Whitewater Clarification Using a Dual Flocculation/Ultrasonic Method

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As a novel approach to solids removal, a dual chemical flocculation/ultrasonic method to clarify a whitewater stream was investigated. The technology first considers the use of flocculants to create larger particles or flocs. Then, an ultrasonic field is applied to the flocs to obtain a clarified water stream and a stream of concentrated flocs. A laboratory ultrasonic separation system was used to demonstrate the clarification concept. Experiments at different flow rates, ultrasonic frequencies and acoustic intensity levels were made. Best results were observed using the flocculant system poly(ethylene oxide)/phenolic formaldehyde resin (PEO/PFR). A clean stream with less than 100 ppm of solids and a clarification efficiency close to 80% of the maximum achievable efficiency in the experimental setup were obtained. A preliminary economic assessment of the technology was performed.

Nous avons analysé une nouvelle méthode d'extraction des matières solides permettant de clarifier l'eau d'un circuit d'eau blanche par ultrasons et floculation. Cette technologie utilise des floculants pour créer de plus grosses particules ou flocs. Puis on applique un champ ultrasonore aux flocs pour obtenir un circuit d'eau clarifiée et un circuit de flocs concentrés. Un système de laboratoire pour la séparation par ultrasons a été utilisé pour démontrer le concept de clarification. Des essais à divers débits et niveaux d'intensité acoustique et diverses fréquences ultrasonores ont été effectués. Les meilleurs résultats ont été obtenus à l'aide du système de floculants PEO/PFR. Lors de l'essai, nous avons obtenu un circuit propre contenant moins de 100 ppm de matières solides et une efficacité de clarification de près de 80 % du maximum d'efficacité réalisable. Une évaluation économique préliminaire de la technologie a été effectuée.

INTRODUCTION

Accumulation of solid materials such as colloid suspensions, fines, fillers, and fibres in paper mills water systems is detrimental to both the papermaking process and the final products. For example, an increase in pitch and stickies will cause a serious deposition problem. Also, the undesirable presence of contaminants will reduce the performance of chemical additives by competitive adsorption and impair water drainage during formation.

Solids accumulation can be alleviated by improving the retention rate of colloidal and fine materials during papermaking. Arguments in favour of this conventional approach include (a) recovering fines, fillers and valuable wet-end additives and (b) reducing costs in water treatment and waste management. Unfortunately, since the retention rate is not 100%, chemical retention must be supplemented by the use of solids removal technologies. Conventional removal methods include flotation using dissolved air, centrifuging and screening [1–5]. Another removal method, which is the subject of the present study, involves the combined advantages of chemical flocculation and ultrasonic clarification to remove efficiently contaminants from a water stream.

The use of an ultrasonic field to agglomerate and separate particles in gases and fluids is not new. For example, as early as 1949, Clair [6] studied the agglomeration of smoke, fog and dust particles using sonic waves. In 1981, Chou et al. [7] reported a study of aerosol agglomeration using high-intensity ultrasonic fields. Barmatz et al. [8] and Peterson et al. [9] have been issued patents on ultrasonic separation methods in fluids. In 1990, Apfel [10] reported on the principles and applications of acoustic separation methods. Whitworth et al. [11] reported on the transport and harvesting of fluid-suspended particles using modulated ultrasound. Frank et al. [12] used an ultrasonic field to remove micrometre size particles from water; an enriched suspension and a cleaned fluid were obtained. They indicated that 80% of the particles (40 μm polystyrene latex) could be removed from water. Mandralis and Feke [13] studied the fractionation of suspensions using synchronized ultrasonic and flow fields in 1993. Trampler et al. [14] used ultrasonic resonance fields to induce aggregation and increase the solid sedimentation rate of cells. Klunder and Koopmans [15] studied ash removal in mining pulp using ultrasound in the presence of chemical flocculants. They found that the ash content could be significantly reduced.

The Institute of Paper Science and Technology (IPST) has been engaged for some time in the development of a novel separation technology relying on ultrasonic principles [16–20]. The technology is aimed at processing large quantities of liquids and/or pulp stocks. More precisely, a traveling (unidirectional) ultrasonic wave field is used to redistribute water-suspended particles in such a way as to separate them according to particle radius and, to a lesser extent, particle density. As a possible

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industrial application, it was hypothesized that the separation technology could be used to clarify whitewater in a paper mill. However, since whitewater solids are relatively small (<100 μm), they would be barely affected by the ultrasonic wave field. Hence, chemical flocculation was proposed as a simple means to increase particle size in preparation for efficient ultrasonic clarification. The desired goal is to process a whitewater stream in a continuous mode and obtain two output streams: a clarified or clean stream, and a stream of concentrated solids or flocs. In some ways, the proposed dual flocculation/ultrasonic clarification method can be described as an active sedimentation method into which a weak gravitational force acting on small particles is replaced by a strong acoustic force acting on large flocculated particles.

Dissolved air flotation (DAF) systems are commonly used to clarify whitewater [21]. These passive systems use high pressure to introduce dissolved air in whitewater. When the pressure is released, air microbubbles form and attach themselves to fibres and particles, which then float to the top where they are mechanically skimmed off. The clarification efficiency is greater than 98%. There is an economical incentive to explore alternatives to the DAF technology to drive down the cost of whitewater processing and minimize the use of chemicals. Also, the installation capital cost for a DAF system is significant and a typical DAF system takes up quite a bit of space.

We report on a feasibility study of the dual flocculation/ultrasonic whitewater clarification method. The experimental methodology is described next. Then, experimental results are presented and discussed. Finally, an economic assessment of the technology is provided.

EXPERIMENTAL

The experimental methodology had two stages. First, an optimization study of flocculants suitable for clarification experiments was undertaken. Then, a series of clarification experiments was performed using an experimental in-line ultrasonic separation system developed at IPST.

TABLE I
WHITEWATER SAMPLES USED IN THE STUDY

Whitewater Sample	Description	Particle size distribution (%<75 μm)	Consistency (%)	Colloid titration (meq/L)
W1	From 24% OCC and 76% unbleached kraft softwood	97%	0.054	−0.42
W2	From 100% OCC	78%	0.072	−0.30
W3	From 100% ONP (Cloudy whitewater)	72%	0.036	−0.28

TABLE II
FLOCCULANTS USED IN THE STUDY

Symbol	Chemical	Chemical Composition	Charge Density (meq/g)	Supplier
APAM	Percol 172	Anionic PAM	−0.315	Allied Colloids
CPAM1	Percol 175	Cationic PAM	1.0	Allied Colloids
CPAM2	7523	Cationic PAM	0.163	Nalco
PEO	PEO	Poly(ethylene oxide)	0	Aldrich
PFR	CASCOPHEN	Phenolicformaldehyde resin	0	Borden Chemicals

The molecular weight (Mw) of PEO is 8 million. One part of PEO is used with two parts of PFR.

Flocculant Optimization Study

Whitewater is the filtrate from the forming fabrics of paper machines. Since the chemistry of whitewater is not well documented and varies from mill to mill, three whitewater samples and different flocculants widely used as retention aids in the paper industry were considered in the study. Table I describes briefly whitewater samples. As seen in Table II, flocculants included an anionic polyacrylamide (APAM), two cationic polyacrylamides with different charge densities (CPAM1 and CPAM2), and a dual flocculant of poly(ethylene oxide) (PEO) with a water-soluble phenolic formaldehyde resin (PFR) [22]. Charge density was determined by colloidal titration [23].

Particle size distribution was analyzed using a Malvern System 2600 Laser Particle Sizer. This apparatus was also used to evaluate flocculation efficiency. Since the solids in whitewater are mostly fines and fillers with a particle size less than 75 μm (assumption of particles going through a 200 mesh screen with 75 μm holes), the flocculation efficiency was determined from the percentage of particles larger than 75 μm in whitewater before and after flocculation. A typical flocculation test was as follows. A specific flocculant dosage was added to 600 mL of whitewater with mechanical stirring at 500 rpm for 10 s. The solution was then poured into the particle analyzer sample cell, gently stirred, and recirculated at a velocity of 0.6 m/s. Finally, the particle size distribution was analyzed as a function of circulation time.

Figure 1 shows the percentage of particles larger than 75 μm for different flocculants using whitewater W3. One observes that the anionic polymer APAM is not effective for whitewater flocculation, while cationic polymers CPAM1 and CPAM2, and neutral dual flocculants PEO/PFR are all very effective. It is known that solid suspensions in whitewater are mainly anionic charged. The electric repulsion between the solid suspensions and the anionic APAM will reduce the adsorption ability of this flocculant, thus preventing satisfactory flocculation. On the other hand, the adsorption of CPAM1 and CPAM2 is facilitated by electrostatic attraction, thus increasing the flocculation efficiency. However, the high cationic demand of the whitewater makes CPAM1 and CPAM2 inefficient at low dosages (<10 mg/L). The mechanism of PEO/PFR flocculation is different from that of cationic flocculant. A complex reaction between PEO and PFR is involved in the flocculation [24]. Because PEO is a nonionic polymer, the anionic nature of the suspensions does not affect the flocculation efficiency of PEO/PFR. This flocculant system also shows the best flocculation efficiency at low dosages (2 mg/L PEO:4 mg/L PFR).

The stability of the flocculates formed by the different flocculants (except APAM) is shown in Fig. 2 for whitewater W3. It is observed that the flocs formed by CPAM1 and PEO/PFR slowly break up as a function of time,

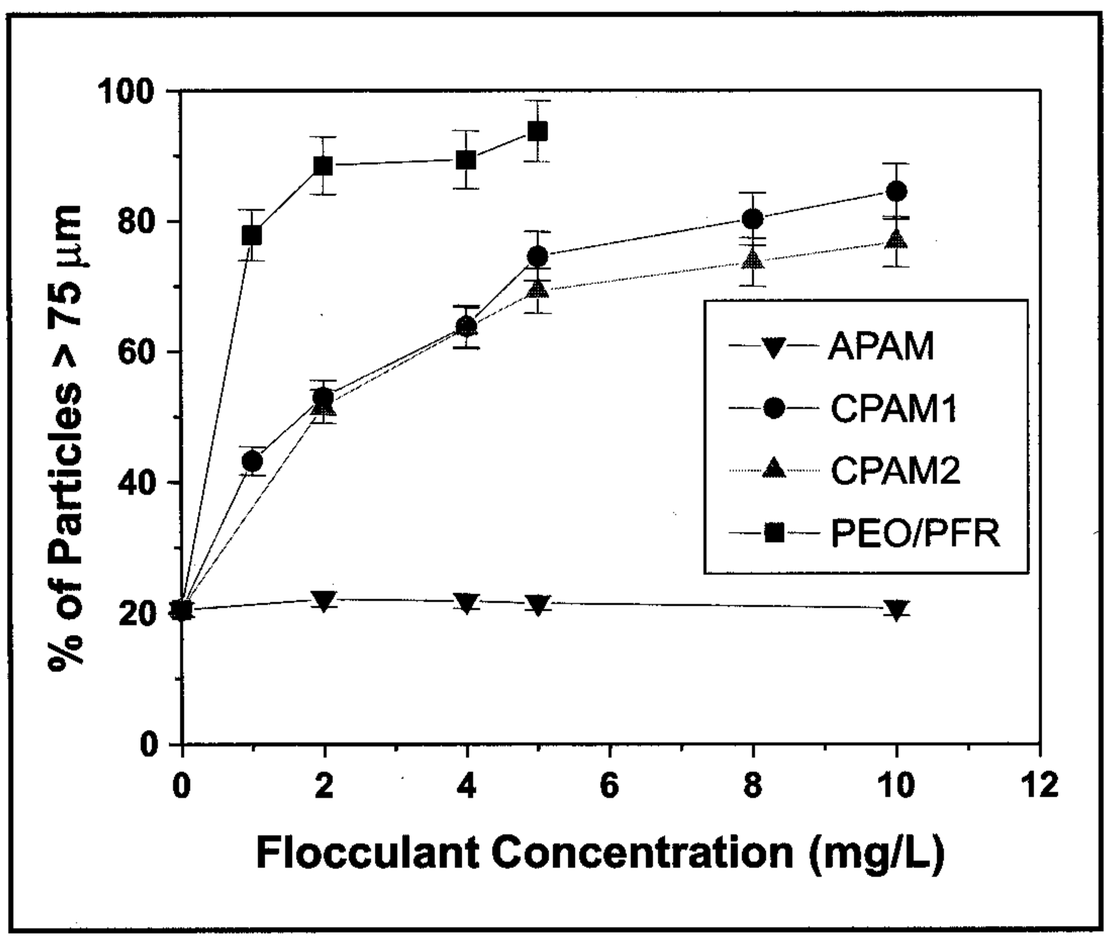

Fig. 1. Percentage of particles larger than 75 μm in whitewater W3 as a function of flocculant dosage for the flocculants listed in Table II. The circulation time is 1 min in the particle sizer.

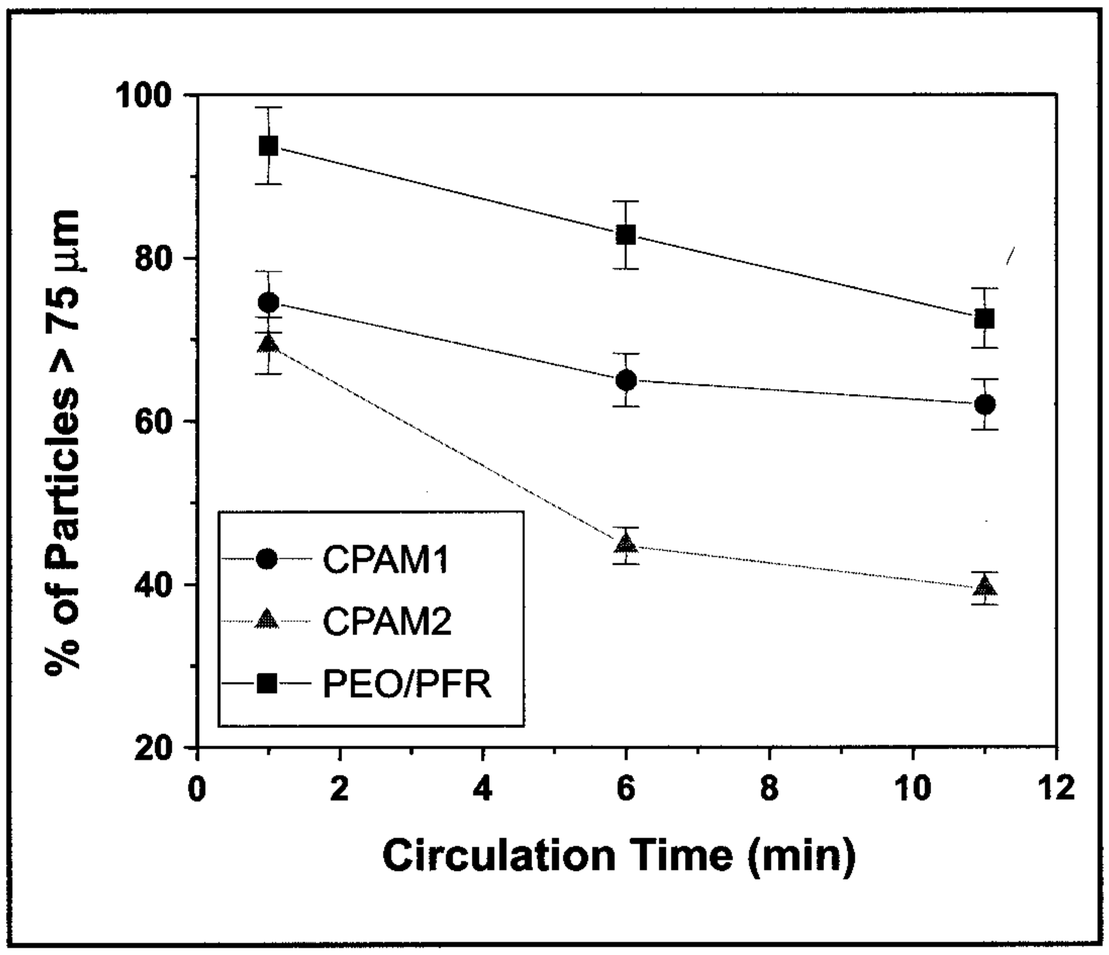

Fig. 2. Percentage of particles larger than 75 µm as a function of circulation time for whitewater W3. The flocculant dosage and circulation velocity are 5 mg/L and 0.6 m/s, respectively. Circulation was done in the particle sizer.

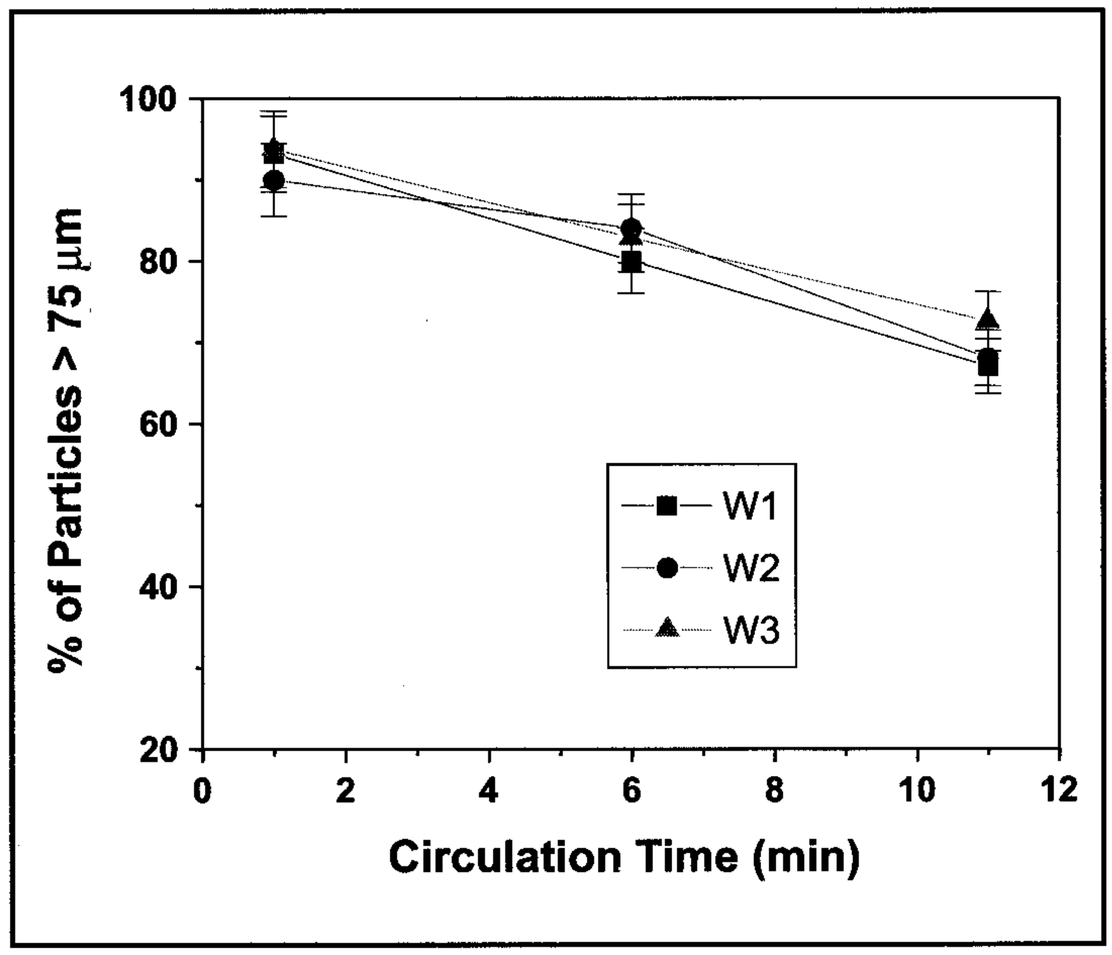

Fig. 3. Percentage of particles larger than 75 µm as a function of circulation time in the particle sizer for whitewater samples W1, W2, and W3 using the PEO/PFR flocculant system. The dosage is 5 mg/L:10 mg/L.

while the flocs formed by CPAM2 cannot resist the shear force and quickly break up. The flocculation of different whitewaters using the PEO/PFR system was also studied and results are shown in Fig. 3. No obvious effect of whitewater on the flocculation was observed. Results from the flocculant optimization study led to the conclusion that the PEO/PFR system should perform well during clarification experiments at relatively low dosages. This flocculant system was utilized in all clarification experiments.

Ultrasonic Clarification

Schematic diagrams of the flow and electrical–acoustic systems for ultrasonic clarification experiments are shown in Figs. 4 and 5, respectively. A close-up schematic of the clarification process is also shown in Fig. 5. Referring to Fig. 4, the main components of the clarification system are a 500 L feed tank, a 450 L/min centrifugal pump, a vertically mounted nonpressurized flow cell identified as the in-line acoustic separator, and two 200 L collection tanks. A mixer is used to prevent sedimentation in the feed tank and a magnetic flow meter is used to monitor the flow rate. Whitewater from the feed tank enters the flow cell from the bottom and passes through the separator. Clean and concentrated output streams exit from the top and are transferred to the collection tanks for sampling. These tanks can be bypassed if desired.

The separator comprises three distinct sections: a flow development section, an acoustic section, and an atmospheric pressure mechanical separation section. The flow development section has a length of 190 cm; its purpose is to control undesirable turbulence patterns from the entrance inlet. Acrylic walls are used on two sides to allow visual flow inspection. The acoustic section is 30 cm in length and refers to a series of three flush-mounted, 5 cm (W) x 10 cm (L) custom-made piezoelectric ceramic transducers on one side of the cell and three sound absorbers opposite to the transducers (see Fig. 5). The clarification process takes place in this section. Sound absorbers are used to alleviate undesirable reflections of the ultrasonic field in the acoustic section. Transducers and absorbers are removable and easily replaceable. Both the flow development and the acoustic sections have similar rectangular cross-sections. One dimension is fixed to 5 cm (corresponding to the width of transducers and absorbers) and the normal dimension (corresponding to the transducer–absorber separation distance) is adjustable from 5 to 15 cm (in 5 cm steps). The mechanical separation section is composed of an adjustable mechanical divider blade whose purpose is to separate clean and concentrated streams. The blade design allows for air to flow through its tip so that flocs do not become stapled to the blade.

The electrical–acoustical system depicted in Fig. 5 illustrates that each transducer can be controlled independently from the oth-

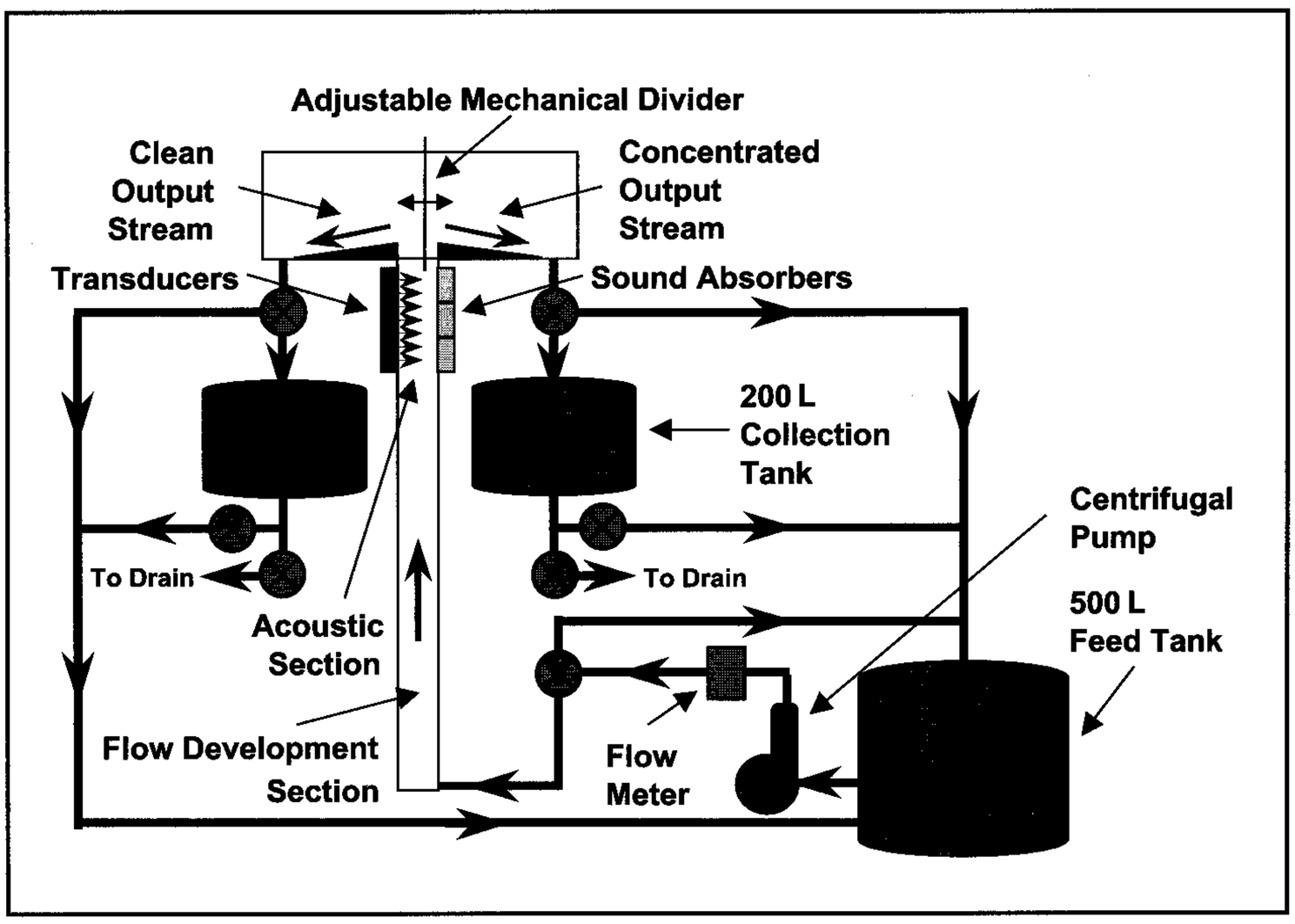

Fig. 4. Schematic diagram of the flow system for clarification experiments. Whitewater flows from bottom to top in the vertically mounted pipe located between the 200 L collection tanks. The clarification process takes place in the acoustic section.

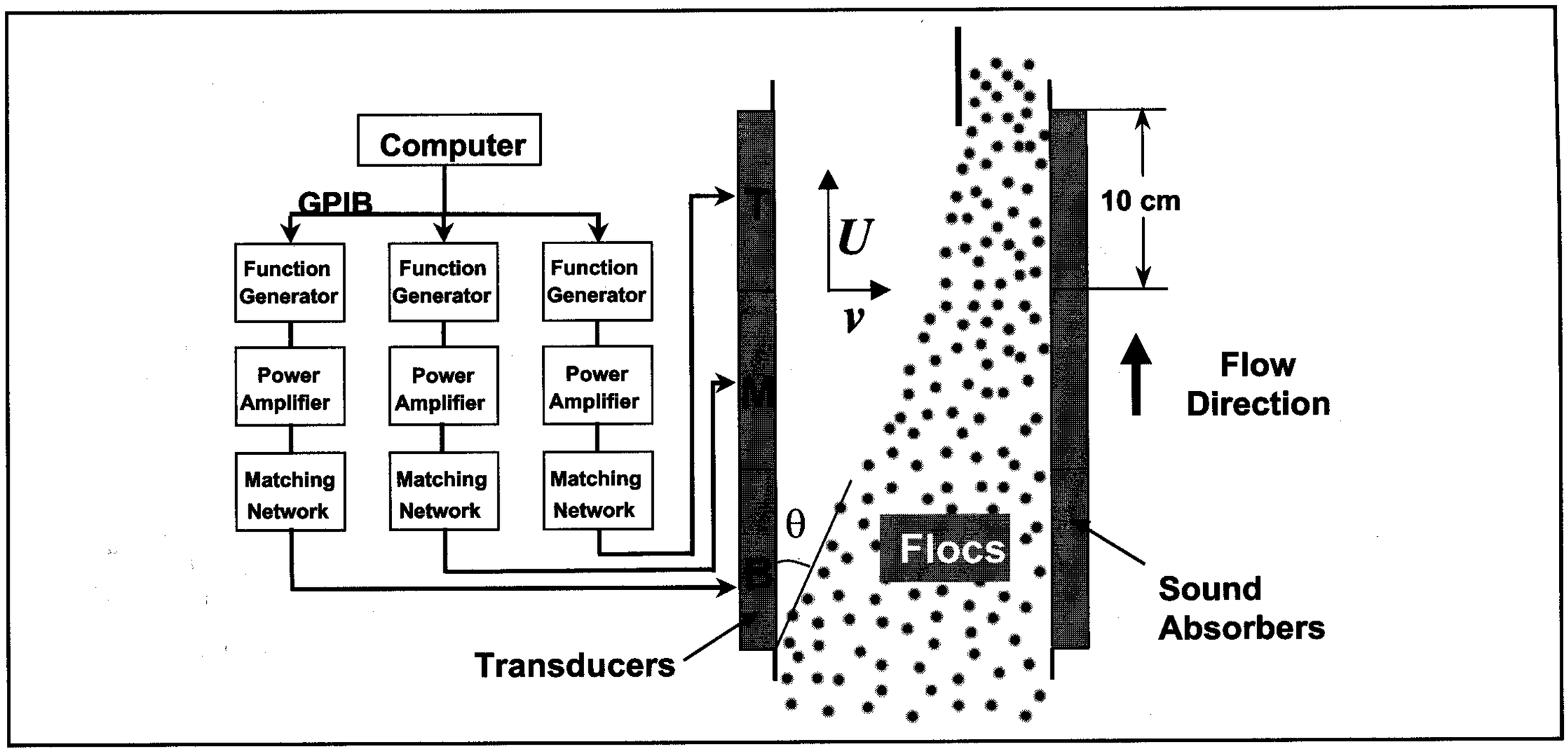

Fig. 5. Schematic diagram of computer-controlled electrical/acoustical system and close-up of clarification process. T, M, and B refer to Top, Middle, and Bottom ultrasonic transducers, respectively. *U* and *v* represent the flow and flow migration velocities, respectively. Flocs are deflected toward the absorbers by an angle θ as they move upward and interact with the ultrasonic field.

ers. Function generators (HP Model 33120A) are set to produce continuous sine waves to match the specified operating frequency of the transducers. Outputs from the function generators are fed into broadband power amplifiers (ENI Models 1140LA and 240L) capable of delivering the necessary output power to drive the transducers. As the electrical output impedance of the power amplifiers is 50 Ω and the electrical input impedance of the transducers is significantly larger, matching impedance networks are used to optimize transfer of electrical power to the transducers. Built-in meters supplied with the amplifiers are used to monitor the electrical power applied to the transducers. In order to determine the electrical-to-acoustic power efficiency conversion, acoustic-force-equivalent mass balance measurements were performed using individual transducers mounted in a special water tank [20]. Results showed that for transducers operating at 60 kHz, 150 kHz and 1.5 MHz, the power conversion efficiency factor exceeded 80, 90 and 70%, respectively.

Feasibility Study

Preliminary clarification experiments were conducted at the 5 cm transducer–absorber separation distance. Deflection of flocculated whitewater was easily observed. However, the relatively small separation distance did not allow satisfactory sampling of clean and concentrated streams. For this reason, it was decided to increase the separation distance to 15 cm. Also, the mechanical divider was set constant at the middle (50:50) position. When the separation distance was changed from 5–15 cm, whitewater samples W1 and W2 were no longer available, and all subsequent results were obtained using only sample W3 (cloudy whitewater from 100% ONP).

Table III summarizes the experimental design for the demonstration of whitewater clarification. All experiments involved varying the acoustic intensity (acoustic power per unit transducer area) at constant transducer frequency and constant flow velocity. Three transducer frequencies were investigated: 60 kHz, 150 kHz, and 1.5 MHz. The flow velocity was varied between 0.1 and 0.4 m/s in increments of 0.1 m/s. This velocity range corresponds to flow rates of 45–180 L/min and Reynolds numbers of approximately 7500 to 30 000 at room temperature (turbulent flow regime conditions). Equipment limitations did not allow testing at acoustic intensities higher than 3 W/cm^2 when using 1.5 MHz transducers. The PEO/PFR flocculant dosage was generally set to 5 mg/L:10 mg/L. Additional runs at 1.5 MHz were performed at 2 mg/L:4 mg/L.

TABLE III
EXPERIMENTAL DESIGN

Transducer Frequency	PEO/PFR Dosage	Flow Velocity (m/s)	Acoustic Intensity (W/cm²) 0	1	2	3	6	10
60 kHz	5 mg/L:10 mg/L	0.1	X	X	X	X		
150 kHz	5 mg/L:10 mg/L	0.1	X	X	X	X	X	X
		0.2	X	X	X	X	X	X
		0.3	X	X	X	X	X	X
		0.4	X	X	X	X	X	X
1.5 MHz	5 mg/L:10 mg/L	0.1	X	X	X	X		
		0.2	X	X	X	X		
		0.3	X	X	X	X		
		0.4	X	X	X	X		
1.5 MHz	2 mg/L:4 mg/L	0.1	X	X	X	X		
		0.2	X	X	X	X		

A typical run involved approximately 180 L of fresh whitewater in the feed tank. PFR was first added to the whitewater. Once the flow velocity was adjusted according to the experimental design, PEO was added, thus triggering flocculation. Considering the relatively small volume of water, the flow system was operated in a batch mode to allow observations at different acoustic intensity levels or different number of transducers. The need for recirculation necessitated the use of flocculants at a higher dosage than would be required under a constant supply of fresh whitewater to compensate for the rapid degradation of the flocculation effect due to multiple shearing through the pump.

An analog camera connected to a SVHS video recorder was used to record the deflection of flocculated whitewater in the acoustic section. A fibre optic backlight was used to create

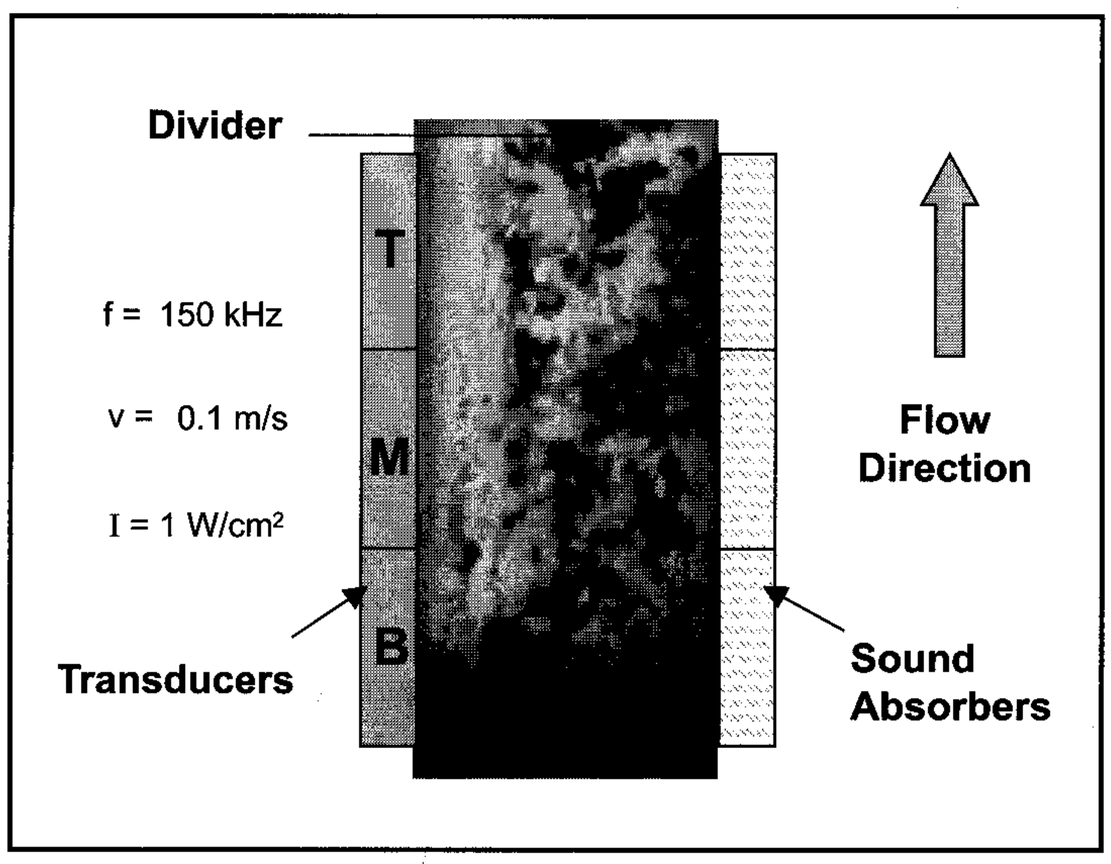

Fig. 6. Whitewater clarification using three 150 kHz transducers. The PEO/PFR level is 5 mg/L:10 mg/L.

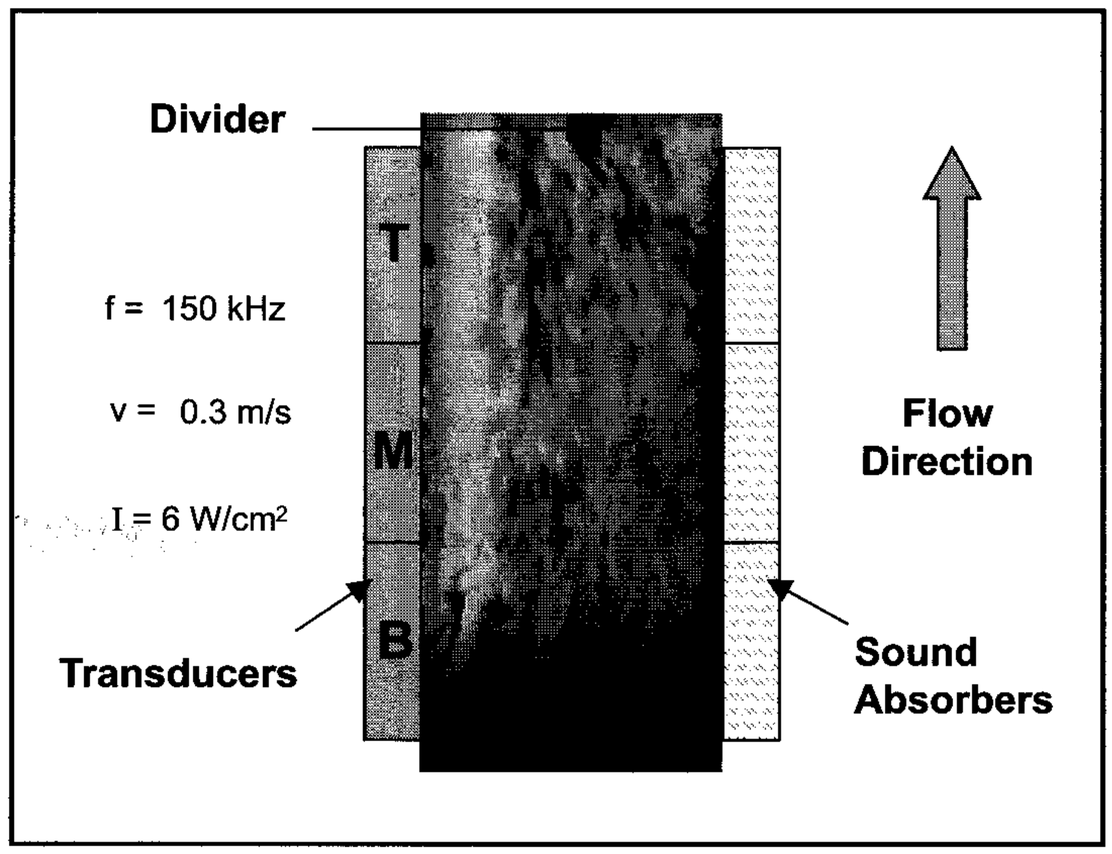

Fig. 7. Whitewater clarification using three transducers operating at 150 kHz. The PEO/PFR level is 5 mg/L:10 mg/L.

uniform lighting conditions. Analysis of the video recordings consisted of determining the initial deflection angle θ as depicted in Fig. 5. Three seconds of video (at 30 frames/s) were digitized and averaged together frame by frame. After the operator identified the initial deflection line, the computer calculated the angle. Five successive 3 s segments were analyzed for each recording. Average and standard deviation were then computed. As a first approximation, the initial deflection angle θ can be related to the flow velocity U and the floc migration velocity v (normal to the flow velocity) using the following equation (see Fig. 5):

$$\tan\theta = \frac{v}{U} \tag{1}$$

One should note that velocity gradients across the flow cell are neglected here. Assuming that v is constant at constant acoustic intensity, Eq. (1) can be rearranged as:

$$\frac{1}{\tan\theta} = \left(\frac{1}{v}\right)U \tag{2}$$

where $1/v$ is the slope of the linear relationship between $1/\tan\theta$ and U. Equation 2 can be used to determine v.

Simultaneous sampling of clean and concentrated streams was achieved using 10 L buckets. Only 500 mL of whitewater was kept for consistency measurements (TAPPI Test Method T 240 [25]) and the leftover liquid was put back in the feed tank to minimize depletion of whitewater for subsequent runs. The flocculation effect degraded after a certain number of runs (can be seen visually), and additional flocculants were added or the whitewater was simply replaced with fresh whitewater.

Finally, equations describing the clean stream solids removal efficiency and clarification efficiency as a function of the divider blade position and feed and clean stream consistencies were derived (see Appendix):

% Clean Stream Removal Efficiency

$$= \left(1 - \frac{C_{clean}}{C_{feed}}\right) \times 100\% \tag{3}$$

% Clarification Efficiency

$$= \left(\frac{\ell_t}{\ell}\right)\left[\frac{C_{feed} - C_{clean}}{C_{feed}\left(1 - \frac{C_{feed}}{100\%}\right)}\right] \times 100\% \tag{4}$$

where C_{feed} and C_{clean} are the percent consistencies of the input feed stream and output clean stream respectively, and ℓ and ℓ_t are the transducer–absorber separation distance and position of the divider blade from the transducer side, respectively. In order to achieve 100% clarification in Eq. (4), all solids must be completely separated from the water, and the divider blade position must be such that only solids are in the concentrated output stream and only water is in the clean output stream.

RESULTS AND DISCUSSION

Several clarification experiments were conducted using whitewater W3 and the flocculant system PEO/PFR. In general, it was found that experiments performed using the 60 kHz transducers were not satisfactory. This may be attributed to a lower threshold for cavitation at this frequency when compared to observations at 150 kHz and 1.5 MHz [20]. For a given amount of acoustic power coming from the 60 kHz transducer, a larger percentage of power is put into cavitation at this frequency than at higher frequencies and, hence, less power is available to deflect the fibres. Therefore, results obtained at 60 kHz are not reported.

Selected frames from the video recordings of the clarification effect at 150 kHz are shown in Figs. 6 through 8. In these figures, flocculated whitewater (dark areas) is deflected toward the right (absorbers); white areas represent clarified water. Comparison of Figs. 6 and 7 shows that a 0.1 m/s flow velocity and a 1 W/cm² acoustic intensity produce a similar deflection effect as a flow velocity of 0.3 m/s and an acoustic intensity of 6 W/cm². While these observations are qualitative and subject to experimental error, they indicate that a more intense ultrasonic field is generally required to counterbalance a larger flow velocity. In both cases, deflection of flocs occurs very early in the acoustic section (bottom transducer position). Although not clearly visible in Figs. 6 and 7, the deflection effect past the initial stage is

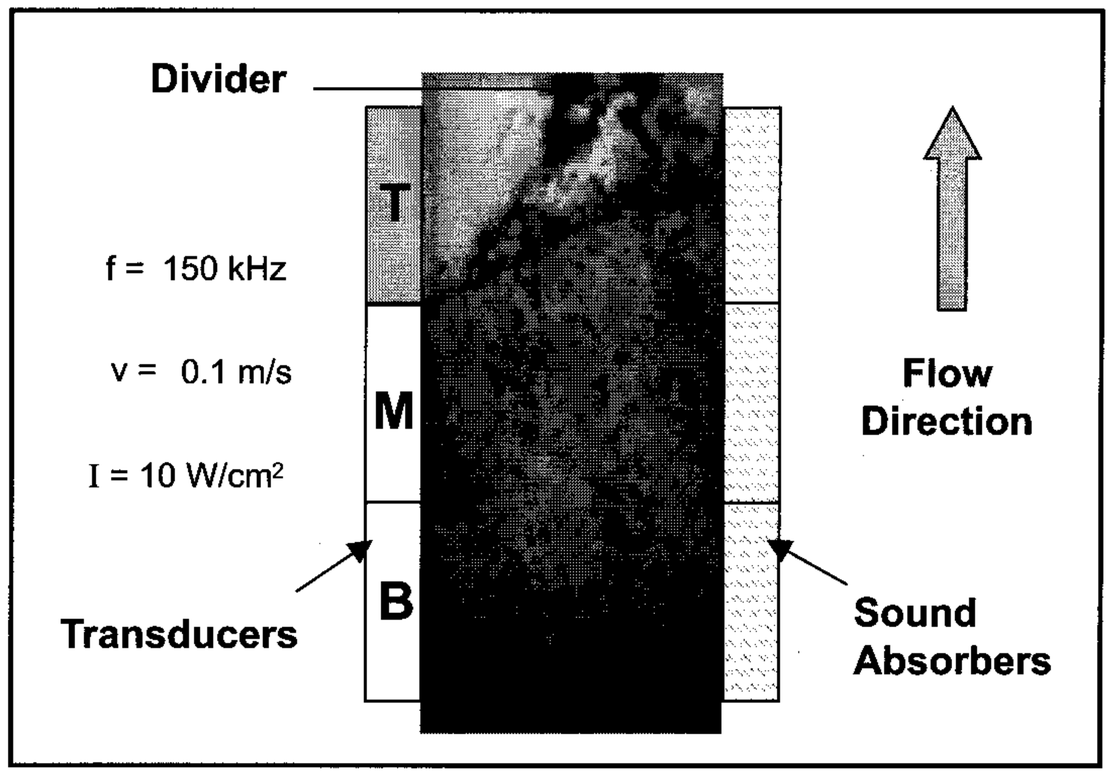

Fig. 8. Observation of clarification using only the top transducer. The transducer frequency is 150 kHz. The PEO/PFR level is 5 mg/L:10 mg/L.

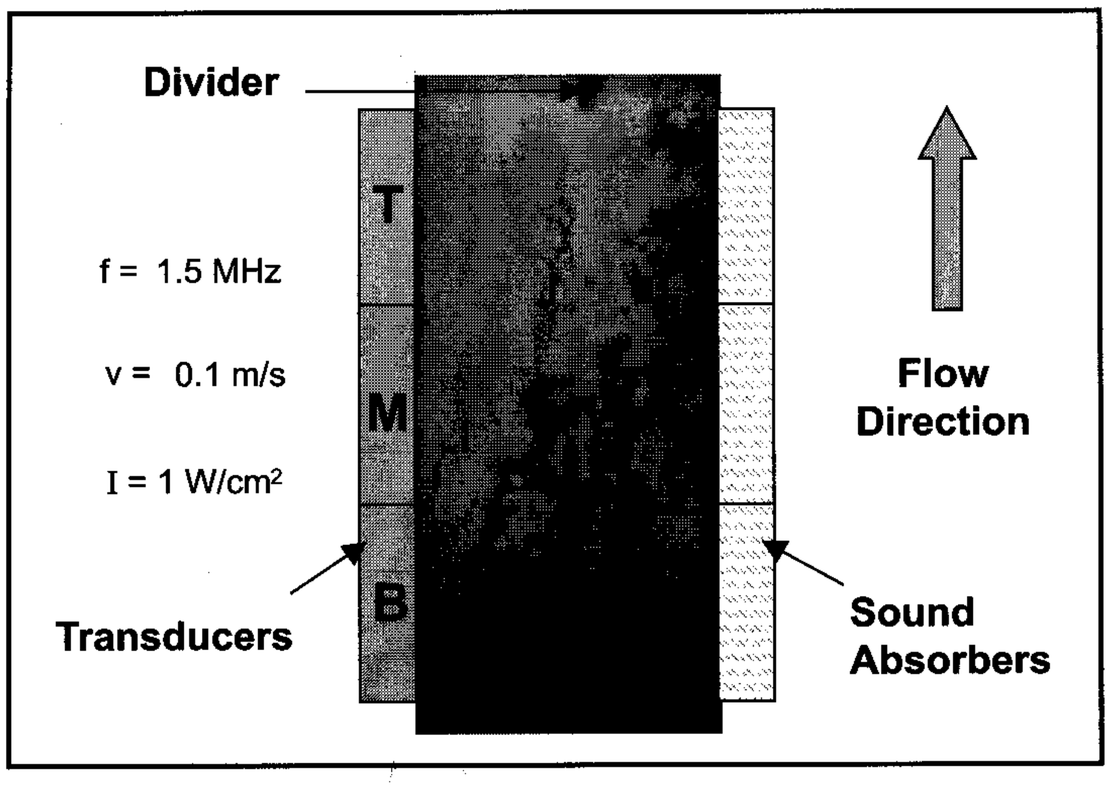

Fig. 9. Whitewater clarification using three 1.5 MHz transducers. The PEO/PFR level is 5 mg/L:10 mg/L.

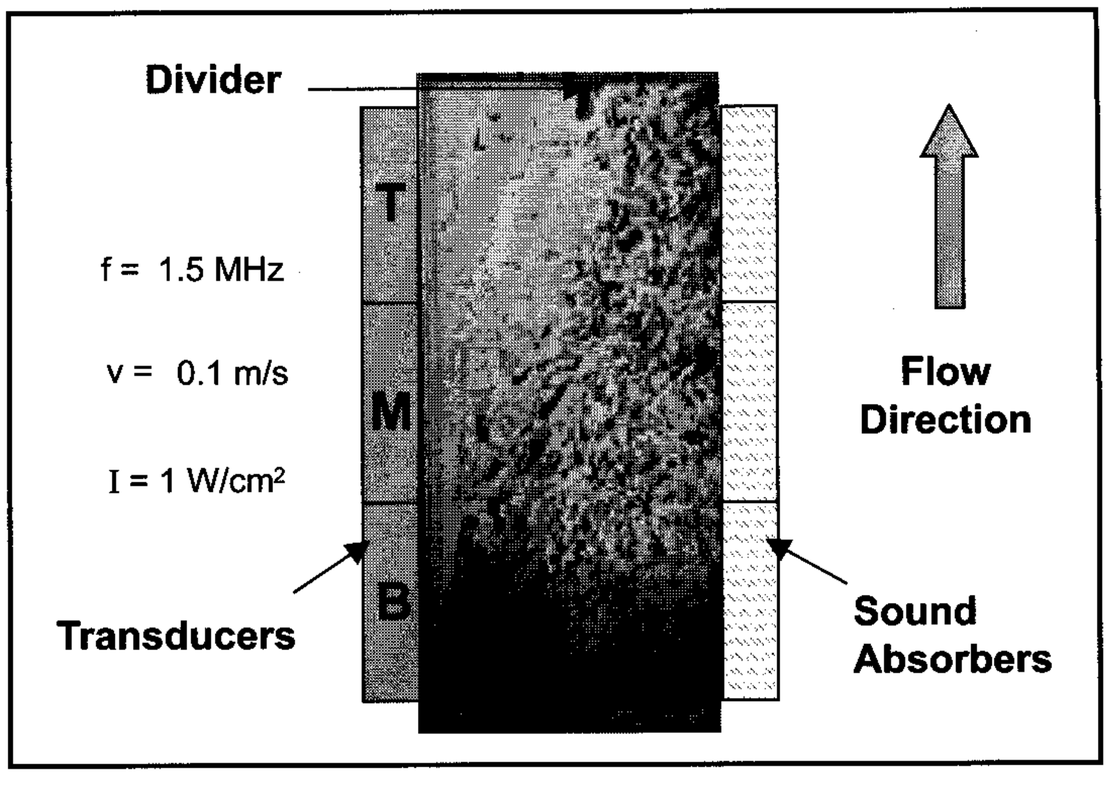

Fig. 10. Clarification recording using three transducers operating at 1.5 MHz. The PEO/PFR level is 2 mg/L:4 mg/L.

somewhat mitigated by the presence of undesirable back flows at the walls (edge effects). Possible causes include nonuniformity of the ultrasonic field, undesirable reflections of the ultrasonic field in the acoustic section, and the rectangular cross-section of the flow cell. Neither a detailed analysis of the back flows nor any attempt to eliminate them was made.

Figure 8, which involves the excitation of the top transducer only, is interesting because it indicates that an intensity of 10 W/cm^2 at 0.1 m/s produces a significantly larger deflection than seen in Fig. 6. However, the intensity level is such that the absorber is not very efficient in preventing reflection of the ultrasonic field transmitted through the whitewater. The end result is an apparent mirror deflection effect located between transducers and absorbers. Optimization of this effect by replacing the absorber by a reflective surface (or a transducer) might provide an alternative approach to the clarification process by collecting flocs from the centre of the acoustic section.

Figure 9 provides an example of a recording at 1.5 MHz. To facilitate comparison with Fig. 6, all test conditions but frequency are identical. A smaller initial deflection angle is denoted. However, since undesirable secondary flows are less prevalent at this frequency (presumably because the ultrasonic field is more uniform), floc deflection occurs over the full length of the acoustic section. This leads to superior clarification efficiency, but at the possible expense of a less economical use of ultrasonic equipment. The reduction in flocculant dosage from 5 mg/L:10 mg/L to 2 mg/L:4 mg/L in Fig. 10 does not significantly degrade the deflection effect seen in Fig. 9 as long as flocculated whitewater is not recirculated several times in the flow system.

Just as excessive cavitation appears to be detrimental to the deflection effect at low frequency (60 kHz), the reduced level of cavitation at 1.5 MHz appears to be counterproductive as well. Because the ratio of the density of air bubbles to water is much smaller than the ratio of the density of flocs to water, air bubbles are easier to manipulate by the ultrasonic field than flocs are. It is possible that cavitation bubbles forming on the surface of the flocs significantly enhance their deflection. Hence, the proper balance between the amount of acoustic power going into bubble formation and the amount available for deflection may lead to optimal deflection of the flocs. At 1.5 MHz, the balance is tipped away from bubble formation, preventing efficient deflection of the flocs. One can hypothesize that the cavitation level at 150 kHz is such that the number and/or size of air bubbles offers a superior set of conditions for floc deflection. Whether or not 150 kHz is an optimized frequency for whitewater clarification remains to be determined through observations at other frequencies between 60 kHz and 1.5 MHz.

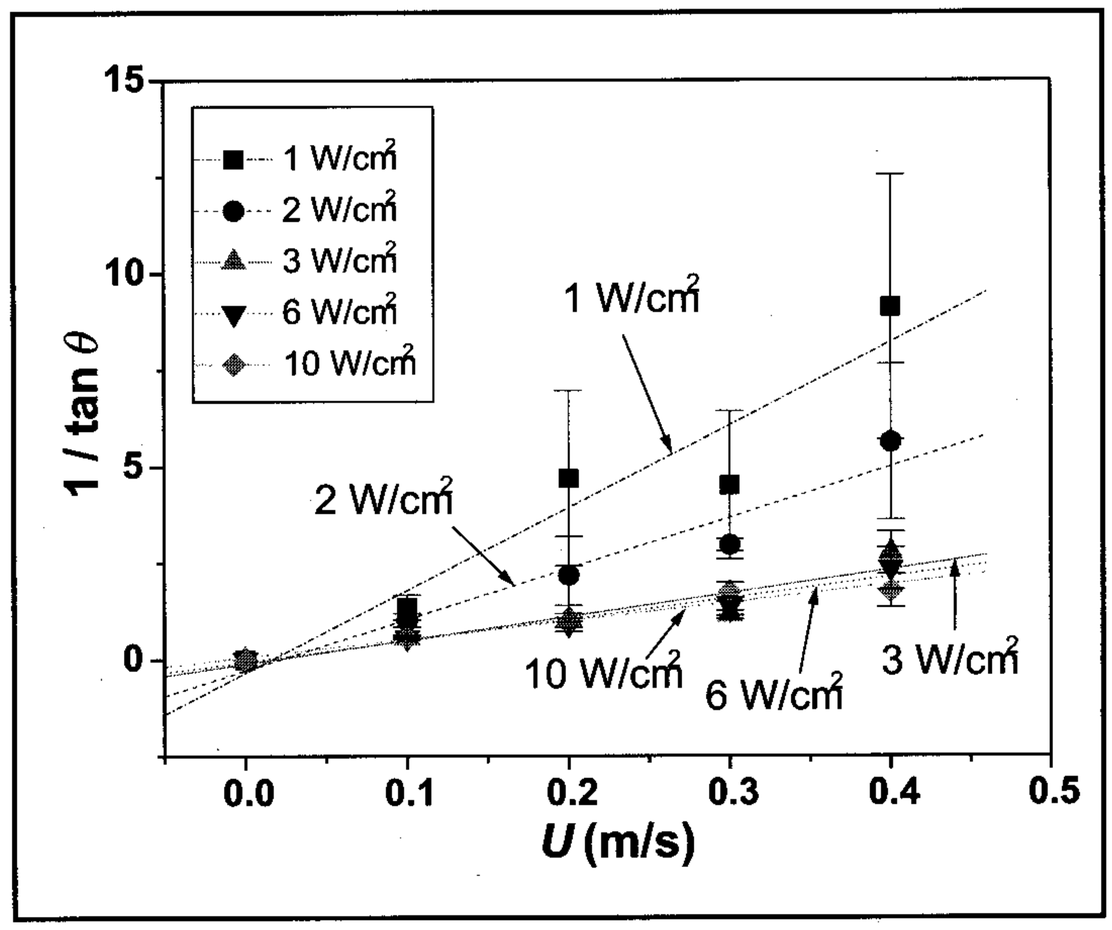

Fig. 11. Plot of 1/tan θ vs U for different acoustic intensity levels at 150 kHz. Linear curve fitting from 0 to 0.4 m/s was used to determine the floc migration velocity v per acoustic intensity level. Results are presented in Fig. 13.

The initial deflection angle for all test conditions at 150 kHz and 1.5 MHz was determined according to the method previously described. In agreement with Eq. (2), results expressed as 1/tan θ versus U are presented in Figs. 11 and 12. Even though some results appear problematic (see below), an overall inspection supports linear trends. At constant acoustic intensity, 1/tan θ linearly increases when the flow velocity increases. Also, at constant flow velocity, 1/tan θ decreases when the acoustic intensity increases. Overlapping of the 150 kHz measurements at 3, 6, and 10 W/cm^2 (Fig. 11) suggests that there is a plateau for the acoustic intensity. In other words, too much intensity does not improve floc deflection and can be considered as wasted energy. Results gathered at 1.5 MHz (Fig. 12) also show linear trends. Since measurements above 3 W/cm^2 are not available, the existence of a plateau at/or above 3 W/cm^2 cannot be confirmed at 1.5 MHz. Difficulties in getting better quality results can be explained by variations in the flow velocity (±10%), the presence of secondary flows (especially at 150 kHz), degradation of the flocculant during experiments, and variations in flocculation efficiency between experiments.

Linear curve fitting applied to the results shown in Figs. 11 and 12 was used to determine the floc migration velocity as a function of acoustic intensity. Results are reported in Fig. 13. Since a strong linear relationship (R^2 = 0.997) is observed at 1.5 MHz, it is likely that there is a linear relationship as well at 150 kHz even though data points are more scattered. Larger velocities at 150 kHz confirm that energy is more efficiently used at this frequency in

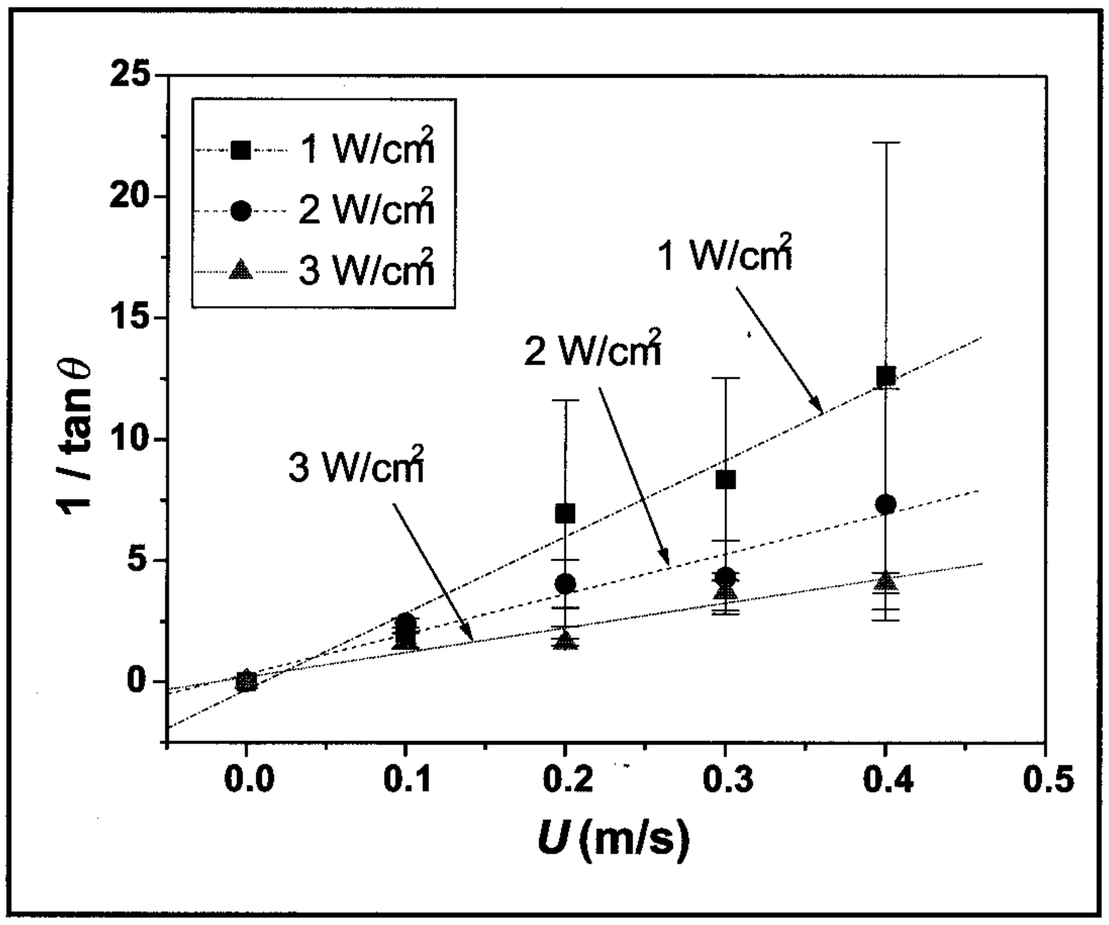

Fig. 12. Plot of 1/tan θ vs U for different acoustic intensity levels at 1.5 MHz. Linear curve fitting from 0 to 0.4 m/s was used to determine the floc migration velocity v per acoustic intensity level. Results are presented in Fig. 13.

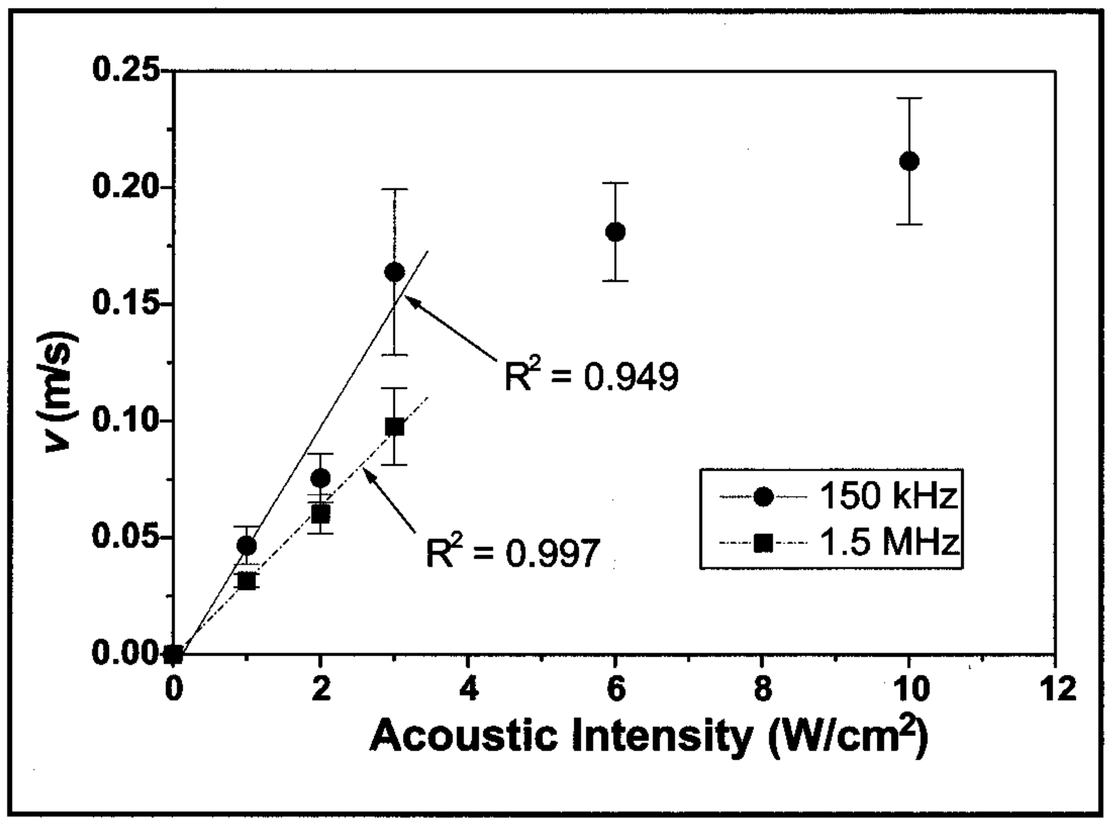

Fig. 13. Graph of the floc migration velocity v vs acoustic intensity for measurements obtained at 150 kHz and 1.5 MHz. Linear curve fitting between 0 and 3 W/cm^2 was used to relate v and acoustic intensity: slope at 150 kHz: 0.052 ± 0.008 $\left(\frac{m}{s}\frac{cm^2}{W}\right)$; slope at 1.5 MHz: 0.032 ± 0.001 $\left(\frac{m}{s}\frac{cm^2}{W}\right)$.

the initial stage of deflection.

Consistency measurements performed on the clean and concentrated output are shown in Figs. 14 and 15 for experiments at 150 kHz and 1.5 MHz, respectively. Even though there is a distinctive change in consistency between the two output streams at 150 kHz (Fig. 14), secondary flows present at this frequency adversely affected performance. Also, too much intensity (e.g. at 10 W/cm^2) further degrades performance, as previously observed in Fig. 8. Consistency results at 1.5 MHz (Fig. 15) show larger changes in consistency between the two output streams (between 80 and 90%). The clean stream consistency is less than 0.01% or 100 ppm of solids, i.e. in agreement with measurements typically obtained using a DAF system.

The clean stream solids removal efficiency and clarification efficiency were determined using Eqs. (3) and (4). Results are presented in Figs. 16 and 17 for 150 kHz and 1.5 MHz observations, respectively. As expected from consistency measurements, best efficiency results were obtained at 1.5 MHz. Since the divider blade position was set to 50:50, the maximum achievable clarification efficiency was 50%. Hence, the nearly 40% result at 1.5 MHz corresponds to 80% of the maximum achievable clarification efficiency in the experimental setup. This is not anywhere close to the clarification efficiency obtainable using a commercial DAF system, which is typically higher than 90%. However, as illustrated in the Appendix, one expects optimization of the ultrasonic technology to provide a comparable

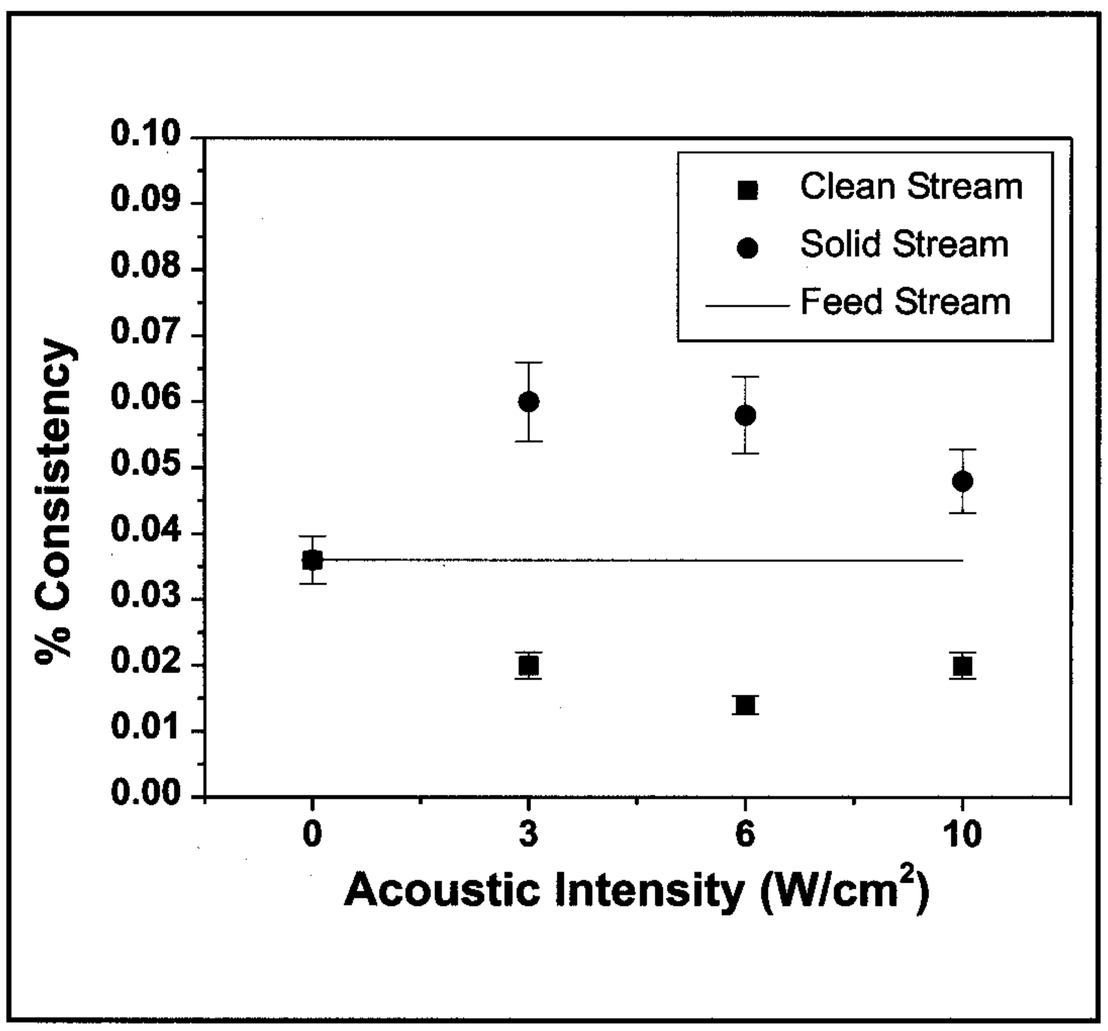

Fig. 14. Clean and concentrated streams consistency measurements vs. acoustic intensity for experiments performed at 150 kHz using the top transducer only. The flow velocity and flocculant dosage are set to 0.1 m/s and 5 mg/L:10 mg/L, respectively. The feed stream consistency is provided as a reference point for comparison.

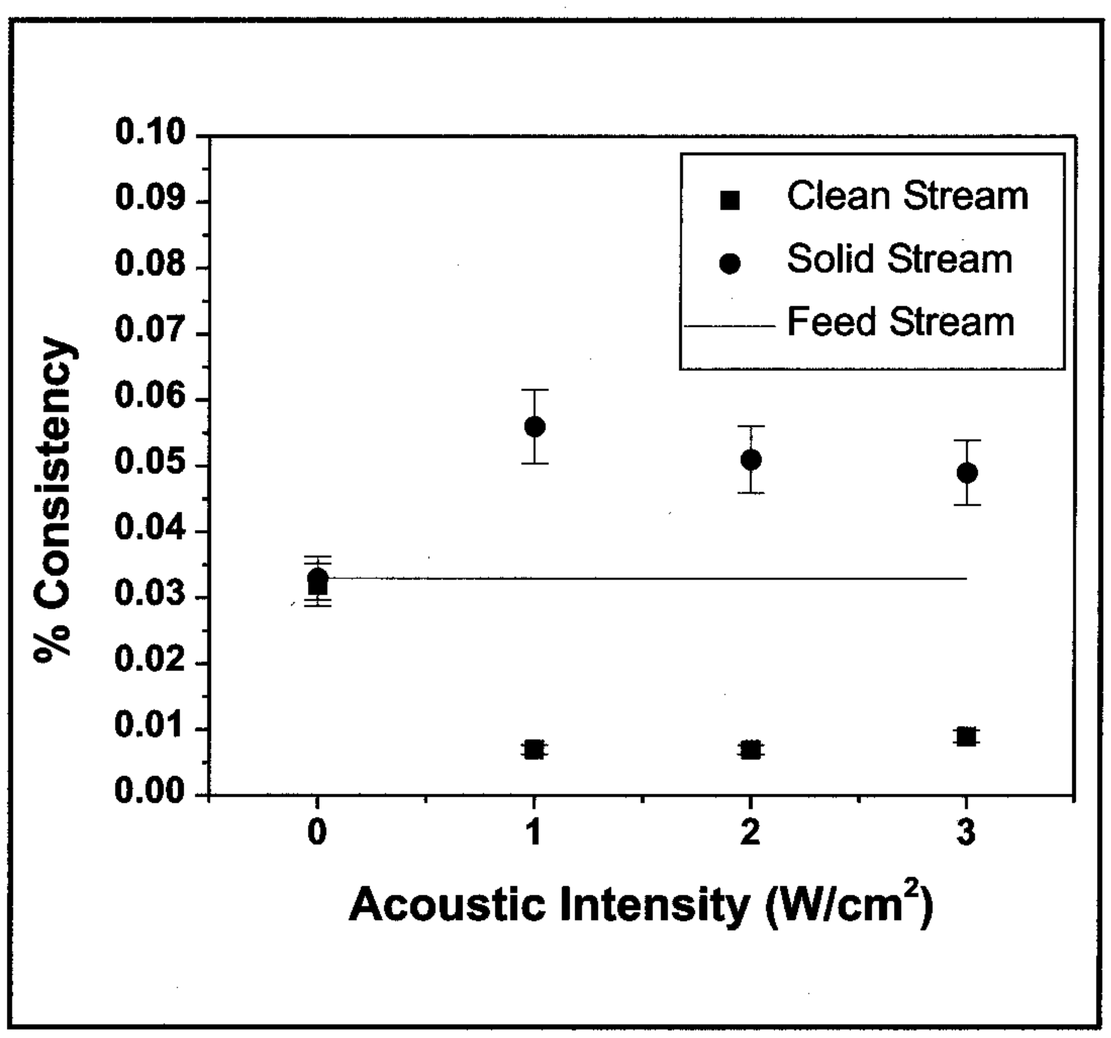

Fig. 15. Clean and concentrated streams consistency measurements vs. acoustic intensity for experiments performed at 1.5 MHz using three transducers. Flow velocity and flocculant dosage are set to 0.1 m/s and 5 mg/L:10 mg/L, respectively. The feed stream consistency is provided as a reference point for comparison.

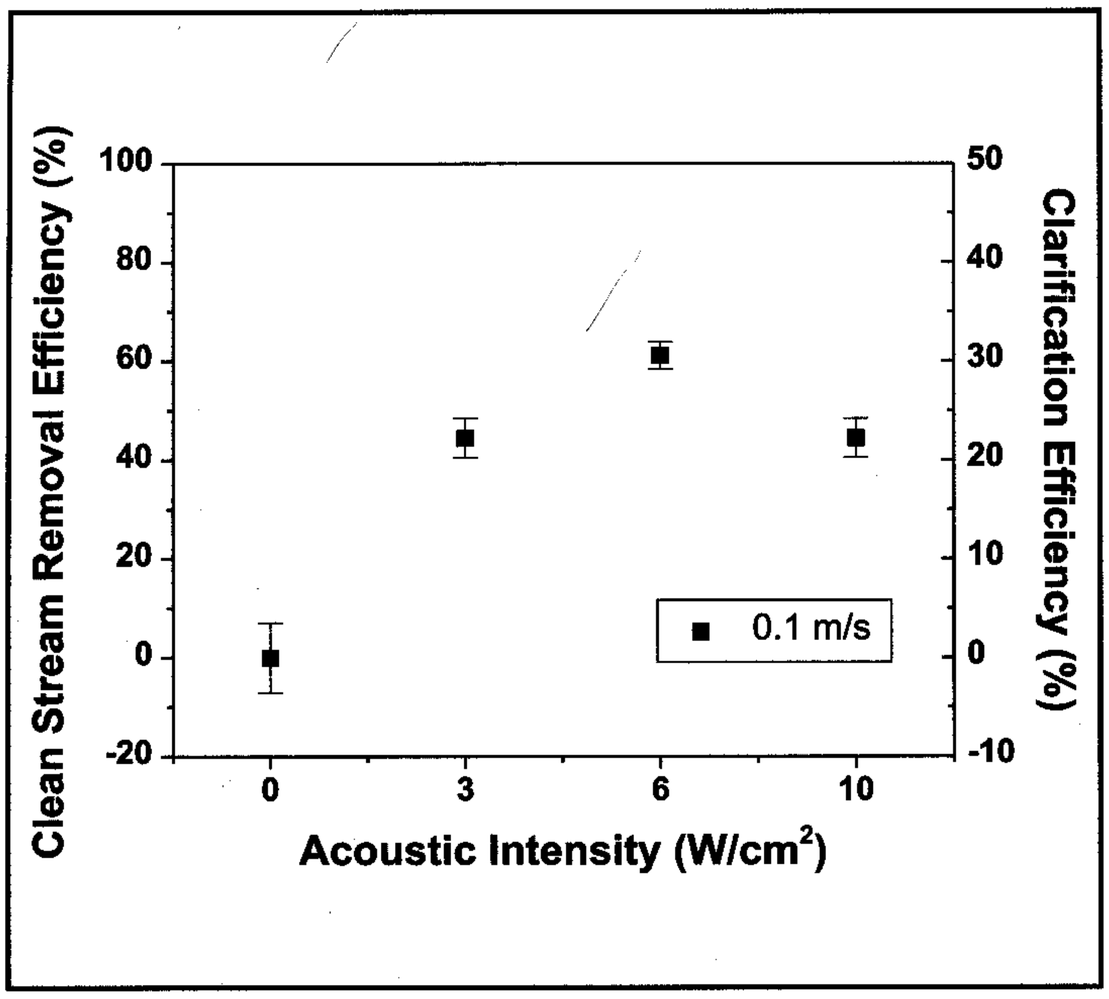

Fig. 16. Clean stream solids removal efficiency and clarification efficiency for the 150 kHz results shown in Fig. 14. Since the divider blade position is at the 50:50 position, the clarification efficiency cannot exceed 50%.

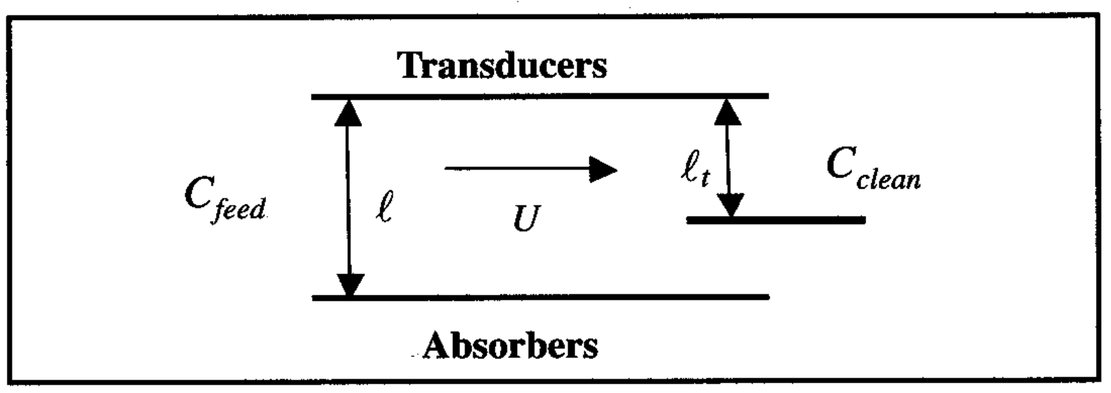

Fig. 17. Geometry of flow cell. C_{feed} and C_{clean} are the feed and clean stream consistencies, respectively; ℓ is the separation distance between the transducers and absorbers; ℓ_t is the distance between the transducers and the divider blade; and U is the flow velocity.

TABLE IV
ESTIMATED COST FOR A 22 750 L/min (6000 gal/min) HYPOTHETICAL ULTRASONIC CLARIFICATION SYSTEM AND COMMERCIAL DISSOLVED AIR SYSTEM

Item	Ultrasonic Clarifier ($k)	DAF System ($k)
Capital and Installation Cost	352	1073
Annual Energy Cost for Ultrasonic Equipment	45	0
Annual Chemicals Cost for Pumping	8	103
Annual Chemicals Cost	168	250
Total Annual Operating Cost	221	353

level of efficiency.

ECONOMIC ASSESSMENT

A preliminary economic assessment of the clarification method was conducted. Chemical costs for PEO and PFR are approximately $5/kg and $1/kg, respectively. This means that the cost associated with using these chemicals at the 5 mg/L:10 mg/L and 2 mg/L:4 mg/L dosages are $0.035/1000 L ($0.133/1000 gal) and $0.014/1000 L ($0.053/1000 gal), respectively. Since the need to maintain flocculation for several cycles would not apply for continuous in-line treatment in a mill environment, the use of a lower dosage level is expected and, hence, expected chemical costs should be lower than the above figures.

Initial deflection angle measurements presented in Figs. 11 and 12 were used to predict the cost of a hypothetical in-line whitewater ultrasonic clarification system aimed at increasing the feed stream consistency by a factor of 10. The basis for comparison was a 22 750 L/min (6000 gal/min) commercial DAF system. Table IV shows capital (including installation cost in the mill) and total annual operation costs for the ultrasonic clarifier and DAF system. It is assumed that the ultrasonic clarifier operates under the following conditions: frequency of 150 kHz, flow velocity of 0.3 m/s, and acoustic intensity of 3 W/cm^2. Also, the PEO/PFR flocculant dosage is 2 mg/L:4 mg/L. For this scenario, a unit-annualized cost of $0.025/1000 L ($0.094/1000 gal) was estimated for the ultrasonic clarifier (including chemical costs). Even though data presented in Table IV are favourable to the technology, a more realistic economic analysis needs to be performed using a pilot clarifier operated on a continuous basis in a mill.

In addition to the expected cost reductions with the ultrasonic technology, there are other advantages over a conventional DAF. First, the ultrasonic clarifier will be much smaller in footprint. A 22 750 L/min clarifier will require less than 5 m^2 (55 ft^2) of floor space, compared to the several hundred square metres (several thousand square feet) for a DAF of the same size. Second, because the ultrasonic clarifier is a closed system, no special environmental equipment will need to be installed to control emissions because there will be no open surface for emissions to escape.

CONCLUSIONS

A laboratory feasibility study using chemical flocculation in combination with an ultrasonic wave field to clarify whitewater was reported. In a preliminary set of experiments, different flocculants were tested and the flocculant system PEO/PFR was determined to be the most effective to increase the size of whitewater solids in preparation for ultrasonic clarification. Observations of floc deflection at different ultrasonic frequencies showed that the process was more efficient at 150 kHz than at 60 kHz or 1.5 MHz. A trend of increasing deflection angle with increasing acoustic intensity was seen at 150 kHz and 1.5 MHz, up to an intensity of 3 W/cm^2. Beyond this, an increase in intensity did not yield significantly higher deflection angles. Increasing flow velocity at constant acoustic intensity reduced the deflection angle. Clarification efficiency was largest at 1.5 MHz, even though floc deflection was lower at this frequency when compared to observations at 150 kHz. Lower clarification efficiency at 150 kHz was a consequence of undesirable secondary flows disrupting the deflection mechanism. Finally, as a preliminary economic assessment of the technology, a hypothetical 22 750 L/min (6000 gal/min) ultrasonic whitewater clarifier was compared to a DAF system of the same size. The clarifier was estimated to cost 66% less than the DAF to purchase and install, and 35% less to operate.

The technology remains to be demonstrated at the pilot level. An improved design of the flow system is needed to minimize secondary flows and optimize floc deflection. Larger transducers operating under pressurized conditions must be developed. Experiments using a continuous supply of whitewater are required to determine the lowest flocculant dosage and better appreciate the various operating features (consistency, flow velocity, ultrasonic frequency, acoustic intensity). Also, observations as a function of the divider blade position are necessary to optimize clarification efficiency.

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APPENDIX: CLARIFICATION EFFICIENCY

In order to achieve 100% clarification efficiency, both the divider blade position and the clean stream solids removal efficiency should

be optimized, i.e.

% Clarification Efficiency

= (Optimal Divider Position)

× (% Clean Stream Removal Efficiency) (5)

Referring to Fig. 17, the clean stream consistency is optimized when it goes to zero. Hence, the clean stream solids removal efficiency is given by,

% Clean Stream Removal Efficiency

$$= \left(1 - \frac{C_{clean}}{C_{feed}}\right) \times 100\% \quad (6)$$

where C_{clean} is the % clean stream consistency and C_{feed} is the % feed stream consistency.

The divider position is optimized when it reaches the position furthest from the transducer that is theoretically possible. Referring to Fig. 18, if the water and concentrated solids (flocs) are 100% separated, with pure water on the top of the cell and only flocs on the bottom, the water forms a layer ℓ_{water} thick, and the flocs forms a layer ℓ-ℓ_{water} thick.

Hence, optimal divider position is achieved when $\ell_t = \ell_{water}$, which can be written mathematically as:

$$\text{Optimal Divider Position} = \left(\frac{\ell_t}{\ell_{water}}\right) \quad (7)$$

The thickness of the water layer for 100% separation is simply the percent water in the feed stream [(100% – C_{feed})/100%] multiplied by the cell width (ℓ):

$$\ell_{water} = \ell\left(1 - \frac{C_{feed}}{100\%}\right) \quad (8)$$

Hence combining Eqs. (7) and (8) yields

$$\text{Optimal Divider Position} = \frac{\ell_t}{\ell\left(1 - \frac{C_{feed}}{100\%}\right)} \quad (9)$$

Substituting Eqs. (6) and (9) into Eq. (5) then gives the clarification efficiency:

% Clarification Efficiency

$$= \left(\frac{\ell_t}{\ell}\right)\left[\frac{C_{feed} - C_{clean}}{C_{feed}\left(1 - \frac{C_{feed}}{100\%}\right)}\right] \times 100\% \quad (10)$$

In order to illustrate Eq. (10) and the hypothetical performance of an acoustic clarifier, one can consider a whitewater stream entering the flow cell at 0.03% consistency. If the clean stream consistency is 0.001%, and the divider blade is placed at 97% of the way across the flow cell ($\ell_t/\ell = 0.97$), the efficiency of the clarification process is then 94%.

This is comparable to a typical DAF system.

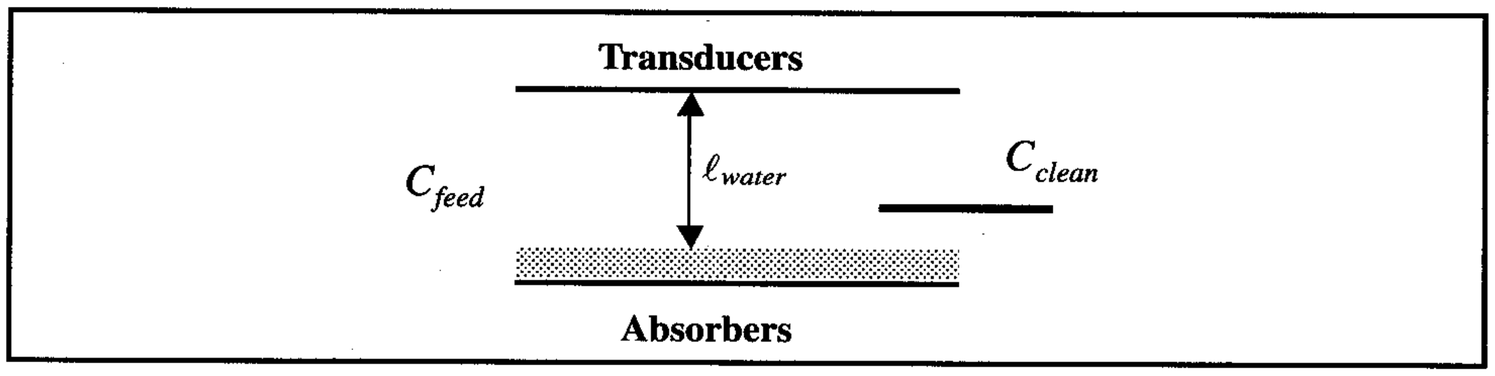

Fig. 18. Flocs on bottom of flow cell are completely separated from water on top of flow cell. Thickness of water layer is ℓ_{water}.

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