A Novel Ultrasonic Dynamic Drainage Tester

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ABSTRACT

The Dynamic Drainage Jar (DDJ) is commonly used to assess furnish drainage. However, contrary to the drainage process in a commercial paper machine, drainage in a DDJ normally occurs without turbulence because any impeller mixing increases filtration resistance enormously. A novel Ultrasonic Dynamic Drainage Jar (UDDJ) has been developed to simulate the dynamic drainage conditions found in the forming section of a paper machine. In the UDDJ, ultrasound is directly imparted to the Jar, causing it to oscillate and produce turbulence near the screen. The apparatus is able to simultaneously measure drainage, retention, and web porosity. The influence of ultrasound on fines retention and drainage behaviour of a newsprint furnish were investigated at various impeller mixing speeds in the absence and presence of a cationic retention aid. The results indicated that the ultrasonic forces applied in UDDJ were able to prevent blocking of the filtration screen, to deflocculate the pulp, and to create and enlarge dewatering channels in the forming web. As a result, the ultrasound accelerated pulp drainage, reduced fines retention and produced a more porous web. In this manner, UDDJ resembles the drainage elements of a paper machine, although no low frequency pressure pulses were generated. The UDDJ could be a very useful laboratory tool to determine the drainage performance of furnishes and chemical additives under dynamic conditions.

INTRODUCTION

In paper manufacture about 99% of the water in paper furnish is removed in the forming and press sections and the rest is evaporated in the drying section. Although the drying section removes only about 1% of the water, it is the largest energy user in the paper machine. It was reported that each percent of reduction in sheet moisture entering the drying section reduces drying cost by 4-5% [1,2]. In addition, web moisture content determines the strength of the wet web, which in turn affects machine runnability. Therefore, fast drainage is desirable for good paper machine runnability and for decreasing the overall production cost. To promote fines retention and improve paper machine drainage, polymeric additives and other chemicals are commonly used in the machine wet-end. The effectiveness of these chemicals as a drainage aid is often established in laboratory tests prior to any machine trials. Thus, a reliable laboratory drainage tester would be very useful for the development and applications of the additives, and for the optimization of wet-end chemistry.

BACKGROUND

The Canadian Standard Freeness (CSF) tester is often used to characterize pulp drainage. The CSF tester measures the rate at which a pulp with a consistency of 0.3% is drained by gravity [3]. Although CSF is a useful tool for pulp quality control and for comparing pulp stocks, the results obtained with the freeness tester often show little correlation with the drainage of the stock on a paper machine wire. Clark [4] pointed out that the drainage of the thin agitated web on a paper machine wire was affected more by the wet compressibility of the fibers and less by the fines content when compared to the thick and quiescent mat formed in the freeness tester.

Awareness of the freeness tester's limitations led researchers to develop alternative drainage tests to measure drainage under turbulent conditions. In the early 70s, Britt developed the Dynamic Drainage Jar (DDJ) in which, turbulence is introduced by an impeller rotating at a high speed [5]. The DDJ has been proven to be a useful tool to study first-pass retention, and is used in a standard method to determine fines content of paper stock [6]. Due to its simplicity and small specimen requirement, the DDJ is widely applied in the pulp and paper industry. For a drainage measurement, the DDJ is usually modified to allow the application of vacuum beneath the forming mat [7-10]. Several modified DDJ versions are commercially available, for instance, the Dynamic Drainage Analyzer (DDA) produced by AB Akribi Kemikonsulter [11] and the Muteck DFR-40 from BTG Muteck GmbH [12]. Though these devices are claimed to be dynamic drainage testers, the drainage is actually performed under static conditions because the agitation is stopped prior to dewatering [13]. It is observed that the fines retention is higher and drainage is slower when using a DDJ tester compared to commercial paper machines where dewatering proceeds under high turbulence. The lack of turbulence and shear forces in a DDJ causes that the drainage responds to polymeric additives more dramatically than in a paper machine. Thus, although modified DDJ's can provide a rough guide as to how pulp stocks drain, they do not simulate the dynamic drainage conditions in the forming section of a paper machine.

During the initial stage of dewatering in the forming zone of a paper machine, pressure and vacuum pulses are generated by forming foils and rolls. Each pressure pulse disrupts the web structure and opens water passages. The subsequent vacuum pulses wash away fines and accelerate dewatering. To simulate this pressure pulsation, the Moving Belt Drainage Tester (MBDT) was developed at Helsinki University of Technology in the early nineties [14,15] and later modified to allow for the collection of the sheet formed by the apparatus [16]. The MBDT consists of a cogged belt, moving between a stationary forming wire and vacuum box. The moving cogs provide scraping action and upward pulses to the wire above, while the gaps between pairs of cogs act as suction slits. The MBDT imitates the conditions on a Fourdrinier wire more realistically than a conventional DDJ. The z-directional filler distribution of the formed sheet was found to be close to that produced by a Fourdrinier machine. However, the MBDT only monitors a part of the drainage process, giving no information on the initial dewatering stage prior to the wet line. The sheets formed by the MBDT are also much wetter than those leaving the couch of a commercial machine. In addition, the level of turbulence cannot be controlled due to limitations on belt speed [14,15]. Despite these shortcomings, the MBDT represents an appreciable step towards the simulation of dynamic conditions of a commercial paper machine.

Another drainage tester simulating pressure pulsation in the forming section is the Pulsed Drainage Device (PDD) developed by Betz PaperChem [17,18]. Instead of using a moving belt, pulsation is generated by a rotating hydrofoil located directly beneath the circle-shaped wire of the PDD. An inherent drawback of this approach is the non-uniformity of pressure pulsation along the radius of the forming wire. Nevertheless, the PDD method gives a more complete picture than the CSF and DDJ by producing drainage time, vacuum response, retention, and a handsheet in one trial.

Clearly, there is still a need to have an improved laboratory drainage tester which should be able to incorporate turbulence during drainage and overcome the limitations of the existing methods. The objective of this work was to explore a new way of generating turbulence by applying ultrasound energy. This report describes a prototype of an ultrasonic assisted DDJ, and the effect of ultrasound on retention and drainage. It is shown that ultrasound induces additional turbulence and accelerates the furnish drainage rate while avoiding the pitfalls of the conventional DDJs.

Ultrasound and Its Applications

Ultrasound is acoustic waves traveling through a medium at a frequency higher than that which human ears can detect. Frequencies are usually greater than 20 kHz [19]. In a commercial ultrasonic device, ultrasound is generated by a transducer which commonly uses a piezoelectric crystal. The piezoelectric properties make the crystal vibrate when rapid reversing electric charges are applied to it. Absorption of acoustic energy by a fluid could result in acoustic streaming (or fluid flow) and produce turbulence. Apart from acoustic streaming, the fluid is subject to alternating rarefaction and compression cycles resulting from the propagation of ultrasonic waves [20]. At a sufficiently high power, the rarefaction cycle may exceed the tensile strength of the fluid so that a bubble cavity is formed. These ultrasonic effects have been successfully used to disperse particles in liquid and to increase the filtering rate [21]. Ultrasound has been broadly used in cleaning, laboratory mixing, welding, biological cellular dismembrating and sensor technologies, but very rarely in the pulp and paper industry, although some research work has been done. For instance, ultrasound has been considered to enhance recycled pulp deinking, pulp refining, clarification of water streams, and the measurement of pulp consistency and paper stiffness [22]. Jong et al. applied ultrasound to thicken a pulp by redirecting the fibre movement in the flow [23]. Mckay and Aidun employed ultrasonic waves to disrupt fibre mats and to refluidize pulp on simulated forming board in an attempt to enhance dewatering and formation [24].

The Prototype of an Ultrasonic Dynamic Drainage Jar (UDDJ)

The ultrasound-assisted drainage testing apparatus, as sketched in Figure 1, was developed based on a modified DDJ system manufactured by the FPInnovations-Paprican Division. It is composed of a drainage jar, a filtration collecting flask, a vacuum pump, a balance and a computer. The drainage jar consists of an upper plastic chamber and a lower base. The two parts are threaded to fit each other and to hold an ultrasonic filtration screen made of a stainless steel wire of 60-mesh. An ultrasonic horn is connected laterally to the screen frame which also functions as a resonant ring. The resonant ring generates turbulence in the pulp and the entire system. In this way, ultrasound energy is evenly spread over the entire screen and its frame in order to avoid over-intensive ultrasonic forces near the tip of a conventional laboratory ultrasonic mixer. It is expected that the ultrasound produces three primary effects by wave propagation: (1) *turbulence* in the pulp that is intended to reduce colloidal flocculation; (2) *acoustic forces* on the forming mat that increase drainage channels and promote fines and water migration through the channels; (3) *deblinding or unblocking* on the screen. Ultrasound may be applied or stopped at any point throughout the drainage process. The amplitude of ultrasound can be adjusted between 20% and 100% of the maximum power.

For a drainage experiment, the sample is added to the DDJ and pre-mixed using an impeller. The pre-mixing imitates the approach system in a commercial machine while the subsequent filtration stage simulates the wire section. During drainage, the shear force and turbulence are generated by the impeller and ultrasonic oscillations. The device allows drainage testing to be conducted under various levels of vacuum. During drainage, the weight of filtrate is monitored with a balance and the vacuum level under the screen is measured with a pressure transducer. The weight and pressure data are automatically recorded, and processed by a computer to produce drainage profiles of the tested furnish.

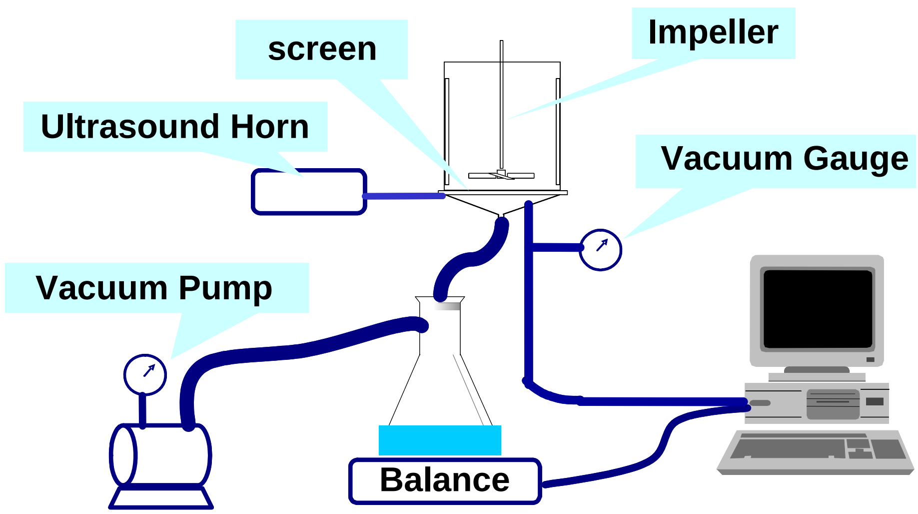

Figure 1. Schematic of the Ultrasonic Dynamic Drainage Jar (UDDJ) system.

EXPERIMENTAL

Materials

A newsprint furnish (TMP) provided by a Canadian paper company was used in this work. The pulp consistency was around 5%. The CSF of the TMP was 120 mL and its average fibre length was 1.51 mm. The fines content (FC) of the pulp was 38.9%, which was measured according to TAPPI T261 cm-00. An aqueous chitosan solution prepared at a concentration of 0.1% was employed as a polymeric retention aid. The dosage of chitosan was 0.5 g/kg fibre (o.d.).

Retention Without Mat Formation

First-pass retention (FPR) and fines retention without mat formation (R_f) were measured at room temperature using the UDDJ. To avoid mat forming, the filtrate flow-rate was restricted to 200 mL/min. The distance between the impeller blade and the screen was set at 3 mm. Before testing, the pulp was diluted with deionized water to a consistency of 0.2%. Then, 500 g of the diluted pulp suspension was poured into the UDDJ with mixing at a specified impeller speed between 0-1500 rpm. The filtration valve was opened after 15 seconds of mixing and the mixing continued during the filtration. In some tests, ultrasound was applied from the time of valve opening, until the end of drainage. To determine fines retention, the first 100 g of filtrate was collected. Collected filtrate was filtered through a pre-weighed glass fibre filter paper to retain the fines, then the filter paper was oven-dried and weighed. This procedure gave the weight of fines in the filtrate. FPR was calculated according to Equation 1:

$$FPR = (C_p * W_{filtrate} - W_{fines}) / C_p * W_{filtrate} \tag{1}$$

where C_p is the pulp consistency and $W_{filtrate}$ and W_{fines} refer to the weight of the filtrate collected and the weight of fines in the filtrate, respectively.

The fines retention, R_f, was calculated according to Equation 2:

$$R_f = (C_p * FC * W_{filtrate} - W_{fines}) / C_p * FC * W_{filtrate} \tag{2}$$

where FC is the fines content of the pulp.

Measurement of Drainage and Retention with Mat Formation

The drainage measurement was conducted using the UDDJ at the agitator speed of either 400 rpm or 1000 rpm. A pulp slurry at 2% consistency was first premixed for 15 seconds in the jar. If chitosan was used, the suspension was agitated for another 20 seconds. After the premixing period, the drainage valve was opened, and pre-mixing was stopped, or continued if turbulence conditions were needed. The filtrate drained into a flask which had a vacuum level of 200 mmHg. Ultrasound could be applied during the drainage. Combinations of ultrasound with mixing during drainage create four categories of drainage conditions with different degrees of turbulence as listed in Table I. The no-turbulence testing conditions were equivalent to those of a conventional DDJ.

Table I: *Turbulence conditions imparted during drainage testing*

Category	*No turbulence*	*Mixing*	*Ultrasound*	*Ultrasound +Mixing*
Description of Turbulence conditions	*Stop mixing when drainage valve was opened. No ultrasound was applied.*	*Continue mixing at the same speed as premixing during drainage. No ultrasound was applied.*	*Stop mixing but start ultrasound at the moment that drainage valve was opened*	*Continue mixing and start ultrasound when drainage valve was opened*

The drainage profiles based on both filtrate weight and vacuum pressure in the UDDJ were recorded and processed with a computer. The fines were separated from the filtrate at the end of drainage to quantify the fines retention. The drainage time was defined as the time needed to reach the inflection point on the filtrate profile curve calculated by the second derivative of the weight-time curve. The first-pass retention and fines retention with mat formation (R_{fm}) were calculated in the same way as described earlier.

Fibre Quality Analysis

Mat formed on the screen of the drainage tester was split into five layers using a Beloit sheet splitter. Each layer was disintegrated in deionized water, and analysed using a Fibre Quality Analyzer (FQA - LDA02 from OpTest Equipment Inc). Length-weighted length (L_w) and length-weighted fines content (C_{lw}) were calculated according to Equations 3 and 4, respectively [25].

$$L_w = (\sum N_i L_i^2)/(\sum N_i L_i) \tag{3}$$
$$C_{lw} = (\sum n_k L_k)/(\sum N_i L_i) \tag{4}$$

Where:

i and k = 1, 2, ….m categories
N_i = fibre number in the "i th" category
L_i = fibre length in the "i th" category
n_k = number of fines whose length was less than 0.2 mm in the "k th" category
L_k = fines length in the "k th" category

RESULTS AND DISCUSSION

1. Effect of Impeller Mixing on DDJ Drainage Test

The primary function of the drainage elements on paper machines is to accelerate dewatering. In the initial stage of mat formation, the drainage elements generate pressure pulses and produce turbulence to disrupt the fibrous mat, and to prevent over-flocculation of the fibres. These pulses also reduce the effect of retention aids. To imitate the dynamic drainage conditions on paper machines, turbulence should, therefore, be included into a drainage tester. For the conventional DDJ, the rotating impeller is a direct and simple way to generate turbulence in the draining pulp, and to disrupt the mat formed. One might expect that such mixing should lead to accelerated drainage if it functions like machine drainage elements. In order to determine the effect of mixing, the drainage profiles of a newsprint furnish were determined when impeller mixing was applied during the drainage. The drainage curves were compared to those obtained without mixing.

Figure 2 shows the influence of impeller speed on the drainage behaviour of the newsprint furnish. Contraintuitively, the impeller agitation applied during dewatering actually slowed down the filtration rate, resulting in prolonged drainage time. When drainage was tested without turbulence, that is, the mixing stopped at the beginning of drainage, the drainage time was 14.1 s. When drainage was measured with mixing continued during drainage at an impeller speed of 400 rpm, the drainage time increased to 17.0 s. The drainage time of the same pulp was prolonged to 38.1 s when agitated at 1000 rpm. Obviously, increasing mixing speed reduced drainage rate.

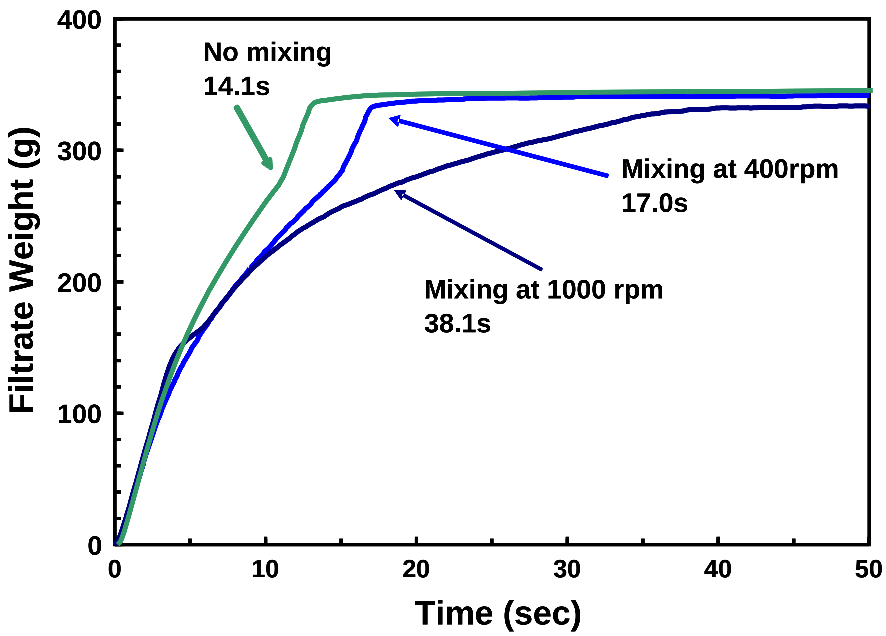

Figure 2. Influence of impeller speed on the drainage behaviour of a newsprint furnish. The numbers under the legends are drainage time.

To better understand this phenomenon, fines distribution in the mat obtained from drainage testing under continuous mixing was analyzed with a Fibre Quality Analyzer (FQA). As shown in Figure 3, fines content decreased from the wire side to the top side of the mat. The fines content was 26.6% in the wire-side layer and only 7.7% in the top layer. The average fibre length (L_w) in the respective layers was 0.95 mm and 1.82 mm. During drainage under rapid mixing and vacuum, pulp suspension was exposed to a strong downward force produced by vacuum and to a centrifugal force from the impeller's rotation. Fines passed through the wire more easily than fibres, but some would be trapped in the openings of the wire and contribute to the initial mat. On the other hand, fibres on the surface of the forming mat were more easily swept off by the impeller and returned to the pulp suspension. As the mat built up, fines migrated toward the wire side with water flow and tended to clog the pores and interstices of the mat, while fibres could not so easily migrate through the mat due to their large size. Consequently, fines were more concentrated on the wire side. The z-direction fines distribution of the mat formed in a DDJ under impeller mixing was actually the converse of that of a commercial paper, where the wire-side contains fewer fines [15]. Therefore, a rotating impeller alone is not a suitable turbulent generator for drainage testing. To simulate more closely machine drainage, other means of generating turbulence and de-clogging are required.

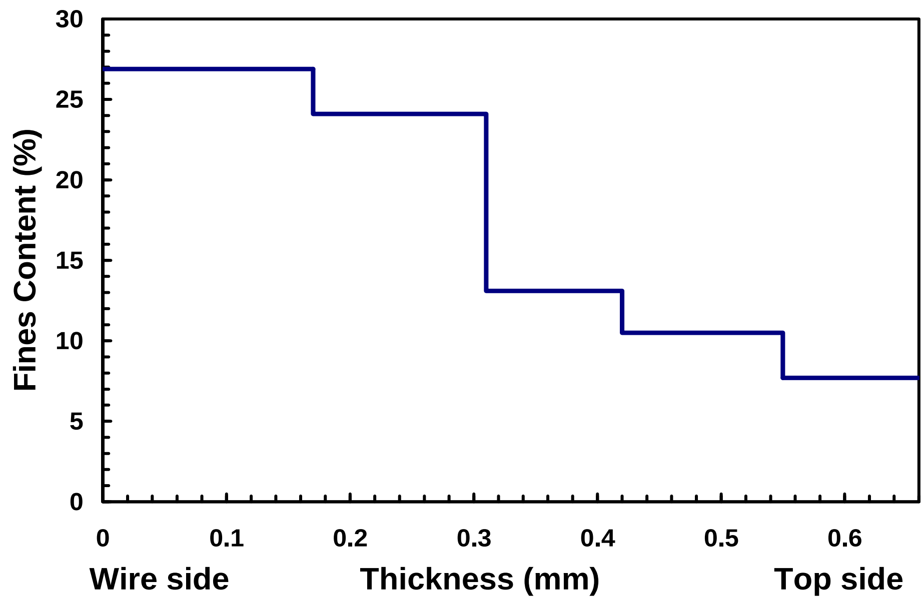

Figure 3. Fines distribution of a sheet formed in a DDJ under continuous mixing.

2. The Effects of Ultrasound on Screen Unblocking and Deflocculation

To explore the effect of ultrasound on deflocculation and screen-unblocking, the operating conditions of UDDJ were set up in such a way that mat formation was avoided by limiting drainage flow to 200 mL/min, similar to those conditions used in a conventional DDJ for retention tests. The first-pass fines retention of the newsprint furnish (at 0.2% consistency) was measured under various impeller mixing speeds with and without application of ultrasound.

As shown in Figure 4, first-pass fines retention decreased as mixing speed increased, and reached a minimum level at about 500 rpm. No further decrease in retention was observed beyond this speed. Thus, 500 rpm is sufficient to deflocculate and avoid mat formation under the conditions used in this work. At the same impeller mixing speeds, applying ultrasound reduced fines retention. The greatest impact was observed when the mixing speed was below 500 rpm. The ultrasound reduced the fines retention up to 30%. The lowering of retention could be attributed to deflocculation, mat disruption and screen-unblocking effect from the applied ultrasound. When the mixing speed was 500 rpm or higher, the effect of ultrasound levelled off, resulting in a roughly constant reduction in retention of about 5.5%. At these speeds, the impeller mixing itself was sufficient to destroy flocs and fibre mat, so the effect of ultrasound was diminished, and limited to its function of screen-unblocking.

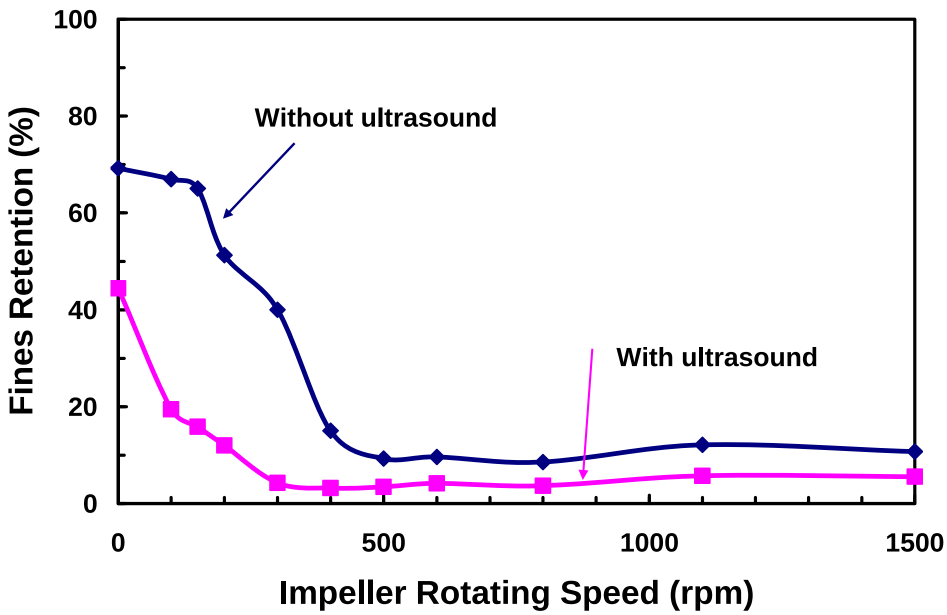

Figure 4. First-pass fines retention of the untreated TMP furnish (0.2% cons.) as a function of impeller rotating speed with and without ultrasound.

Chitosan (poly[β-(1→4)-2-amino-2-deoxy-D-glucopyranose]) is a linear, high-molecular-weight aminopolysaccharide with a structure similar to cellulose. Under slightly acidic conditions, the primary amine group on each glucose moiety renders chitosan cationic, and enables it to interact with negative-charged cellulose fibres and fines as a retention aid [26]. To verify whether ultrasonic forces were able to destroy the flocs induced by retention aids, fines retentions of TMP treated with chitosan were measured. The results are presented in Figure 5. As expected, fines retention dramatically increased in the presence of chitosan. However, flocs were degraded by intensive shear force, especially when mixing speed was higher than 500 rpm. In addition to mixing, ultrasound further reduced the fines retention of the chitosan-treated samples to levels similar to those of untreated samples in the absence of ultrasound (see Figure 4). The effect of ultrasound was most pronounced at a mixing speed of about 400 rpm. Mixing with impeller at this speed was not sufficient to destroy the flocs induced by chitosan. However, applying ultrasonic forces at this mixing level reduced fines retention from 73% to 24%, a reduction of 49%. If the unblocking effect of ultrasound is assumed to be 5.5% as mentioned earlier, the additional reduction of 43.5% in fines retention may be caused mainly by the deflocculation effect of ultrasound. Clearly, ultrasonic forces are capable of destroying flocs induced by polymers.

It was observed that the effect of ultrasound was influenced by the weight of the sample. As shown in Figure 6, without ultrasound, the first-pass retention was independent of pulp weight. When ultrasound was used, however, FPR varied with the weight of the pulp. The retentions of 350 g of pulp furnish were lower in general than those of 500 g of pulp furnish (0.2% cons.). Therefore, ultrasound is more effective with a smaller sample. This is understandable because the intensity of ultrasonic forces increases as the sample becomes smaller. To maximize the effect of ultrasound, 350 g of pulp furnish was employed in the subsequent drainage tests.

3. Effect of Ultrasound on the Drainage Behaviour of TMP

In sheet formation on a paper machine, drainage, retention and formation are influenced by mechanical entrapment of fines elements and by flocculation of fibres, fines and fillers. However, the fines retention discussed in the previous section excludes the influence of mechanical entrapment because of the absence of mat formation during drainage. To obtain a complete view of the drainage and retention performance of a papermaking furnish in the presence of a chemical aid, it is necessary to characterize its performance with mat formation.

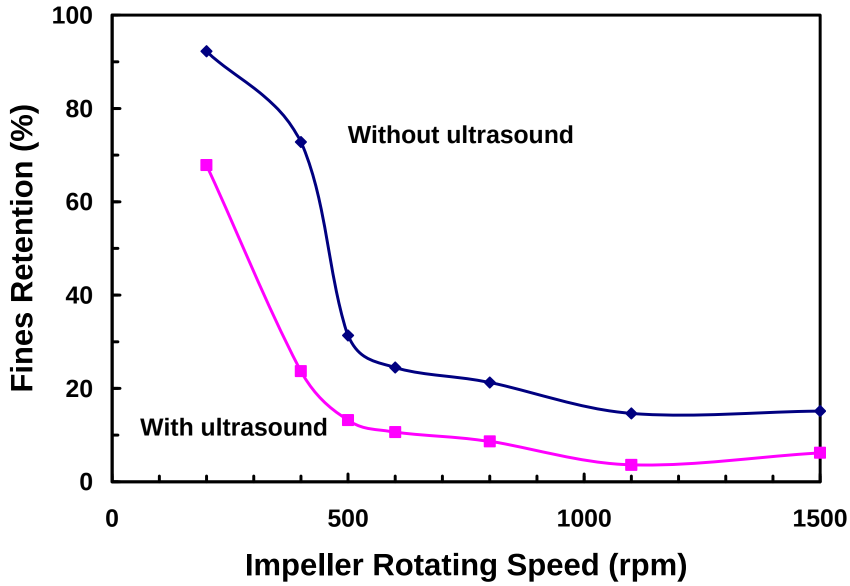

Figure 5. The first pass fines retention of the chitosan-treated TMP as a function of impeller rotating speed with and without ultrasound.

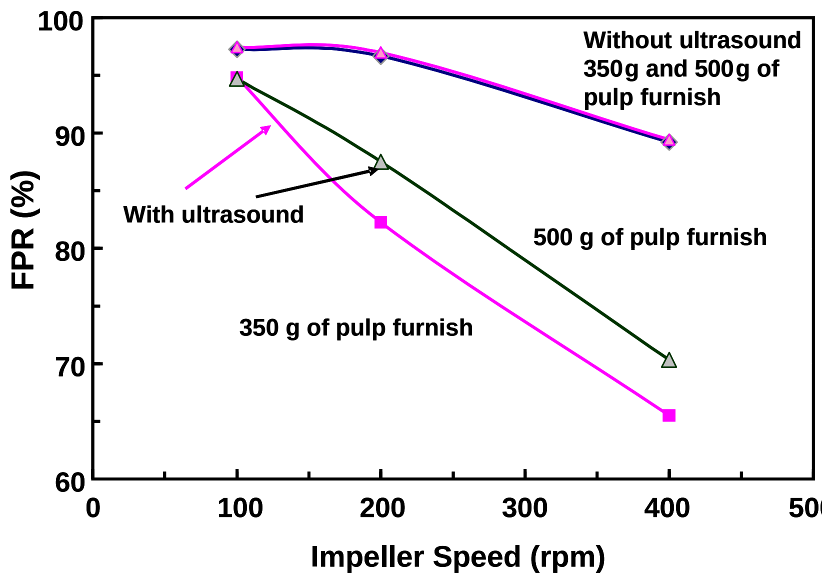

Figure 6. The effect of ultrasound on retention depends on sample weight.

3.1 Drainage with low premixing speed (400 rpm)

As shown in section 2, ultrasonic deflocculation was dominant at 400 rpm. Thus, to maximize the ultrasound effect, the drainage behaviour of the TMP was investigated following a premixing at 400 rpm in this part of work. After premixing, the pulp was exposed to various turbulent draining conditions including: no mixing, mixing at 400 rpm, ultrasound, and ultrasound plus mixing at 400 rpm (see Table I for details). The drainage profiles under each condition are shown in Figure 7. At the beginning of the drainage, when the filtrate was less than 60 g, all the curves were overlapping, indicating that the drainage velocities were the same for all mixing intensities. Afterwards the drainage velocities deviated from one another, probably due to the changes in mat structure under different turbulences. As a result, drainage time varied. Without turbulence, the UDDJ acts as a conventional DDJ, and the drainage time tested was 14.1 s. Continuous mixing at 400 rpm increased drainage time to 17.0 s, whereas ultrasound reduced the drainage time to 11.5 s. With the combination of ultrasound and mixing, drainage time was longer than that without mixing but shorter than that observed for agitated DDJ.

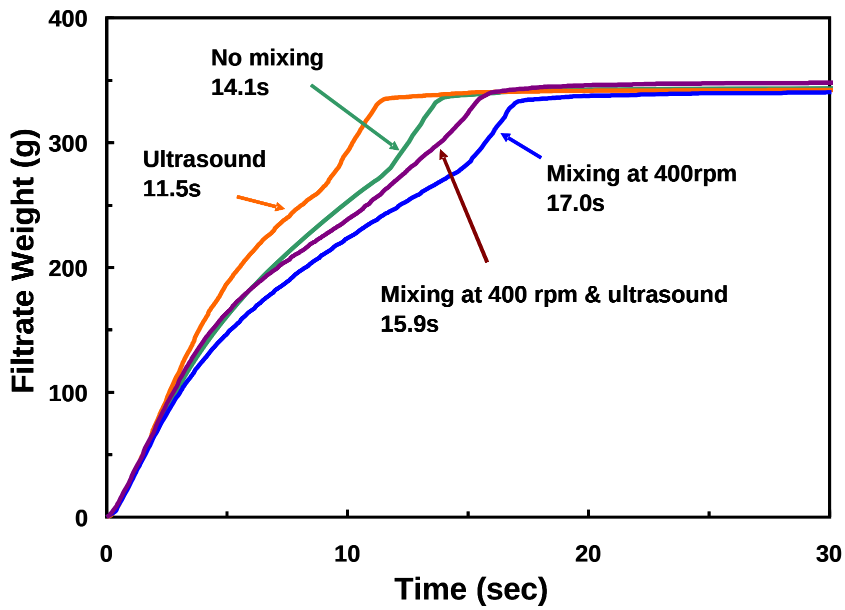

Figure 7. Drainage profiles of a newsprint furnish at various mxing intensities with a low premixing speed (400rpm) in the absence of additives.

The corresponding fines retention without mixing and ultrasound was 77.6%, much higher than the typical fines retention found on a commercial machine which is often below 40% [26]. This high retention was due to the lack of turbulence and increased mechanical trapping. Application of ultrasonic forces reduced mechanical trapping, resulting in a decrease in fines retention, to 64.2%. The effect on mechanical trapping is dependent on ultrasound intensity. As illustrated in Figure 8, as the amplitude of ultrasound increased, the fines retention measured with the UDDJ was reduced further. Overall, ultrasonic forces affect drainage and retention in three ways: screen unblocking, deflocculating, and prevention of fines entrapment during mat formation. Therefore, ultrasonic forces act in a way similar to the drainage elements of a commercial paper machine.

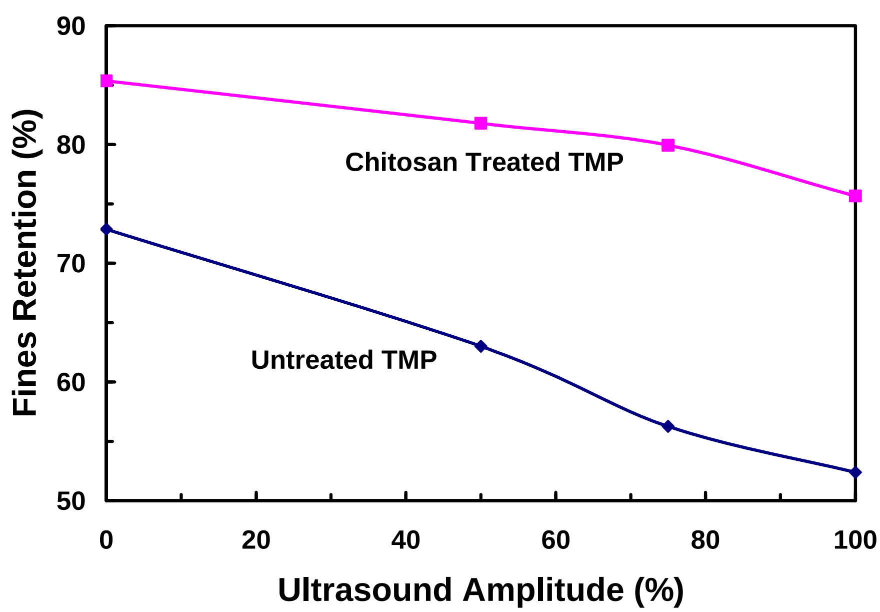

Figure 8. Fines retention as a function of ultrasonic amplitude.

Table II shows the drainage times when chitosan was used. The drainage times were shortened in the presence of chitosan due to pulp flocculation, except when ultrasound was applied. In the presence of ultrasound, drainage times with and without chitosan were similar. This similarity is related to the increase in fines retention when chitosan was used. Without ultrasound, chitosan treatment only increased fines retention by 11% and 8% because a large amount of fines were trapped in the mat. Under these conditions, the contribution of flocculation induced by chitosan to retention was relatively unimportant. Under the influence of ultrasound, the mechanical entrapment of fines was reduced. The flocculation by polymer became more important, which led to a greater increase of fines retention, by about 17%. Thus, chitosan did not improve drainage in the presence of ultrasound because the acceleration of drainage induced by flocculation was counteracted by high fines retention. This counteractive behaviour brought by polymer addition was undetectable using a conventional DDJ.

Table II: *Comparison of drainage time and retention between chitosan-treated and untreated pulps with premixing at 400 rpm.*

sample	*No mixing*	*Mixing at 400 rpm*	*Ultrasound*	*Mixing at 400 rpm + ultrasound*
	Drainage time (s)			
Untreated pulp	*14.1*	*17.0*	*11.5*	*15.9*
Chitosan-treated pulp	*12.3*	*14.1*	*11.8*	*13.9*
	Fines retention with mat formation (%)			
Untreated pulp	*77.6*	*79.7*	*64.1*	*67.0*
Chitosan-treated pulp	*88.6*	*87.3*	*80.9*	*84.3*
	Increase in fines retention by chitosan (%)			
	11.0	*7.6*	*16.8*	*17.3*

3.2 Drainage with high premixing speed (1000 rpm)

Because the turbulent forces generated by mixing at 400 rpm are much weaker than those encountered in the wet-end of a commercial paper machine [27], the drainage behaviour of a pulp was studied under a high premixing speed (1000 rpm) using the UDDJ. The results are shown in Figure 9. Similar to the results obtained at 400 rpm, ultrasound accelerated drainage whereas mixing prolonged drainage time. Compared to that achieved with mixing only, ultrasound reduced drainage time by a factor of 3. The order of drainage time (t) was:

$$t_{(ultrasound)} < t_{(ultrasound/mixing)} < t_{(no\ mixing)} << t_{(mixing)}$$

These results further support the argument that impeller mixing alone does not generate the proper turbulence to simulate machine drainage. Ultrasound is able to introduce additional shear forces into pulp without impeding drainage.

Different from its impact on drainage under low speed premixing, the addition of chitosan at high premixing speed failed to improve drainage velocity under the first three mixing conditions as shown in Table III. On the other hand, chitosan still improved fines retention (also shown in Table III). The high pre-mixing speed might have reduced polymer-induced flocculation. The reduced flocculation and increased fines retention are probably the reasons why chitosan failed to improve drainage under these conditions. It is interesting to note under the combination of both ultrasound and high speed mixing, the fines retention was reduced significantly, to a level similar to that found in commercial paper machines. Under high mixing intensity, chitosan increased fines retention by only ~ 5%. As expected, chitosan was able to shorten drainage time, from 10.7 s to 9.4 s in this case, when the increase in fines retention was not great. These results illustrate that the UDDJ may be used to simulate various turbulence conditions occurring at the wet-end of fast paper machines by a proper combination of ultrasound and mixing. Only under these high turbulence conditions, can the functions of polymeric additives be estimated realistically.

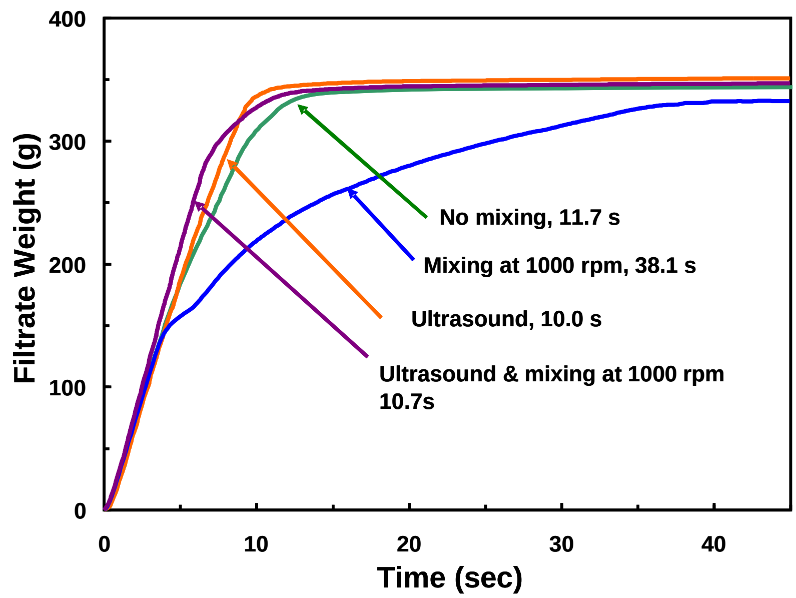

Figure 9. Drainage profile of the newsprint furnish at 1000 rpm.

Table III: *Comparison of the drainage time and fines retention between chitosan-treated and untreated pulps under premixing at 1000 rpm.*

Sample	*No mixing*	*Mixing at 1000 rpm*	*Ultrasound*	*Mixing at 1000 rpm + ultrasound*
	Drainage time (s)			
Untreated pulp	*11.7*	*38.1*	*10.0*	*10.7*
Chitosan-treated pulp	*12.8*	*38.3*	*13.1*	*9.4*
	Fines retention with mat formation (%)			
Untreated pulp	*69.3*	*68.9*	*53.6*	*30.9*
Chitosan-treated pulp	*80.0*	*79.9*	*73.9*	*35.6*
	Increase in the fines retention by chitosan (%)			
	11.0	*11.0*	*20.3*	*4.7*

Figure 10 shows the pressure profiles of the corresponding drainage curves of Figure 9. In general pressure first decreased (higher vacuum), and then fluctuated, except for the curve obtained under continuous shearing at 1000 rpm. The vacuum became constant afterwards, which was defined as the equilibrium vacuum whose value reflects the porosity of the wet web [18]. The first pressure peak during the pressure fluctuation usually corresponded to the wet line in web formation. It is interesting to observe that pressure profiles under various drainage conditions were very different. When pulp was drained with mixing, the equilibrium vacuum was higher because more fines blocked the screen and the wire-side web, resulting in a much more closed web and a lower drainage rate, as discussed in the first section. In contrast, applying ultrasound made the web more porous as evidenced by the lower vacuum. Due to the loose structure of the web formed with ultrasound, the filtration resistance was low and water drained more rapidly. The correlation between equilibrium vacuum and drainage time is shown in Figure 11. For comparison, the corresponding fines retention was also plotted against the drainage time. Clearly, drainage time was more correlated with equilibrium vacuum pressure, than to the fines retention. Since the equilibrium vacuum pressure reflects the porosity and compressibility of forming sheet, the higher correlation indicates that the web structure plays a more important role in drainage than the fines content, like in commercial paper machines [4].

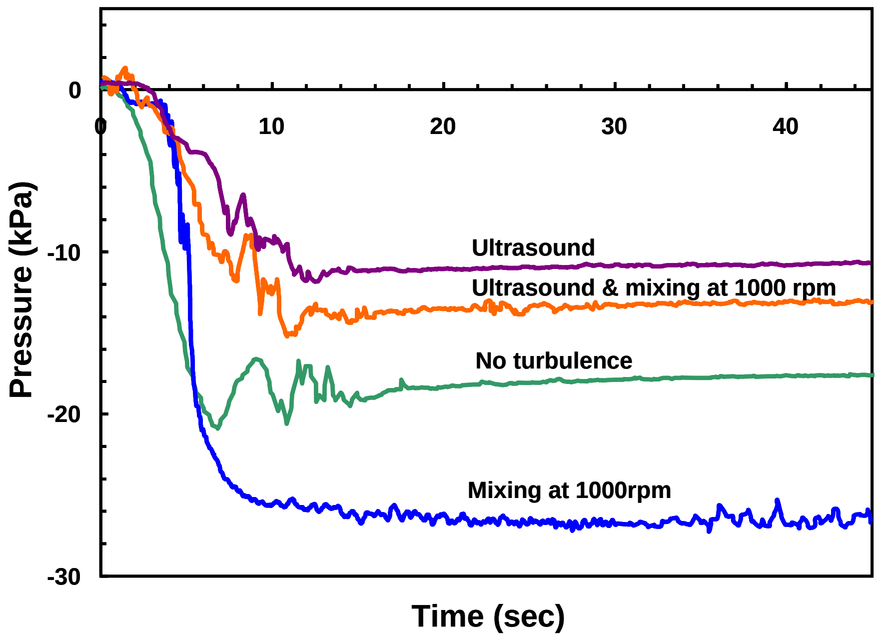

Figure 10. Pressure profile of the newsprint furnish at various turbulence conditions corresponding to Figure 9.

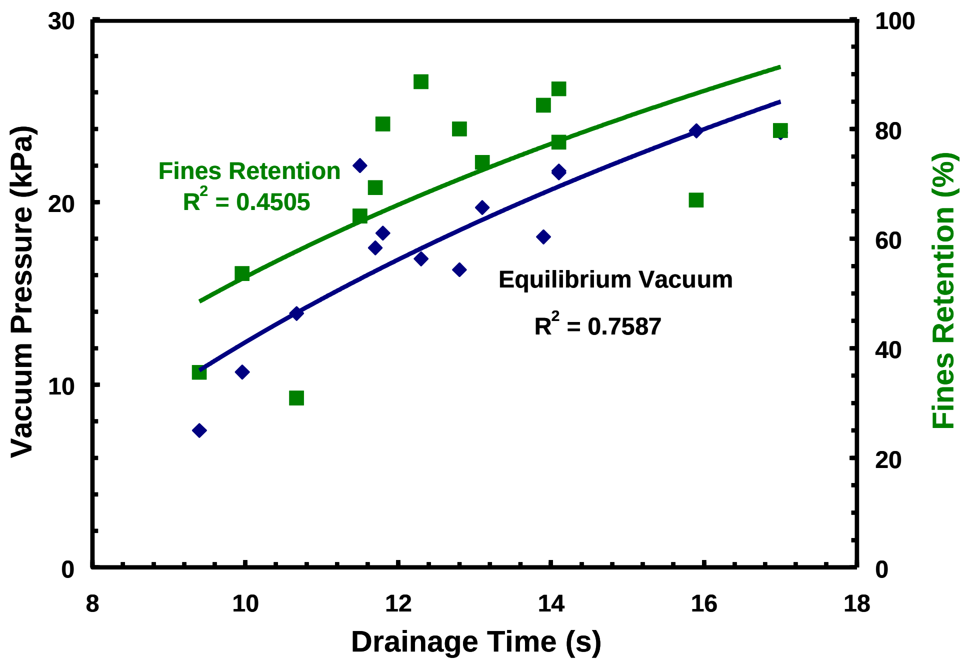

Figure 11. Logarithmic Correlations of drainage time to equilibrium vacuum pressure and fines retention.

3.3 Mechanism of Drainage under Various Turbulences

As shown in the previous section, applying ultrasound increased drainage rate and reduced fines retention, while mixing with an impeller had the opposite effect. Based on the drainage behaviours and mat structure, the drainage processes in the presence of ultrasound or mixing are schematically depicted in Figure 11.

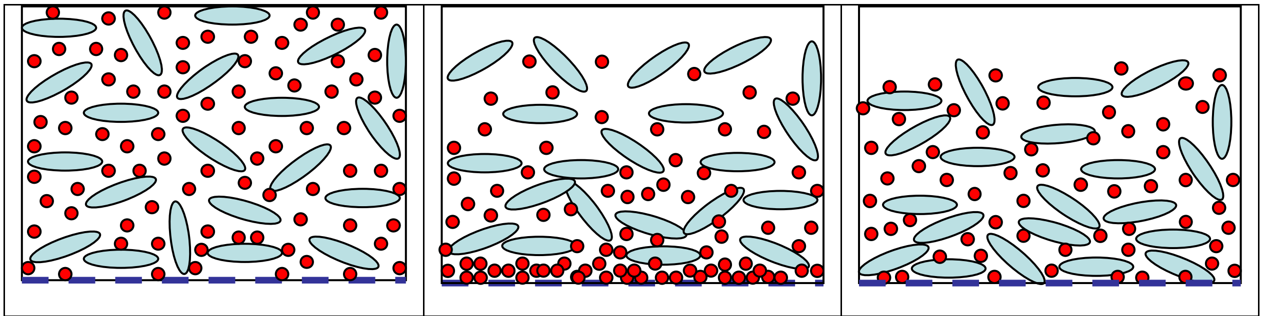

Figure 12. The proposed schematic of dewatering under various turbulent conditions. The red small circles represent fines, the blue ovals symbolize the fibres, and the bottom dashed line indicates the forming wire.

Before drainage starts, both fibres and fines are evenly dispersed. When the pulp is drained while mixing, some fines are readily trapped by the wire and form the initial mat. Because the fines fill up the pores and interstices, the drainage rate is low and the formed web has low permeability. When the pulp is drained in the presence of ultrasound, the fines go through the wire more easily with less entrapment of fines in the openings of the wire and in the formed web, resulting in a more porous web, faster drainage, and reduced fines content in the web.

CONCLUDING REMARKS

An Ultrasonic Dynamic Drainage Jar (UDDJ) has been developed for studying the drainage performance of papermaking furnishes by directly generating ultrasonic vibration in the tester. The UDDJ generates both drainage and pressure profiles instantaneously. The drainage time can be computed based on these profiles. The vacuum level at the end of drainage reflects web porosity and compressibility. The first-pass retention can be determined by measuring the fines concentration in the filtrate. The preliminary results show that the ultrasonic forces produced by UDDJ are able to deflocculate pulp suspension, to reduce fines retention, to accelerate drainage processes and to produce porous wet web, while these functions cannot be achieved by the conventional impeller mixing alone. By applying ultrasound together with impeller mixing, UDDJ can be used to simulate various turbulence conditions occurring at the wet-end of a fast paper machine, so that the performance of polymeric additives can be assessed under more realistic conditions. The results suggest the effect of ultrasound in the UDDJ includes the following three aspects:

1. Unblocking forming wire and retarding the formation of the initial mat.
2. Deflocculating the pulp suspension.
3. Creating or enlarging dewatering channels in the forming web.

The ultrasonic DDJ can simulate the drainage in the paper machine former better than commercially available laboratory testers. It is also conceivable that ultrasound could be potentially used in the forming section of a real paper machine to accelerate its drainage rate.

The Ultrasonic DDJ possesses several additional advantages over the conventional DDJs:

1. The intensity of turbulence can be easily controlled by adjusting the amplitude of ultrasonic power. The amplitude and the acting time can both be programmed to simulate the varying turbulence conditions along the forming section.
2. The apparatus is able to simultaneously measure drainage, retention, and web porosity. There is also the potential to obtain handsheets made under dynamic conditions.
3. Unlike impeller mixing, the ultrasound could act on a very thin layer of pulp suspension, which provides possibilities to make handsheets at high consistency and low basis weight.

Thus, the UDDJ could be a very useful laboratory tool to evaluate the drainage performance of furnishes and chemical additives under dynamic conditions. The future work includes optimization and automation of the device, and validation of the results using a pilot paper machine.

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REFERENCES

1. Hoyland, R.W., "The Role of the Press Section in Energy Conservation", *Paper Technology and Industry*, 19(10): 329-332 (1978).

2. Gess, J.M., *United States Patent 4,613,406* (1986).

3. TAPPI T 227 om-04, Freeness of Pulp (Canadian Standard Method) (2004).

4. Clark, J.D'A, "Freeness Fallacies and Facts", *Svensk Papperstidning* 73(3): 54-62 (1970).

5. Britt, K.W., "Mechanisms of Retention during Paper Formation", *Tappi* 56(10): 46 (1973).

6. TAPPI T 261 cm-00, Fines Fraction of Paper Stock by Wet Screening (2000).

7. Britt, K.W., Unbehend, J.E. and Holman, J.C., "Dynamic Drainage of Paper Stock", *Tappi J.* 65(11): 64-66 (1982).

8. Abson, D., "Predicting the Performance of Shear-Sensitive Additives", *Tappi J.* 63(6): 55-58(1980).

9. Springer, A.M., Chandrasekaran, S. and Wegner, T.H., "The Influence of Starch on Drainage and Retention in Paperboard Mill Systems", *Tappi J.* 67(2): 104-108 (1984).

10. Unbehend, J.E., "Laboratory Drainage Testers – A Critical Review", *1990 Tappi Papermakers Conference,* 363-375 (1990).

11. The Dynamic Drainage Analyzer Manual, AB Akribi Kemikonsulter, Sundsvall, Sweden (2001).

12. Chabot B. and Daneault C.A., "Methodology of Determine Retention and Drainage in Laboratory", *Paperi ja Puu/Paper and Timber*, 86(6): 445-449 (2004).

13. Krogerus, B., "Laboratory Testing of Retention and Drainage", in *Papermaking Chemistry*, edited by Leo Neimo, Fapet Oy, 82-93 (1999).

14. Karrila, S., Raisanen, K., and Paulapuro, H., "The Moving Belt Drainage Tester (MBDT)", *1992 Tappi Papermakers Conference*, 275-299 (1992).

15. Raisanen, K. and Paulapuro, H., “Wire Section Simulation with the Moving Belt Drainage Tester (MBDT)”, *1993 Tappi Papermakers Conference,* 103-113 (1993).

16. Mitchell, C., Parker, I. and Johnston, R., “Development of the Moving Belt Sheet Former/Drainage Tester”, *56th Appita Annual General Conference*, Rotorua, New Zealand, 287-292 (2002).

17. Lin, J.T. and Schuster, M.A., *et al*., “Apparatus for Simulation Processing Parameters and Predicting Variables in a Papermaking Operation Including Sequential Pulsation, Gravity and Vacuum Drainage, Fines Retention and Paper Formation”, *US Patent 5314581* (1994).

18. Sutman, F.J., “Development and Validation of an Improved Drainage Testing Methodology”, *Tappi,* 83(4): 69-70 (2000).

19. Kuttruff, H., “Applications of High Intensity Ultrasound” in *Ultrasonics Fundamentals and Applications*, Elsevier Science Publishers Ltd., London and NewYork, 395 - 429 (1991).

20. Lamminen, M.O., Walker, H.W., and Weavers, L.K., “Mechanism and Factors Influencing the Ultrasonic Cleaning of Particle-Fouled Ceramic Membranes”, *J. Membrane Sci.,* 237, 213-223 (2004).

21. Mason, T.J. and Lorimer J.P., “Miscellaneous Effects of Power Ultrasound” in Sonochemistry: Theory, Applications and Uses of Ultrasound in Chemistry, Ellis Horwood Ltd., Chichester, England, 229-247 (1988).

22. Brodeur, P.H. and Gerhardstein, J.P., “Overview of Applications of Ultrasonics in the Pulp and Paper Industry”, *IEEE Ultrasonics Symposium*, 809-815 (1998).

23. Jong, J.H. and Choi, M.M., *et al.,* “Acoustic Separation of Moving Fibers in a Pulp Flow”, *1999 TAPPI Pulping Conference*, 759-769 (1999).

24. Paul Mckay and Cyrus K.Aidun, “Refluidization of Wood Fiber Mats with High Intensity Ultrasound”, *TAPPI Paper Summit, Spring Technical and International Environmental Conference*, 3-5 (2004).

25. OpTest Equipment Inc., *Operation Manual, Fiber Quality Analyzer Code LDA02* (1999).

26. Laleg, M. and Pikulik, I.I., “Wet-Web Strength Increase by Chitosan”, *Nordic Pulp and Paper Research Journal*, 6(3): 99-109 (1991).

27. Britt, K.W., Unbehend, J.E., and Shridharan, R., “Observations on Water Removal in Papermaking”, *Tappi Journal,* 69(7): 76-79 (1986).