Paper machine white water deaeration and two-stage flotation with channel flow

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ABSTRACT: Detrimental substances that originate from deinked pulps and other raw materials tend to build up in paper machine circulation waters, hindering process efficiency and paper quality. The applicability of selective flotation to remove substances from circulation waters was investigated in a two-stage flotation process in which no chemical additives were used. The first stage of the process consisted of a flow channel for white water deaeration, including first-stage flotation. The overflow of the channel flow flotation was further treated in a separate second-stage flotation. The efficiency of the flow channel and a secondary flotation to remove bubbly gases, ink, stickies, and wood extractives were quantified in relation to the reject flow rates or solids yield. The total removal efficiency of a simulated two-stage flotation process was then analyzed for a specific case. The results showed that a considerable reduction of contaminant load can be obtained using a two-stage flotation process without affecting the deaerating function of the channel flow. Further optimization of the proposed internal white water purification scheme may provide substantial benefits to paper or board machine operations with reasonable solids recovery rate.

Application: This study demonstrates how the application of selective multiphase flotation can be applied to paper machine loops to deaerate and purify circulation waters. It also demonstrates that contaminant removal can be efficient in nonoptimized systems in relation to reject ratios.

The accumulation of detrimental substances in paper machine circulation waters is known to cause diverse runnability and quality issues in the papermaking process. In the paper- and boardmaking processes that use recycled fiber, these contaminants consist primarily of hydrophobic material, such as inks, various adhesives (stickies), and wood extractives (pitch) [1-5]. Furthermore, systematic efforts are being made to minimize water usage in paper mills. As a result, closed water circulation is used, increasing contaminant concentrations to levels that cause agglomeration and the deposition of contaminants [6-10].

Using flotation to clean process water at the closed water loops of a paper machine is not a common practice. Flotation and the associated gas feed into circulation water have been avoided for fear of elevated gas content in the head box flow. Therefore, other means of purifying process waters, such as “kidneys,” have been considered [11]. Recycled pulp processes, however, commonly use flotation and microflotation units to remove detrimental components. The most closely related applications for paper machines are the dissolved air flotation (DAF) units used in some cases to treat effluent waters. Because these units are not able to selectively separate contaminants from beneficial fine components and require special flotation chemicals to function, they cannot be considered for use in internal water purification [6,11-13]. Recently, some investigations of white-water column flotation indicated improved sheet quality over selective water flotation [14-17]. However, these studies also incorporated some level of flotation chemicals and limited their analysis to single-stage unit operation. Separation processes, in general, allow for higher removal selectivity in multistage processes than in a single-stage process, but no studies analyzing such processes are available for flotation treatment of process waters. One possible benefit of multiphase flotation is the use of the flow channel design [18-20] for both deaeration and selective flotation and the incorporation of a separate, secondary flotation as an additional purification and solids recovery stage.

The aim of this study was to evaluate a two-stage white water flotation process and quantify its separation efficiency for detrimental substances with respect to total yield losses when embedded in a paper machine short circulation flow. The first stage took place in an open-channel flow, from which the froth generated was continuously recovered via overflow and floated again in a secondary flotation stage. The removal of stickies, wood extractives, and ink from white water was analyzed over both process stages. Finally, the efficiency of the two-stage system was evaluated in terms of efficiency at removing detrimental substances. The results are presented, along with the total losses of water and solids.

MATERIALS AND METHODS

White waters and contaminant analyses

The white waters used in these experiments were imported from two European paper newsprint mills that primarily use recycled fiber as raw material. The first white water batch originated from a paper machine that used 35% thermomechanical virgin spruce pulp (TMP) and 65% deinked pulp (DIP). The second paper machine operated with 100%

White Water Type	Dry Matter Content[1] (dmc) (%)	Ash[2] (%)	Suspended Solids[3] (%)	Hardness[4] (°dH)	pH[5]	Conductivity[6] (mS/cm)
TMP/DIP	0.30	48.5	0.18	10.0	7.4	1.01
DIP	0.62	55.7	0.48	7.5	8.1	1.53

[1] SFS-EN 20638, "Determination of dry matter content."
[2] ISO 1762, "Determination of residue (ash) on ignition at 525°C."
[3] SFS-EN 872, "Determination of suspended matter content of water."
[4] SFS 3018, "Metal content of water determined by atomic absorption spectroscopy, atomization in flame."
[5] SFS 3021, "Determination of pH-value of water."
[6] SFS-EN 27888, "Determination of electrical conductivity."

I. Characteristics of the studied white waters.

White Water Type	Ink Content (ppm)	Stickies (mg/g)	Triglycerides (mg/g)	Steryl Esters (mg/g)	Fatty Acids and Sterols (mg/g)
TMP/DIP	1048	0.8	4.1	2.8	3.1
DIP	914	0.8	1.3	1.3	2.4

II. Contaminant content in untreated white waters.

deinked pulp. The tested waters are denoted as TMP/DIP and DIP, respectively. The studied process waters are characterized in **Table I**.

Water and solids losses in the two-stage white water flotation process were determined for both flotation loops via the volumetric reject flow rate and mass reject flow rate, as given in Eqs. (1) and (2). The removal efficiency of detrimental substances (i.e., ink, wood extractives, and stickies) from the water batches was analyzed. Removal efficiency was calculated as the ratio of the amount of reject material to the amount of feed material for the process, Eq. (3):

$$RR_V = \frac{V_R}{V_F} \cdot 100\ [\%] \qquad (1)$$

$$RR_m = \frac{m_R}{m_F} \cdot 100\ [\%] \qquad (2)$$

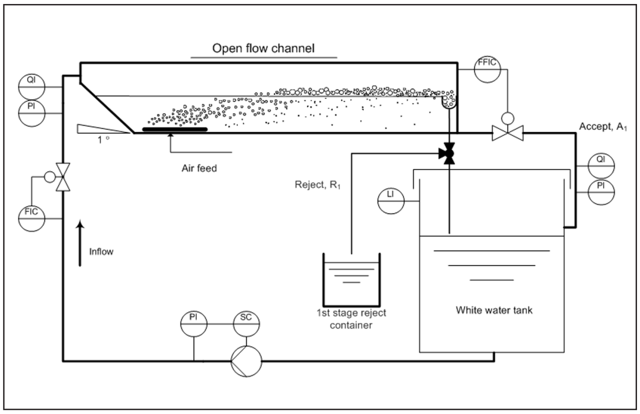
$$E_r = \frac{\dot{m}_R \cdot x_R}{\dot{m}_F \cdot x_F}, \qquad (3)$$

where:

RR_m and RR_V are the reject flow rates by mass and volume, respectively [%];
Q is the volumetric flow rate (L/s);
$\dot{m}$ is the mass flow rate (kg/s);
Er is the removal efficiency (%);
x is the concentration of a given component;
F and R subscripts represent feed and reject, respectively.

The ink content in each of the waters was measured with a Lorentzen & Wettre Elrepho 070 spectrophotometer (AB Lorentzen & Wettre, Kista, Sweden) from 30 g/m² sheets according to the previously described method [21,22] and for residual ink determination from process waters with repeatability of 5.1% from parallel sheets [23]. On the basis of dry weights, the sheets were made from a mixture of 70% hyperwashed SC grade fiber (HWSC) and 30% white water solids. The measured absorption coefficient of the fiber used, k_{fiber}, was 0.4 m²/kg. The prepared sheets satisfied the opacity limitation (below 97%) for scattering coefficient measurement. The ink content, stickies, and wood extractives in untreated water samples are given in **Table II**.

The samples were also analyzed for their stickies and wood-originating extractives content by solvent extraction with tetrahydrofuran (THF) and quantified using high-performance liquid size exclusion chromatography (HPLC-SEC) similar to [24]. Five milliliters of each sample were freeze dried before extraction by reflux with 20 mL of THF for 1 h. The samples dissolved in THF were injected into an HPLC system consisting of a size-exclusion column (Jordi 550A, Jordi Labs; Bellingham, MA, USA) and an evaporative solvent light scattering detector (ELSD) (Sedex 80, SEDERE; Alfortville, France) with a nebulizer temperature of 40°C. The effluent was THF at a flow of 1.0 mL/min. External calibration was performed using a prepared solution of the saturated fatty acid C21:0 (heneicosanoic acid, CAS 2363-71-5) dissolved in THF. Using peak fitting software in Origin 8.0 (OriginLab; Northampton, MA, USA), we accomplished peak separation. This method has the advantages of being able to more accurately determine the stickies and other soluble components, such as wood extractives [24], and to allow for the quantification of component groups exceeding 1.5 mg/L, which in most instances corre-



1. Layout of channel flow flotation (first treatment stage). White waters were circulated from the storage tank to an open flow channel, from which the overflow and froth were collected once a steady state of operation was achieved with the parameters given in Table III.

sponds to approximately 0.5 mg/g [25]. The current HPLC methods can also be seen as simple to use and rapid to perform, as recently reviewed by Valto [26].

EXPERIMENTAL

In these experiments, we used the Oulu University deinking pilot plant (**Fig. 1**). The first white water flotation stage took place in an open flow channel that divided the water flow into a reject overflow and an accept flow through the channel base. Both white waters were tested in two batches of approximately 8 m³. Overflow with the generated froth was collected and treated separately in a secondary flotation cell. The results obtained from these two flotation stages were then used to calculate the total separation efficiency of a simulated two-stage white water flotation process.

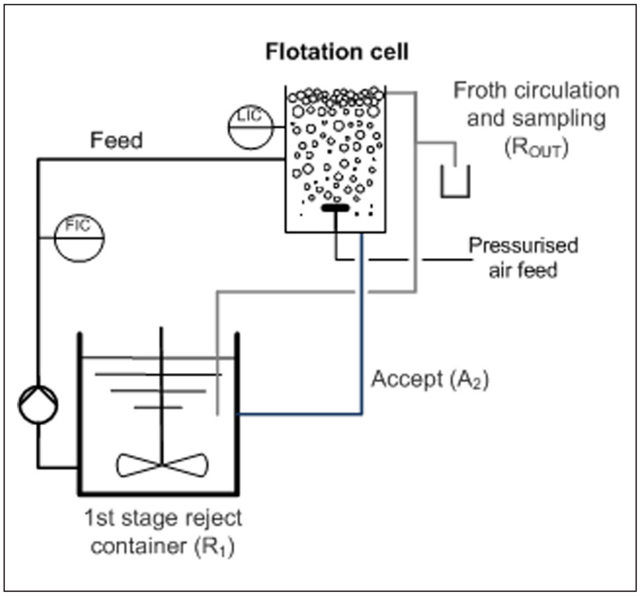
Flotation stage 1: channel flow frothing

The closed loop of the first flotation stage consisted of a storage tank with a steam and water cooling casing, a flow channel that housed the air feed membrane system, and an adjustable overflow and collection system for the overflow (Fig. 1). The gas content in the channel flow feed and accept flow was monitored with online microwave analyzers (QI in Fig. 1), a feature similar to that in previous designs [19,27]. The channel was 1 m wide and 4 m long, and the surface level was fixed at 0.5 m, creating an average flow residence time of approximately 40 s. The white water temperature was kept at 45°C.

The channel flow loop was run as a continuous single-stage flotation. First, the circulation was operated as a closed loop from a storage tank through the flow channel and back to achieve a steady-state process. Next, approximately 800 L of the overflow and surface froth from the channel flow (i.e., the reject) was collected in a separate container (Fig. 1) for 20 min. This first-stage reject was then used as the feed for the secondary flotation. In addition, trials were run both with and without channel flow aeration, as shown in **Table III**. To enhance froth formation by flow aeration, pressurized air

White Water Type	Flow in Channel	Aeration
TMP/DIP	2400 L/min	None
	2400 L/min	780 L/min
DIP	2400 L/min	None
	2400 L/min	780 L/min

III. Channel flow flotation parameters. Chemical flotation aids were not used.

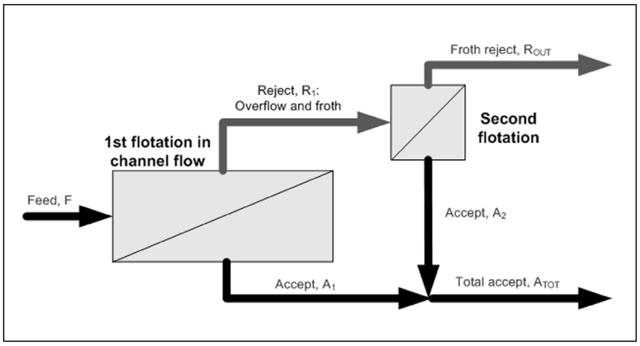


2. Schematic of the second flotation stage. The overflow from channel flow flotation was circulated through a continuous secondary flotation cell. Accept and reject were returned to the feed tank, and samples were taken when steady-state cell operation was achieved.

(780 L/min) was fed through a battery of membrane tube diffusers (ABS Nopon HKP 600, ABS Group; Malmö, Sweden) at the beginning of the channel flow. Air was fed into the channel flow in the form of macrobubbles, ranging from 3 to 5 mm in diameter, in accordance with manufacturer specifications. Samples before and after flotation were analyzed for their solids, ink, stickies, and extractives content.

Flotation stage 2: secondary flotation

Overflow from the first flotation loop was collected in a 1 m³ container. Suspension was used at the second flotation loop independently of the operations at the first loop (**Fig. 2**). In the second flotation loop, a continuous flotation cell of 65 L was operated at 45°C with a suspension inlet flow rate of 12 L/min and an air flow rate of 20 L/min. These parameters were determined in a preliminary study to be applicable. An air-to-suspension ratio of 165% and a residence time of slightly over 5 min were considered appropriate, as values in flotation deinking of pulp typically vary around 40%–300% [28–30].



3. Flowchart of the forward-connected scheme of a simulated two-stage flotation process. Parameters for system evaluation were selected from the preferred test cases that were performed in the processes depicted in Figs. 1 and 2.

This second flotation loop treatment was performed in the same way for all four white water samples that were obtained from the channel flow. The flotation reject was continuously returned to the mixed feed container, and samples were collected from the secondary flotation loop only after the cell operation had reached steady state. These samples were analyzed similarly to the first loop samples for their solids, ink, stickies, and extractives content.

Combined two-stage flotation arrangement for white water purification

The removal efficiency of the two-stage white water flotation scheme was determined by a modeling process, which involved combining the channel flow flotation and secondary flotation as a forward-connected configuration. This configuration is shown in **Fig. 3**. This simplified flowchart depicts one possible example of the two-stage flotation process connection and enables evaluation of total process efficiency through mass balances. The total removal efficiencies of the process between the channel feed (F) and the total process rejects (R_{OUT}) were calculated according to Eq. (3). Other possible connections of accept and reject flows were considered to be outside the scope of this study.

RESULTS

Flotation stage 1

Froth buildup on the channel flow was visually observed to be quite weak without the added aeration. However, in every instance the DIP water produced a stable froth, and its quantity was higher than that obtained for TMP/DIP water. When air feed was used, frothing was clearly improved and the froth of both white waters was noticeably darker due to the accumulated dirt. **Table IV** presents data on the solids content distribution, by both volume and mass, in the tested flotation cases and the reject flow rates. Total accept dry matter content was calculated using a mass balance.

Removal efficiency of contaminants in channel flow frothing

The contaminant removal from the channel flow surface froth and the overflow fraction were calculated according to Eq. (3). The composition of each untreated white water is shown in Table II, and the removal efficiencies are presented in **Table V**. The removal of contaminants was consistently better in the batches using air feed to the channel base than in instances where the channel overflow was collected without aeration. We saw an especially good response for TMP/DIP water, from which a clear increase in ink, extractives, and stickies removal was obtained.

Influence of air feed on channel flow residual gas content

The gas content development in the accept channel flow pipeline was monitored similarly to previous studies [18,20,31,32], using microwave analyzers (QI, in Fig. 1). The measured residual gas content was 0.3% for TMP/DIP water and 0.4% for DIP water. Channel flow deaeration performance was not affected by either flow aeration with macrobubbles having a terminal velocity [33] high enough to sufficiently enable their timely evacuation or by the resulting increase in froth content.

Flotation stage 2: contaminants removal efficiency

Reject samples of both white waters from secondary flotation are shown in **Table VI**. For the TMP/DIP water, the flotation cell surface level was adjusted in such a way that a minimal amount of froth (about 0.3 L/min) was removed to minimize solid losses. For DIP water, this mode of flotation control was changed to allow a greater removal of froth (about 2.8 L/min). The higher reject flow rate and contaminant removal can be seen in Table VI. The separation of wood extractives and stickies was poor in TMP/DIP waters compared to that in DIP water, while the removal of ink remained the same. With a higher reject flow rate for the DIP water, a substantial removal of wood extractives and stickies was obtained.

White Water	Aeration	Feed dmc (%)	Reject dmc (%)	Accept dmc (calc.) (%)	RR_V (%)	RR_m (%)
TMP/DIP	No	0.30	0.32	0.30	9.8	10.8
	Yes	0.27	0.31	0.26	10.6	12.5
DIP	No	0.62	0.68	0.61	11.3	12.6
	Yes	0.62	0.81	0.59	11.5	15.2

IV. Development of the dry matter content in channel flow flotation (values for accept flow calculated from mass balance).

	TMP/DIP No Aeration	TMP/DIP Aeration	DIP No Aeration	DIP Aeration
Ink removal efficiency (%)	15	15	13	15
THF extractives removal efficiency (%)	14	21	13	16
Stickies removal efficiency (%)	11	17	15	23
Ash removal efficiency (%)	12	14	14	17
RR_V (%)	9.8	10.6	11.3	11.5
RR_m (%)	10.8	12.5	12.6	15.2

V. Removal of contaminants in the channel flow flotation loop (RR_V and RR_m are the same as in Table IV).

Channel Flow Aeration Mode	TMP/DIP No Aeration	TMP/DIP Aeration	DIP No Aeration	DIP Aeration
Ink removal efficiency (%)	17	18	45	45
THF extractives removal efficiency (%)	12	18	41	55
Stickies removal efficiency (%)	36	65	72	90
Ash removal efficiency (%)	12	10	38	40
RR_V (%)	2.3	1.0	22.0	24.0
RR_m (%)	8.8	7.3	34.7	36.4

VI. Removal of contaminants in the secondary flotation loop.

Channel Flow Aeration Mode	TMP/DIP No Aeration	TMP/DIP Aeration	DIP No Aeration	DIP Aeration
Ink removal efficiency (%)	2.5	2.6	5.9	6.8
THF extractives removal efficiency (%)	1.7	3.7	5.1	10
Stickies removal efficiency (%)	4.0	5.6	10	21
Ash removal efficiency (%)	1.4	1.3	5.1	6.7
RR_V (%)	0.2	0.1	2.5	2.8
RR_m (%)	0.9	0.9	4.1	5.5

VII. Removal efficiency of detrimental materials and losses in the two-stage white water flotation.

Combined two-stage flotation arrangement for white water purification

Table VII presents the total separation efficiency of components and the losses of solids and water in the two-stage process. A better total separation of contaminants in the first stage was seen in both white waters when the channel flow reject was obtained with added aeration. By far, the best removal was obtained for stickies, which was as high as 21%, and wood extractives, which was as high as 10%. The ink content was reduced the least, with a maximum reduction of 7%. Higher separation efficiency in regard to reject ratios indicated moderate selectivity in component removal. The results were also notably affected by the differing reject flow rates used in the second flotation stage. The total losses remained significantly lower in TMP/DIP water treatment than in DIP water due to the differences in secondary flotation operations.

DISCUSSION

Although the effect of water purification on paper qualities was not investigated here, previous studies have indicated that the 15% decrease observed in ink content and the 13%–21% decrease in wood extractives content can have a significant impact on paper strength and optical appearance [9,10,14,15,17,34]. Similarly, the stickies removal can be considered beneficial. Another concern has been the level of solids losses occurring in selective flotation. Results displayed in Table V indicate a need for secondary treatment to concentrate the contaminants further and to recover some of the beneficial solids.

The selectivity of detrimental component removal appears reasonable when comparing the reject flow rates to the removal efficiencies in Table VII. Of note, such good selectivity can be obtained in process water flotation even without flotation chemicals, as has been reported previously [25]. Even with a very low total reject flow rate of approximately 1% for TMP/DIP solids and a mere 0.1% of the water wasted, the system could remove a fair amount of contaminants. For the DIP water, in which the reject flow rates were higher, continuous removal of 7% of the ink, 10% of the extractives, and 21% of the stickies was obtained. The purification of water can reach the same level observed in laboratory studies [18,25,35] and remain significant when operability and contamination issues are considered.

Good selectivity in flotation means that some solid components can be returned to the process stream while removing the contaminants, although some level of losses in terms of fine fibers, fillers, and process water must be accepted. On the basis of our favored scenarios, 55%–70% of total losses can be considered to originate from minerals. Optimization of multiphase flotation is driven by the fact that the purification target is limited by the performance of the first separation phase, while the level of solids losses is defined in later phases [15,36]. Although other process stream connections can make the case less straightforward, this rule applies in general. Optimization is highly process dependent; it depends on the water purification target and its effects on paper production, including the economic considerations of losses of fine fibers and the amount of rejected material.

Flotation stage 1: channel flow frothing

The foaming tendency and stability of the white water froth layer was adequate without the use of flotation chemicals, although some traces of defoaming chemicals were likely present in process waters during trials. With their elimination, consolidation of carbonate fillers and anionic surface-active compounds will likely generate a sufficient froth layer on channel flow. These components are found in great numbers in the process waters that use mechanical or recycled pulps; they are due to the presence of deinking chemicals, coating colors, and fines from recycled coated paper, for instance.

The enrichment of components to the channel flow froth increases the separation efficiency of ink, wood extractives, and stickies. It was clear that hydrophobic solid materials accumulated quite well in the froth, and the dry matter content of the channel reject flow was consistently higher than the accept flow. As shown in Tables IV and V, the air feed used here clearly improved component separation. In comparison to the removed solids (RR_m), the differences were minor except for stickies, which were mostly removed, in accordance with previous investigations [2,5,24,25].

In addition, the results appear to be in close agreement with the previous work on white water flotation [14,15,17,18,25,36] and effluent treatment in dissolved air flotation [12,18,31,35,37], although comparison to DAF or column flotation are problematic due to their fundamentally different operational characteristics and use of flotation chemicals. The longer dwell time provided by the column can be beneficial and will likely lead to higher removal efficiency than that obtained in channel flow alone. Channel flow functions well as the first stage of a process where it also performs its gas removal function.

Limits for gas content given in the literature for trouble-free operation start from as low as 0.4% in fine paper and 0.1% in newsprint production [38] and go up to 2.5% for liner grades [39]. The residual bubbly gas contents of 0.3% and 0.4% observed here are in close agreement with a previous study [20]. The substantially lower solids content of DIP/TMP water was likely the cause of its slightly better deaeration performance [33]. The fact that the deaeration performance was unaffected by air feed into the channel flow is related to the macrobubbles that were evacuated from the flow in the given flow residence time. Channel flow design can also operate, if needed, alongside the conventional deculator deaeration gas removal pumps [40] or hydrocyclones [41].

Flotation stage 2: secondary flotation

The dwell time in the secondary flotation was markedly higher than in the channel flow flotation, which enabled the build-up of a thicker froth and, apparently, more selective component removal. The froth layer was also notably more stable in the secondary flotation than on top of the channel flow. This result was likely due to the higher concentration of carbonate filler and surface-active extractives. These components are believed to act similar to the collector systems used in deinking applications, although the exact operating mechanism of such a system remains unclear [30,42,43].

Wood extractives were separated with high efficiency and the removal of stickies was significant in respect to total reject rates, especially when the channel flow frothing had been enhanced with the added aeration, as seen in Table VI. Use of an air feed in the previous stage also increased the relative solids losses. The higher reject flow rate in DIP water resulted in a higher removal of contaminants, reaching 40%-55% removal for wood extractives and a 70%-90% reduction in stickies content. Similarly, for TMP/DIP water extractives, reduction was almost 20% and stickies content removal was nearly 40%. A small difference in ink removal was seen between TMP/DIP and DIP waters, but considering the reject flow rates in Table VI, the separation of ink from flotation chemical-free white water was not very good.

CONCLUSIONS

Froth formation similar to selective flotation was obtained in turbulent channel flow of white water without the presence of flotation aids, which enabled the combined process of passive channel flow deaeration and overflow collection of contaminants. Therefore, high removal of stickies and wood extractives can be achieved while the deaeration function of the channel flow remains unaffected. The channel flow flotation determines the maximum detrimental component separation efficiency of the process, while the presence of a secondary flotation stage substantially reduces the overall losses of water and solid components; in instances where the second stage accept contains more dirt than first stage accepts, it also reduces the total efficiency of detrimental component separation. As an integrated process, the studied process arrangement removed up to 7% of ink, 5%–10% of wood extractives and 10%–20% of stickies content with a reasonable mass reject flow rate of 1%–5% and volumetric reject flow rate of 0.1%–3%. **TJ**

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ABOUT THE AUTHORS

We chose this topic because novel low-cost strategies are needed to treat only stock flow, and circulation waters have not received sufficient attention. Deaeration and removal of contaminants have a direct effect on the runnability, quality, and cost-effectiveness of paper machine production. There have previously been numerous investigations on the subject, but the channel flow and multiphase flotation approach have not been given as much consideration.

The most difficult aspect of this study was to ensure representative sampling from the channel flow, but sufficient sampling and analyses provided the necessary information. Otherwise, the pilot scale operations and white water deliveries from mill sites were conducted with ease, thanks to our industrial partners contributing to the study.

It was interesting to observe how beneficial the white water flotation can be if there is no need to salvage the solid fines and fillers. On the other hand, the fines recovery can also result in substantial purification of process waters with minimal raw material losses if the process is optimized according to a low reject removal rate. This study would benefit paper and board mills by allowing them to understand how significantly the trash content in their short circulation could be reduced with fairly simple processes.

As white water flotation remains a subject studied by few, our next step is to consider suitable analysis methods to better quantify the impact of white water contaminants on end products. Also, we plan to review the concept of white water flotation based on our own experiences, those dealing with white water column flotation, and other previously published investigations.

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