A new vacuum pulsation drainage procedure for determining fine particle retention

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ABSTRACT *Our standard laboratory technique of using gravity drainage to determine fine particle retention was modified by a vacuum pulsation device to simulate more accurately the drainage process on a fast paper machine. This device causes pulsed disruption of a forming fiber mat and reduces both pulp fines and filler retention in the final wet sheet, reflecting fines and filler losses resulting from the rapid movement of the wire over table rolls or stationary foil supports. This drainage procedure has added credibility to laboratory studies designed to predict effects on high-speed commercial machines.*

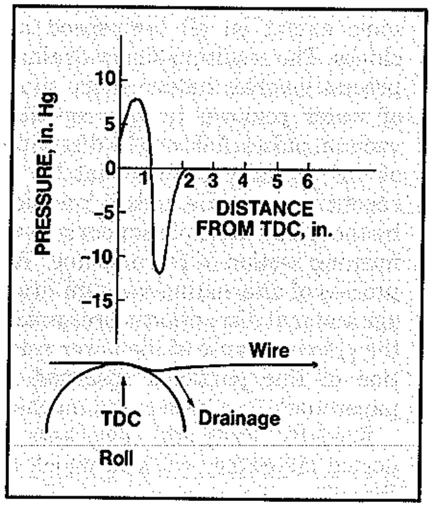
KEYWORDS
Drainage
Filler
Fines
Formation
Retention
Water removal

Modern high-speed paper machines often experience severe losses in fine particle retention (*1*). These losses are caused by a pressure–vacuum pulsation drainage effect produced by the rapid movement of the wire over table rolls or stationary foil supports. Our standard laboratory procedure for measuring fine particle retention, which involves mat formation using gravity drainage (*2, 3*), has sometimes given much higher retention values than observed on the machine itself. To bring our laboratory results into better agreement with commercial papermaking findings, we felt it necessary to simulate more carefully the special drainage process that occurs on these relatively fast fourdrinier machines.

An excellent monograph by J. D. Parker describes the sheet-forming process on paper machines in great detail (*4*). Parker distinguishes between the continuous draining, or "filtration," process and a slurry or "thickening" drainage process that becomes prominent when a commercial fourdrinier machine is run at high speeds. In essence, the thickening drainage mode involves frequent interruptions of the continuous drainage process of a slow machine, so that the pulp slurry increases in consistency as the water drains through the wire. The thickening mode of drainage is produced by a pressure–vacuum pulse that develops when the fourdrinier wire moves rapidly over supporting table rolls or foils, as shown in **Fig. 1**.

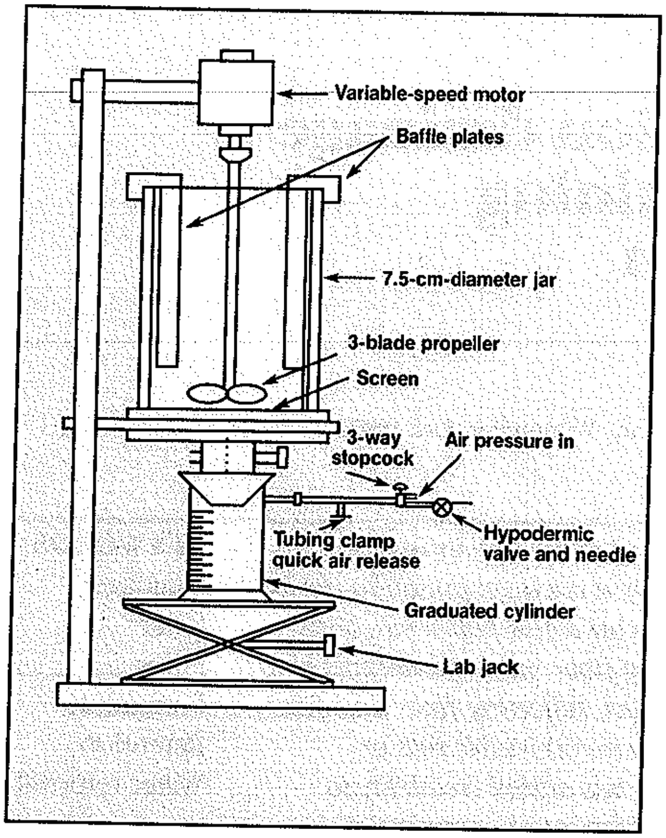
The pressure profile measured at a table roll surface shows the development of a positive upward pressure pulse where the wire passes over the top dead center point (TDC) of the roll. This pulse is caused by water being forced up through the partially formed mat at this "upstream" location. Most of the water drainage occurs at the trailing edge of the roll and is caused by an intense vacuum pulse (negative pressure) at this "downstream" location. Several fundamental studies have contributed to our understanding of pressure–vacuum pulsation drainage for high-speed machines (*5–8*). Many other pertinent studies of the mechanism of sheet formation are cited in the Parker monograph (*4*).

1. Pressure profile at wire over a table roll

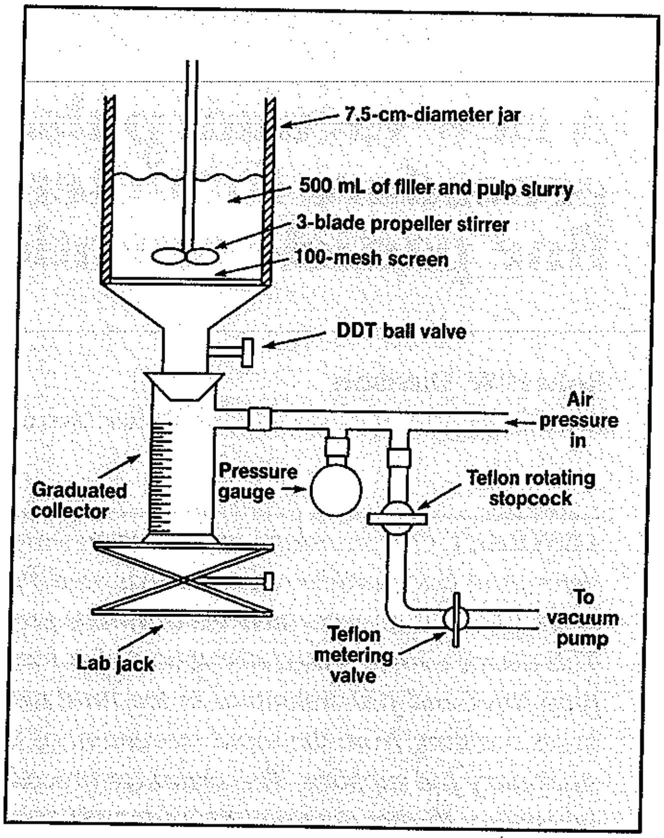


The pressure–vacuum pulse produced by the rapid movement of the wire over table rolls is intensified by increasing the machine speed, but this effect is moderated by the use of fixed

2. Modified Hercules Dynamic Drainage Tester



3. Dynamic Drainage Tester modified for vacuum pulsation



foils in place of table rolls. Regardless of the type of wire supports, however, the pressure–vacuum pulse persists to some extent on all high-speed machines. The resulting slurry drainage process involves sudden sharp spurts of water removal by the repetitive vacuum pulses, followed by disruption of the partially formed mat by the repetitive pressure pulses produced by the wire's multiple supports in the forming section of the machine. This process of alternating vacuum drainage and mat disruption is presumably the primary cause of the lower retention of fine particles observed for paper made on a high-speed machine.

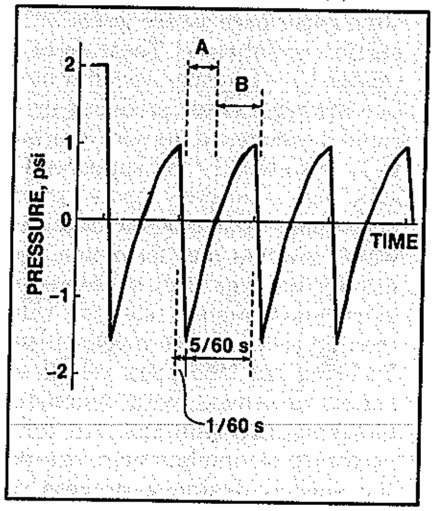
Recently, Britt and coworkers reported laboratory work in which the filtration and thickening modes of slurry drainage were controlled by applying either a constant vacuum or alternating pressure–vacuum pulses (*9*). The researchers measured the effects of these two drainage processes on both drainage rate and fines retention for a newsprint headbox stock. They found that the thickening mode favored fast drainage but low retention of fines, while continuous filtration reduced the drainage rate but increased fines retention.

Thus, we decided to modify our standard approach using gravity drainage and determine fine particle retention by a vacuum pulsation device, to simulate more realistically the drainage process and resulting low retention of pulp fines and mineral filler that are observed on many high-speed paper machines.

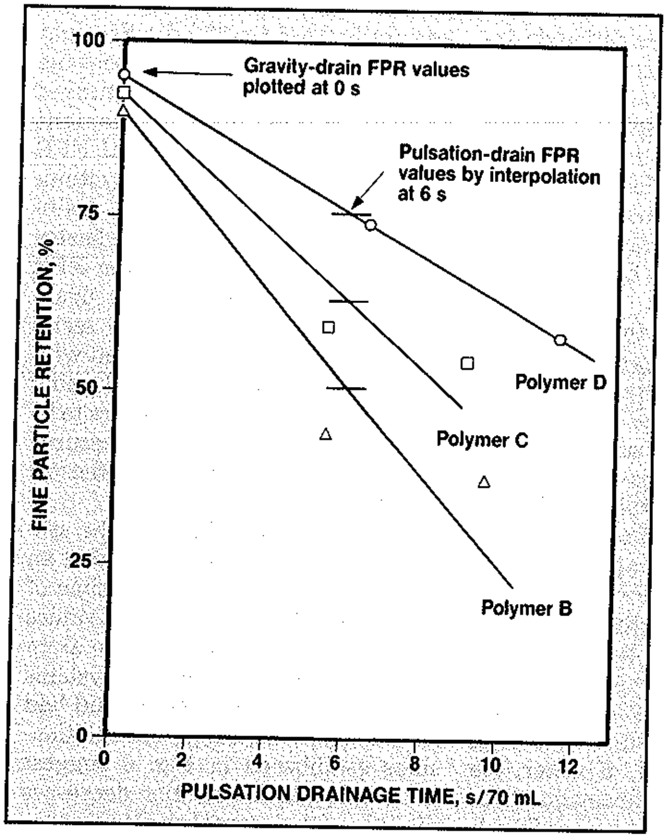
Equipment and procedure

The modified Hercules Dynamic Drainage Tester (DDT) is shown in **Fig. 2.** A variable-speed stirrer with a three-blade propeller located 6 mm above a 100-mesh screen in the bottom of the jar is rotated at 500–1500 rpm to provide high-shear turbulence in a 0.5-L aliquot of filler and pulp slurry. Two baffle plates break up the stirring vortex. A small air flow is applied underneath the screen to give an upward percolating effect that prevents premature slurry drainage. After the slurry is treated with the desired chemical agents, rapid gravity drainage and mat formation are initiated by stopping the stirrer and simultaneously opening the quick-air-release clamp shown near the bottom of the figure. The amount of drainage water collected determines the basis weight of the mat formed on the screen. Rapid gravity drainage of about 70 mL from a 0.4% wood pulp

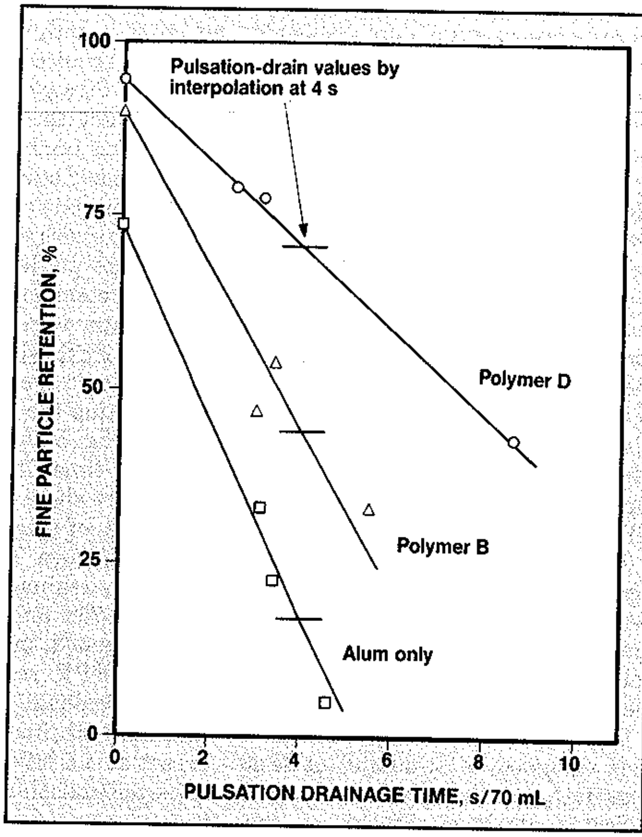
4. Pressure–vacuum pulsation with phases of mat forming (A) and mat disruption (B)



5. Graphical determination of pulsation-drainage FPR



6. Gravity drainage vs. pulsation drainage retention for a simulated printing-grade furnish



slurry will produce a mat of 65 g/m² basis weight in 1-2 s.

The DDT also provides for slow drainage with continuous stirring, but no mat formation. This procedure is used to determine the total fine particle content (pulp fines and filler) of the slurry being studied. The total fine particle content is the reference base from which the percent fine particle retention (FPR) is calculated for runs involving mat formation. The equipment and procedures used in this method of rapid gravity drainage and mat formation have been described in detail in recent publications (*2, 3*).

For use in pressure–vacuum pulsation runs, the equipment in Fig. 2 was further modified by replacing the quick-air-release line with a pulsating vacuum line and a pressure gauge, as shown in **Fig. 3**. (Certain equipment components shown in Fig. 2, such as the baffle plates, were left out of Fig. 3 to simplify this diagram.) The vacuum pulsation modification consists of a 4-mm Teflon plug stopcock, rotated at 300 rpm, and a metering stopcock designed to control the amplitude of the vacuum pulses. These pulses are superimposed on the constant positive air flow through the DDT assembly. Thus, the net strength of the pressure-vacuum pulse (peak-to-trough) is controlled by the air flow rate vs. the vacuum pulse amplitude and frequency. We found that the most satisfactory conditions for pressure–vacuum pulsation experiments involved the following:

1. An air flow rate of about 9.5 L/min up through the DDT equipment, established by 2-psi air pressure supplied by the house-compressed air supply
2. A rotating stopcock speed of 300 rpm
3. Adjustment of the metering stopcock to provide a pressure–vacuum pulse having a peak pressure of not more than 1 psi and a trough value of about -1.5 psi.

For pressure–vacuum pulsation drainage runs, it is imperative that no air leakage occur in the assembled equipment. Any air leak can grossly affect the delicately balanced pressure–vacuum pulse profile and lead to erroneous retention results. With 500 mL of water in the DDT jar, we first established a pulsation drain time of 3-5 s per 70 mL of water drainage, before carrying out fine particle retention runs using the pulsation drainage procedure.

The pressure–vacuum pulsation technique applied rapidly alternating positive and negative pressure pulses to the slurry above the screen in the DDT jar, as shown schematically in **Fig. 4**. Since a vacuum pulse is superimposed on the constant air flow through the equipment once for every 180° rotation of the stopcock, 300 rpm rotation of this stopcock produces 10 pulses/s. Under these conditions, the positive peak of each pulse reaches a value of not more than 1 psi, while the trough produced by the vacuum pulse is between -1 and -2 psi.

These peak and trough values are estimates based on careful observation of the rapid fluctuations between positive and negative pressure values for the gauge mounted in the equipment. The 4-mm bore of the rotating stopcock represents about 1/12 of the stopcock plug circumference, so the air flow period (no vacuum imposed) per pressure–vacuum pulse is about 5/60 s, while a vacuum pulse is applied during 1/60 s. The periods of the resulting positive and negative pressure pulses applied in pulsation drainage runs are shown near the top of Fig. 4. During the period when the pressure on the system is less than zero (i.e., below atmospheric pressure), slurry drainage and mat formation proceed by normal gravity drainage. However, during the period when the pressure is positive, air flows up through the screen and tends to disrupt the partially formed mat. Then the alternating process of mat formation and mat disruption starts all over again.

This pulsing process of mat formation and disruption repeats itself 10 times per second, until the desired amount of drainage water has been collected. Drainage is then stopped by closing the equipment ball valve.

The pulsation drainage procedure was designed to simulate, at least qualitatively, the pressure–vacuum pulsation drainage process as produced on fast paper machines. The loss of fine particles experienced on these machines should be duplicated, in principle, by a reduction in FPR values obtained by pulsation drainage experiments conducted in the DDT, as compared with FPR values obtained under continuous gravity drainage.

Retention results for pulsation vs. gravity drainage

The graphical determination of fine particle retention values for the pulsation drain process is shown in **Fig. 5** for a bleached kraft pulp slurry containing 20% clay filler. A portion of this slurry was added to the DDT jar, stirred at 1000 rpm, and treated with alum to establish a system pH of 4.4. We then added 0.0375% (0.75 lb/ton) of one of three commercial cationic retention aids (designated as Polymers B, C, or D) and allowed 10 s of contact time before initiating either the gravity drainage or the pulsation drainage process to form a 65-g/m^2 mat on the screen.

Gravity-drainage FPR values were 90–95% and were plotted at 0 s of pulsation drainage time in Fig. 5, because a gravity-drainage FPR value results from draining with no pulses being applied. Pulsation-drainage FPR values were plotted in accordance with the pulsation drainage time required to produce 70 mL of water. Straight lines were drawn to represent the pulsation-drainage FPR values produced for each of the three cationic agents tested, with the restriction that each straight line had to originate with the gravity-drainage FPR value produced by the corresponding retention aid.

A comparison of the pulsation-drainage FPR values produced by the three cationic agents was obtained by interpolating the three experimental lines in Fig. 5 at the same pulsation drainage time. In this example, we arbitrarily chose a drainage time of 6 s/70 mL of slurry drainage water, for convenience. This approach gave pulsation-drainage FPR values of about 51–75% for the three retention aids evaluated, much lower than the 90–95% FPR results obtained by gravity drainage runs. Although the pulsation drainage time had been preset at 4.5 s/70 mL of water, the experimental slurry drainage times ranged from 5.5 s to 11.5 s per 70 mL of water. Also, the pulsation-drainage FPR values produced with Polymers B and C appeared somewhat erratic.

We concluded that our pulsation drainage procedure seemed to be in a state of "metastable equilibrium," delicately balanced between the constant air flow and the intermittent vacuum pulsation forces. By empirically adjusting the various parameters involved, we were able to reduce this erratic behavior in later pulsation-drainage retention runs.

For the work summarized in **Fig. 6**, we carefully preset the pulsation drain time to provide a value of 3 s/70 mL of water. The inexpensive printing grade system simulated here contained about 64% groundwood and 36% bleached kraft in the furnish and about 5% clay filler. Alum was added in each DDT run to reduce the slurry pH to 5.1. We then compared the effects of post-adding 0.75 lb/ton of cationic polymer B or polymer D, vs. the FPR result obtained for the alum-containing control. As shown in Fig. 6, alum alone produced 73% FPR, while the two polymeric retention aids increased FPR values to 90–94%, for gravity drainage experiments.

Introducing the pulsation drainage procedure caused serious reductions in FPR values, depending on the pulsation drainage time for the run (generally 2.5–5.5 s/70 mL). Straight lines drawn in Fig. 6 to represent the three chemical systems studied showed rather good agreement among the three experimental FPR values obtained for each system, probably because the pulsation drainage times are considerably shorter than those in Fig. 5. Even the FPR value for the relatively long drain time (8.6 s) in the Polymer D series of runs seems in good agreement with the other two values obtained using Polymer D. This system appears to be a considerably more stable pressure–vacuum pulsation system than the one summarized in Fig. 5.

Pulsation FPR values for the system in Fig. 6 were interpolated at an arbitrary pulsation drainage time of 4 s per 70 mL of water. These values ranged from about 16% for the alum control run to 44–71% for the systems to which a cationic retention aid had been added. The straight line relationships established in Fig. 6 suggest that fine particle retention decreases directly with the number of pressure–vacuum pulses impressed on the screen and slurry. Thus, interpolated FPR values at a pulsation drainage time of 4 s/70 mL represent the severe erosion effects suffered by the imposition of 40 pressure–vacuum pulses during slurry drainage and mat formation.

Note that the pulsation drainage procedure tended to exaggerate the differences in the relative effectiveness of the polymeric retention aids compared in Figs. 5 and 6. This exaggeration may indicate that the pulsation drainage procedure is a more sensitive test of small differences in the relative strengths of fine particle flocs formed by the various retention agents.

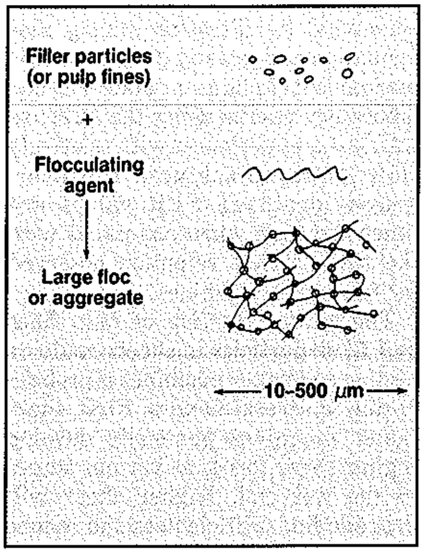
Still another comparison of gravity drainage and pulsation drainage is summarized in **Table I**, for FPR values obtained using a simulated headbox slurry for a mill producing reprographic paper. This system involved diluted mill bleached kraft stock to which we added about 30% filler, based on dry pulp. Portions of this slurry were treated in the DDT jar with alum to a system pH of 4.5, followed by 0.5 or 1.0 lb/ton of one of three cationic retention aids. Table I shows that comparisons ranked Poly-

I. Retention by gravity vs. pulsation drainage using a simulated mill headbox slurry

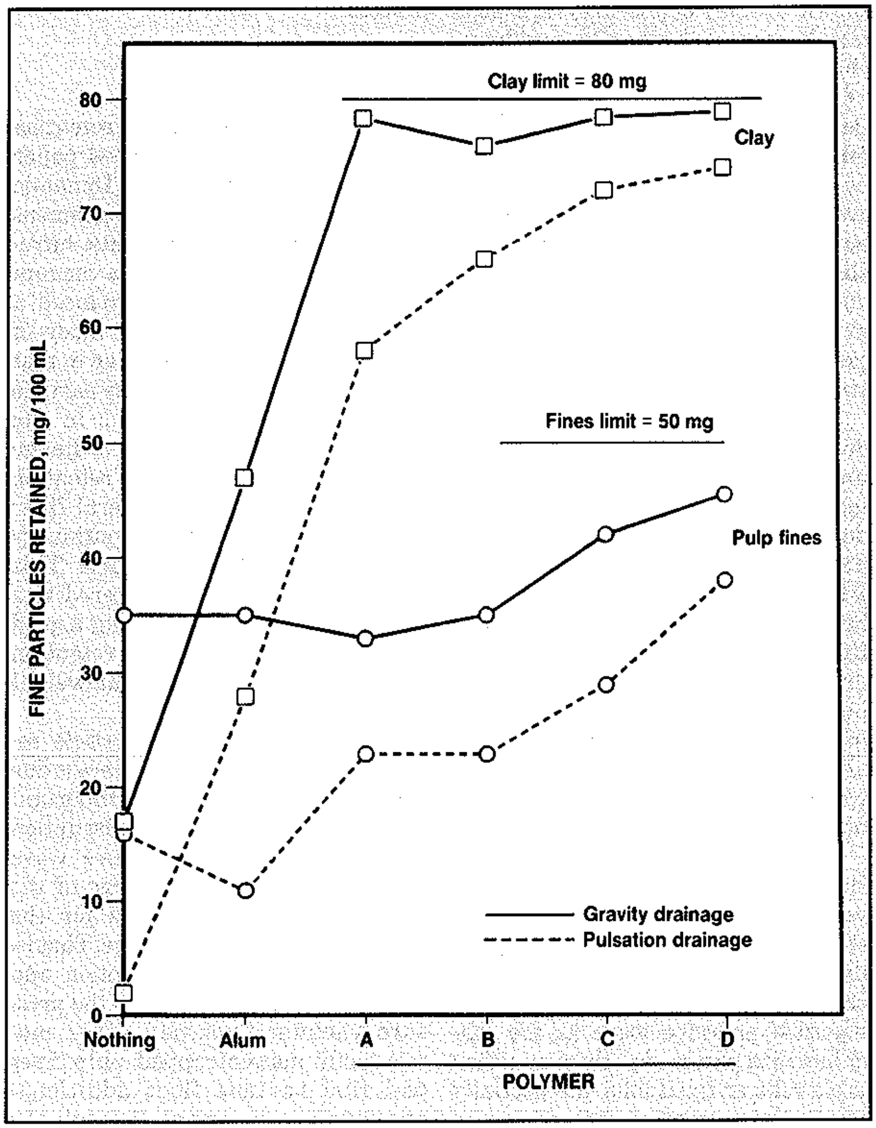
	FPR, %	
	Gravity	*Pulsation*
Polymer D		
0.5 lb/ton	80.2	59.3
1.0 lb/ton	...	68.0
Polymer C		
0.5 lb/ton	75.6	53.5
1.0 lb/ton	...	68.2
Polymer B		
0.5 lb/ton	74.3	59.5
1.0 lb/ton	...	68.2
None	28.5	23.6

System: 0.42% mill furnish, 0.13% added filler, 0.5% alum to pH 4.5, 1500 rpm stirring speed.

8. The fine particle flocculation process



7. Fine particle erosion during pulsation drainage for six different conditions



mers B, C, and D in the same order for both drainage procedures. This result is typical for these experiments.

The FPR values in Table I also show that although pulsation drainage severely reduced retention, much of this loss could usually be recovered by using more retention aid. In other words, using more of the fine particle floc binding agent reduced the loss in FPR. This effect suggests that a vertical shear floc degradation effect, presumably produced by the pulsation drain procedure, may be partly responsible for the observed reduction in fine particle retention in a forming mat.

Analysis of pulsation drainage effects on retention

To compare further the fine particle retention in a mat produced by the gravity drainage process with retention as affected by the pulsation drainage process, we carried out DDT retention runs using a 0.4% bleached kraft pulp slurry containing 20% clay filler at pH 5. The results are summarized in **Fig. 7**, where the weight of fine particles retained is plotted against six different system conditions: with alum, with each of the four polymers, and with no additive.

The ash contents of the drainage water solids for all runs were determined, so that the effects of these DDT experiments on pulp fines retention and clay filler retention could be displayed separately. Since each 100 mL of the clay-pulp slurry contained 80 mg of clay and 50 mg of pulp fines, these values represent the limits for clay and fines retention in a formed fiber mat.

When mat formation was carried out in the absence of any chemical additive, about 70% of the pulp fines (35 mg/100 mL) was retained in a mat formed by the gravity drainage process, as well as slightly more than 20% of the clay (17 mg/100 mL). This percentage of pulp fines retention arises from entrapment of the larger fines by filtration during the formation of the fiber mat. The clay retention is probably due to entrainment of filler particles as the slurry water passes through the long tortuous pores created during the formation of the multilayered fiber mat. When the pulsation drainage process was substituted for gravity drainage, pulp fines retention decreased to about 30% of the 50-mg limit, while clay retention decreased to almost zero. Thus, pulsation drainage severely eroded the retention of both of these fine particle components.

Alum increased clay retention but did not affect fines retention in the gravity drainage runs. This inability to improve pulp fines retention in a mat made from a well-agitated slurry has been reported previously (*10*). Alum does serve as a moderate retention aid for clay filler particles, however. Pulsation drainage reduced the amounts of both clay and fines, demonstrating again, with alum, the severe erosion of pulsation drainage on fine particle retention.

The post-addition of any one of four commercial cationic polymeric retention aids (designated A, B, C, and D in Fig. 7) generally improved fine particle retention under all conditions. For gravity drainage runs, clay retention was increased to values close to the clay limit of 80 mg/100 mL, with all four retention aids performing well. Pulp fines retention was increased to about 90% by Polymer D, with the other agents performing somewhat less effectively. When these same runs were carried out by pulsation drainage, retention values were seriously reduced in all cases. The reduction in clay retention was particularly severe when Polymer A was used as the retention aid.

The results in Fig. 7 indicate that pulsation drainage caused rather severe retention losses for both the pulp fines and the clay filler components of a filler pulp slurry. These findings are consistent with the observations made for fast paper machines. Thus, we conclude that our DDT equipment and mat formation procedure, as modified for pulsation drainage experiments, does qualitatively simulate a high-speed commercial machine in terms of retention losses.

Factors that reduce retention on fast machines

In rapid gravity drainage of a filler and pulp slurry, the improved retention produced by various high-molecular-weight retention aids is postulated to be due to the formation of large fine particle flocs by the bridging mechanism (*2*). These large flocs, as well as the larger pulp fines, are unattached to fibers in a vigorously agitated slurry, but they become entrapped by filtration during mat formation and gravity drainage. This mechanism explains satisfactorily our laboratory results using the DDT, as well as our experiences with relatively slow paper machines. However, gravity-drainage FPR values are much too high when compared with the fine particle retention observed for fast paper machines.

The lower retention of pulp fines and filler particles in sheets made on high-speed paper machines is probably due to several factors. First, these faster machines generally develop higher shear forces at various stages in the wet end. Higher shear will degrade fine particle flocs and reduce their retention by means of entrapment (*2, 3*). We visualize these bridging flocs as being large, highly water-laden, rather fragile structures, as shown in **Fig. 8** (*3*). They are held together weakly by the adsorbed long-chain bridging molecules of a high-molecular-weight polymeric retention aid. These loosely structured flocs form rapidly but are readily degraded by shear forces in the papermaking system. However, this factor should not cause the retention difference observed between gravity drainage and pulsation drainage in experiments conducted in the DDT with the same slurry and the same high stirring speed.

Second, the vertical shear force developed during the pressure-vacuum pulsation that intensifies with increasing machine speed could also degrade flocs and reduce retention. This factor could explain most of the DDT experimental results reported here. However, the severe loss in pulp fines retention produced by pulsation drainage, as shown in Fig. 7 for an untreated slurry, cannot be explained in terms of floc degradation, because all the fines remained as free, solid, well-dispersed entities in this particular DDT experiment.

A third factor that must be considered is the mode of drainage involved—i.e., continuous filtration vs. slurry thickening. Since the pulsation drainage procedure involves a positive pressure pulse followed by a negative pressure wave as the machine wire passes rapidly over either table rolls or fixed foils, the partially formed mat is somewhat disrupted during each pressure pulse, both on a fast paper machine and in the DDT when subjected to pulsation drainage. During a positive pressure wave, partial mat disruption offers an opportunity for retained fine particles to break loose from their initial entrapment. When the vacuum pulse produces the drainage of more slurry water, these fine particles are given a second chance to escape by passing through the relatively large holes in the screen of the machine or the DDT. To the extent that some fine particles use these extra opportunities of repeated pulsation to escape from the momentarily disrupted mat, retention will be reduced. This third factor is the obvious explanation for the severe loss of pulp fines shown in Fig. 7 for an untreated slurry. It is probably also the predominant factor for explaining the loss in retention of fine particle flocs during the pulsation drainage process.

Summary

To simulate the fine particle retention losses produced by high-speed paper machines, we modified the Dynamic Drainage Tester used for continuous gravity drainage experiments, introducing a device that creates a vacuum pulsation. This addition produced a pressure–vacuum pulsation mode of drainage qualitatively similar to that on high-speed machines. Fine particle retention runs carried out in the laboratory under pulsation drainage demonstrated much lower retention of both pulp fines and mineral filler than runs employing the continuous gravity drainage procedure. This adverse effect can be countered to a considerable extent by adding a good commercial fine particle retention aid, such as a high-molecular-weight cationic polymer.

The reduction in fine particle retention for high-speed machines is due to several factors. The most important is probably partial mat disruption during the positive pressure wave produced at the leading edge of the table roll or foil supports for the rapidly moving machine wire. That is, the alternating mat disruption and vacuum drainage caused by the pressure–vacuum pulsation gives momentarily mat-entrapped pulp fines and fine particle flocs additional opportunities to escape through the relatively large holes in the wire support as the fiber mat forms on it. Incorporating this factor in laboratory studies has yielded results that are more credible with respect to high-speed machines.

Experimental procedures

Materials used

The fiber furnish used for the work reported in Figs. 5 and 7 and as a component for experiments summarized in Fig. 6 consisted of a 3:1 blend of hardwood and softwood, bleached kraft, dry lap pulp. This blend was beaten in demineralized water in a Valley beater to a Schopper-Riegler freeness of 450 mL. The beaten pulp contained 12.5% fines (passed through a 100-mesh screen). For most experiments, part of this slurry was diluted to 0.4% consistency with demineralized water; hardness and alkalinity adjustments were made by adding $CaCl_2$ and $NaHCO_3$, respectively. Many retention experiments involved the presence of 20% kaolin clay filler that was added to several liters of the 0.4% pulp slurry. Aliquots of this slurry were used in DDT retention runs.

Papermakers alum, $Al_2(SO_4)_3 18 (H_2O)$, was used to adjust the slurry pH for most of the retention runs. Fine particle retention was improved by various cationic commercial retention aids, designated as Polymers, A, B, C, and D. These products are all copolymers; they have molecular weights estimated in the range of 8-15 million, and their mole fraction of ionic units is reasonably low.

Equipment and general procedure

The equipment and procedure have been adequately described here. Further details on carrying out runs involving continuous gravity drainage are contained in earlier publications (*2*, *3*). To calculate the percent fine particle retention in a mat formed either by gravity or pulsation drainage, the weight of suspended solids per 100 mL of drainage water was determined gravimetrically, by filtration through a piece of pre-weighed Whatman No. 42 filter paper. Subtracting this solids weight from the fine particle weight per 100 mL of slurry yielded the weight of fine particles (per 100 mL) retained by the fiber mat. This weight, multiplied by 100 and divided by the fine particle solids content of the slurry, then gave the % FPR for the run.□

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