[ f(X) \frac{\partial X}{\partial y} \right] \quad (2)$$

in which the conductivity nonlinearly depends on the temperature. Such an equation can be transformed to an ordinary differential equation by assuming a solution of the form $X\{y/(t)^{1/2}\}$. This is known as the Boltzmann transformation, which allows us to treat some simple combinations of boundary conditions with a low-cost numerical solution. Its major restriction in this case is that the solution obtained is only valid for short times, i.e., as long as $X$ remains essentially unchanged at $y = 1$. Moreover, $X$ initially must be uniform over the range of $y$.

In the wet pressing study of Ref. 8, a more elaborate and more flexible numerical solution was presented. In our case, the assumptions of the model are less appropriate, and therefore a similar effort in its solution is not justified.

The details of the numerical solution are provided in the literature *(9)*. The two-point boundary conditions can most easily be satisfied by using an integral equation technique.

**10.** Water flow in the fiber network at the beginning of the suction pulse




**Immediate consequences.** We can evaluate the initial behavior of the wet web with the model presented above. The density (and void ratio) of the fiber mat are constant along lines where $y$ is proportional to the square root of $t$ (clock started at the beginning of the suction pulse). From this the following are apparent:

- The rate of change slows with time, while in the beginning the changes occur very sharply (**Fig. 9**).
- At different (short) times, the shape of $X$ vs. $y$ is exactly the same, although there is some elongation in the $y$ direction. Therefore, the concept of a compression pulse propagating in the fiber mat is correct—this time the propagation takes place by “stretching” and not by shifting with time.
- The amount of water removed is initially proportional to the square root of time. Therefore, the flow rate (time derivative of that amount) is inversely proportional to the square root of time. (However, note that the resistance of the wire and the inertia of the water both limit the initial flowrate.) In the beginning of the suction pulse, the bottom layer of the web experiences a strong throughflow, which decreases with time. The greater the distance from the wire side, the later the maximum flow rate occurs, and this maximum value decreases (**Fig. 10**). The retention profiles observed in practice, namely filler washed out from the wire side, qualitatively agree with our image of the development of flow velocity.

A rough linearization of the nonlinear heat equation is obtained by replacing $f(x)$ with $f(X_{ave})$, where $X_{ave}$ is the average of the initial state and that corresponding to the maximum mechanical pressure (i.e., the suction strength). Such a linearized equation is easy to solve, and the result is of the form:

$$X\left[ \frac{y}{\sqrt{f(X_{ave})t}} \right]$$

Time $t$ is scaled by a factor dependent on the average $X$, or the boundary conditions. In practice, this means that the propagation speed of the compression pulse depends both on the initial state and the compressing pressure difference. A rough calculation, with the compressibility and permeability models presented in connection with the wet pressing study, shows that, with higher suction strengths, the pulse propagation is more rapid.

Considering pulsating suction, when the first suction pulse ends, the bottom layers are compressed. Now they act like compressed springs, trying to expand and sucking water from the upper layers. Given enough time, this would lead to a uniform density profile. Qualitatively, the bottom layers lose water, get compressed, and plug the flow during the suction pulse; after that, they again take on water from above in preparation for the next suction pulse. They perform a kind of pumping action.

The difference between fast and slow pulsation should now be apparent. Fast pulses have no time to penetrate deeply through the layers, but they heavily use the pumping action of the bottom layers. Therefore, retention at the bottom is poor, while in the upper layers no sharp pulse beginnings are felt. Slow pulsation reaches farther but is more gentle on the bottom layers of the web.

We may assume that there is an optimal pulsation profile for a given suction strength and furnish, i.e., a suitable combination of the stages in the pumping cycle that best removes water. Such an optimal pulsation would then correspond to some form of compression profiles. But since these compression profiles advance more rapidly with stronger suction, the cycle time with the optimal profiles should be shorter with stronger suction. This idea, although only vaguely justified by the rough theory presented, matches well with both our experimental results and the rule of thumb for the design of suction box covers.

**Criticism.** The elementary model presented here has several shortcomings. Airflow is neglected altogether, motion of fines or fillers is not accounted for, and continuum approximation and uniformity in the plane of the web are assumed. Moreover, the calculations are one-dimensional, neglecting machine-direction flows altogether. However, the rough model presented is relatively simple to understand and use, and it matches the observations qualitatively (see Figs. 6–10).

## Conclusions

Several different tests were conducted to better understand the high-vacuum dewatering. In particular, the air permeability of the wet fiber mat was examined. Also, the dynamics of dewatering and the influence of the web structure on air permeability were studied.

The observations suggest that water removal by vacuum is mostly due to compression of the web, while airflow at most marginally removes water. The airflow is only a side effect of the pressure difference imposed, coupled with the air permeability of the web. The air permeability has no direct correlation to dewatering.

If the grammage of the web is held constant while increasing the filler content, the air permeability of the wet web will increase. The shear forces prior to sheet forming clearly affect retention but have a lesser effect on vacuum dewatering. The results on the dynamics of dewatering indicate that, for each vacuum level, there is an optimal pulse duration for a given furnish. The duration can be determined with the MBDT. ■

## Literature cited

1. Räisänen, K., Karrila, S., and Paulapuro, H., *TAPPI 1993 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, p. 103.
2. Campbell, B. W., *Pulp Paper Mag. Can.* Convention Issue:48(3):103(1947).
3. Karrila, S., Räisänen, K., and Paulapuro, H., *TAPPI 1992 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, p. 275.
4. Anon., *Pulp and Paper Manufacture, Vol. 7, 3rd edn.*, (B. A. Thorp and M. J. Kocurek, Eds.), Paper Machine Operations, Joint Textbook Committee of the Paper Industry, TAPPI/CPPA, Montreal, 1991, pp. 168, 201.
5. Cheng, Z., Saharinen, E., and Paulapuro, H., *TAPPI 1993 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, p. 15.
6. Tanaka, H., Luner, P., and Côté, W., *Tappi* 65(4): 95(1982).
7. Springer, A. and Kuchibhotla, S., *TAPPI 1992 Papermakers Conference Proceedings*, TAPPI PRESS, Atlanta, p. 533.
8. Jönsson, K. and Jönsson, B., *AIChE Journal* 38(9): 1349(1992).
9. Paulapuro, H., Räisänen, K., and Karrila, S., Finnish Pulp and Paper Research Institute, Helsinki, Finland, RAINA (WEB) Research program, Report 14, "The effects of suction on dewatering and structure of a wet web on a paper machine wire section" (in Finnish), 1993, p. 23.

The support by the Energy Department of the Finnish Ministry of Trade and Industry is gratefully acknowledged. We would also like to thank Krista Nukarinen for meticulous laboratory work.

Received for review Dec. 21, 1993.

Accepted Nov. 7, 1994.

Presented at the TAPPI 1994 Papermakers Conference.