Brownstock washing – A review of the literature

RICARDO B. SANTOS AND PETER W. HART

ABSTRACT: Brownstock washing is a complex, dynamic process in which dirty wash water or weak black liquor (dissolved organic and inorganic material obtained from the pulp cooking process) is separated from pulp fibers. The use of material balance techniques is of great importance to identify potential problems and determine how well the system is operating. The kraft pulping industry was the first known to combine pulp washing with the recovery of materials used and produced in the wood cooking process. The motivation behind materials recovery is economic, and more recently, environmentally driven. The chemicals used in the kraft process are expensive as compared to those used in the sulfite process. For the kraft process to be economically viable, it is imperative that a very high percentage of the cooking chemicals be recovered. To reach such high efficiency, a variety of washing systems and monitoring parameters have been developed. Antifoam additives and processing aids have also played an important role in increasing washing effectiveness. Antifoam materials help attain washing effectiveness by preventing entrapped air from forming in the system, which allows for an easier, unimpeded flow of filtrate through the screens and washers.

Application: Improved understanding of brownstock washing principles and operating practices will help optimize mill operations.

The kraft pulping industry is the first known to combine pulp washing with the recovery of materials used and produced in the wood cooking process [1,2]. The initial motivation behind materials recovery is the higher cost of chemicals used in the kraft process compared to those used in the sulfite process [2]. For the kraft process to be economically viable, it is imperative that a very high percentage of the cooking chemicals be recovered and reused [2]. An additional benefit of the recovery of the pulping chemicals and dissolved organics resulting from the pulping process is that recovery significantly reduces the amount of water pollution associated with the kraft cooking process [1,3-6]. Control of brownstock washing and the additives used in brownstock washing are also instrumental in reducing the concentration of dioxin precursors going forward to pulp bleaching [7]. Inefficient washing results in higher effluent color, chemical oxygen demand (COD), and biochemical oxygen demand (BOD) in the receiving waters associated with kraft pulp mills [8,9]. Pulp washing provides desirable benefits associated with increased efficiency in both screening and bleaching of the pulp [3,7]. Additionally, pulp quality is also improved by good washing [1,3-6]. In short, when brownstock washing is performed poorly, all areas of the mill are negatively affected. When it is done well, increased black liquor solids, decreased carryover to the bleach plant and/or paper machine, and decreased environmental impacts result.

Modern washing systems have been integrated into the heart of the kraft recovery cycle [10,11]. Satisfactory pulp washing is achieved with a multistage counter-current sequence [5,12], where the cleanest water is added in the last stage and the resulting filtrate is used in the preceding stage until it reaches the blow tank or wash zone in a continuous digester [13]. It is important that the amount of "clean water" added to the last washing stage be as minimal as possible to guarantee efficient solids removal because excessive clean water addition effectively results in decreased concentration of black liquor solids being sent to the evaporators [14].

When cooked wood chips are discharged from a digester they consist of a pulp-water suspension containing two main phases: the free liquor phase and the fiber phase. The fiber phase includes wood fibers and the liquor entrained inside the fiber. The entrained liquor is in close contact with the fibers and can be assumed to behave as an immobile liquor phase connected to the free liquor through mass transfer resistance [15]. The free liquor occupies the interstitial spaces between fibers and is quite easily removed during washing [16]. The entrained liquor can only be removed by diffusion or by capillary force [17]. Both of these processes are slow and dependent on the time, temperature, and chemical composition of the wash water [18,19].

Washing is based on four basic processes: dilution (when using dilution washing, it is important to have good mixing in the system), dewatering, diffusion, and displacement. All types of washers apply some or all of these processes during pulp washing. Some washing devices specifically enhance certain types of washing at the expense of other washing aspects. For instance, a press washer specifically enhances the dewatering aspect of washing at the expense of diffusion [18].

The simplest way to perform washing is to dilute the fiber suspension with wash water, mix the suspension, and then filter or press the liquor out of the suspension [20]. In this washing scenario, one of the remaining washing principles, displacement, may be represented by placing a layer of clean wash water on top of the filter mat produced by the dewatering/thickening step and allowing the clean wash water to push the dirtier wash water out of the mat while replacing it within the fiber matrix.

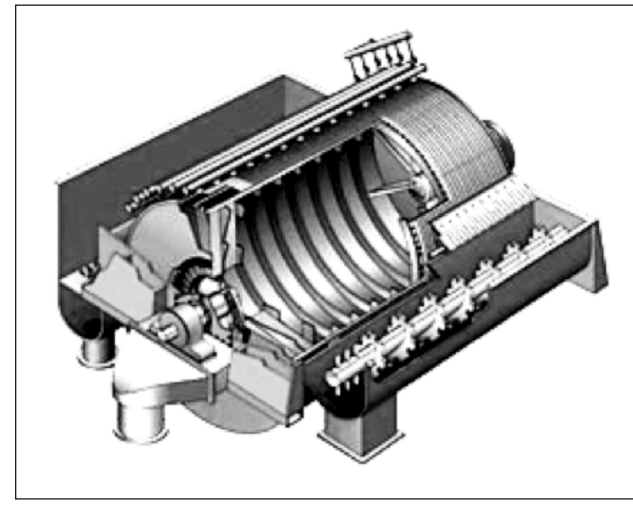
The dominant type of pulp washing has been and still is the multistage rotary vacuum washer. Multistage vacuum washer systems employ dilution/thickening, mixing, diffusion, and displacement washing principles, i.e., every aspect of washing. Modern washing devices offer a more diverse number of techniques, such as pressurized washers (compaction baffle [CB] and displacement drum [DD] washers), presses, diffusion washers, and internal digester washing. These modern washing devices tend to enhance a select type of washing at the expense of other types of washing.

BROWNSTOCK WASHING PRACTICES AND PRINCIPLES

Brownstock washing is a complex and dynamic process, which makes the use of material balance techniques of great importance to identify how well the system is operating. The operation of a brownstock washing system affects a mill in three main areas [21]:

1. Recovery of inorganic chemicals is a primary reason for using pulp washing. Inorganic chemical recovery directly affects the cost associated with make-up chemical purchasing. In modern kraft mills, usually 96%-99% of the inorganic cooking chemicals are recovered back into the system [1].
2. Recovery of organic matter (dissolved lignin and carbohydrates) plays a role further downstream in the process. For mills that have oxygen delignification and/or bleaching sequences, elimination of organic chemicals in the pulp entering these processes reduces operating costs [9,22]. Because these stages are oxidative in nature, improved lignin removal through enhanced brownstock washing will result in reduced process chemical consumption and reduced load to the waste treatment plant [23].
3. Finally, brownstock washing assists in the removal of undesirable material such as metals [24, 25], pitch, and wood extractives. Wood extractives that are not successfully removed from the pulp by washing tend to concentrate in downstream processes and form sticky deposits on equipment, which in turn can result in the production of off-quality paper through the formation of spots and holes [21].

Pulp washing is usually achieved through one of four different methods/mechanisms: displacement, dilution, extraction, and diffusion.



1. Vacuum drum washer.

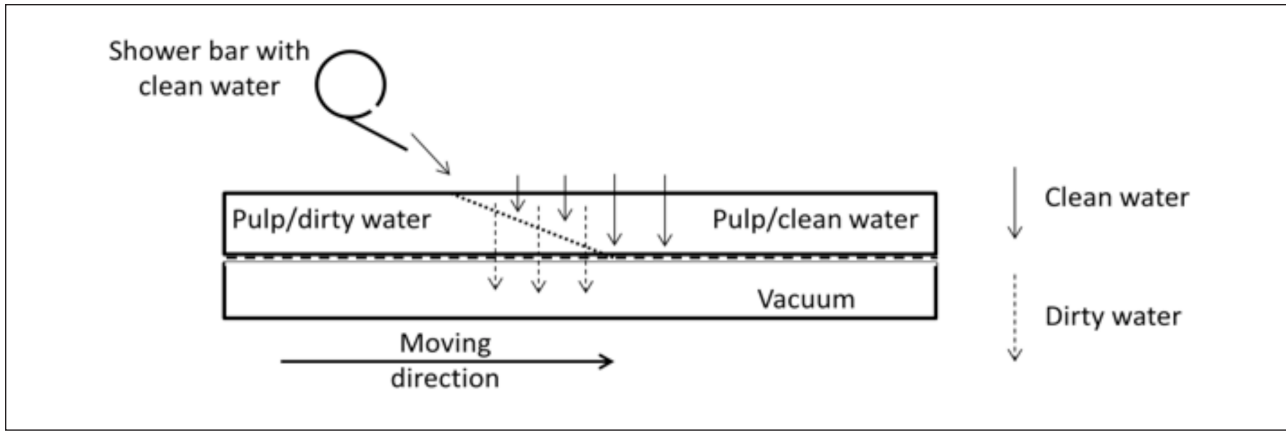
Displacement

A cleaner liquid is added to the pulp mat to displace a dirtier one that is being carried with the pulp. The mechanism works via a pressure differential and pushes or displaces a similar amount of water from the mat. In vacuum drum or pressurized washers (**Fig. 1**), displacement is usually obtained by shower water being applied on top of the sheet and allowed to flow into or through the sheet with the aid of a pressure gradient created by a vacuum underneath the sheet or by pressurized shower water being applied to the top of the pulp mat. Any form of resistance toward uniform drainage such as entrained air bubbles [26] or plugged face wires can lead to nonuniform pulp washing via displacement. Because of these and a number of other factors potentially occurring during displacement washing, multiple displacement steps are required to obtain higher than 80% displacement washing efficiency [13]. **Figure 2** shows the ideal operation and theory of displacement washing.

Displacement washing significantly reduces the amount of dissolved solids in the pulp mat without significantly altering the consistency of the pulp mat within the system. Typically, the amount of water displaced from the mat is about equivalent to the amount of water being applied to the mat via the showers. One significant deviation from this is when channels form in the mat, allowing wash water to pass all the way through the mat and into the resulting washing filtrate from this stage. Ideally, all of the shower water would be applied in a uniform manner and completely push or displace all of the free dirty water from the mat. The ideal amount of wash water applied would be just enough to accomplish this displacement without any of the applied wash water going into the pulp filtrate [10,13]. Typically, five shower bars are used to evenly and uniformly apply wash water to the pulp mat surface.

Dilution/Extraction

Dilution and extraction are two different types of washing that are closely linked and work extremely well together. Be-



2. Displacement washing.

cause they are so closely linked, they will be discussed together. The combined washing effect may be described as the liquor/pulp suspension being diluted with cleaner water followed by subsequent thickening of the slurry. It is the oldest method of pulp washing. The dilution step does not decrease the amount of dissolved solids within a pulp/liquor system. In many cases, dilution washing actually increases the total amount of dissolved solids within the system [26]. It also increases the total volume of the pulp/liquor suspension being washed. The important aspect of dilution washing is that it decreases the concentration of dissolved solids within a given system [26].

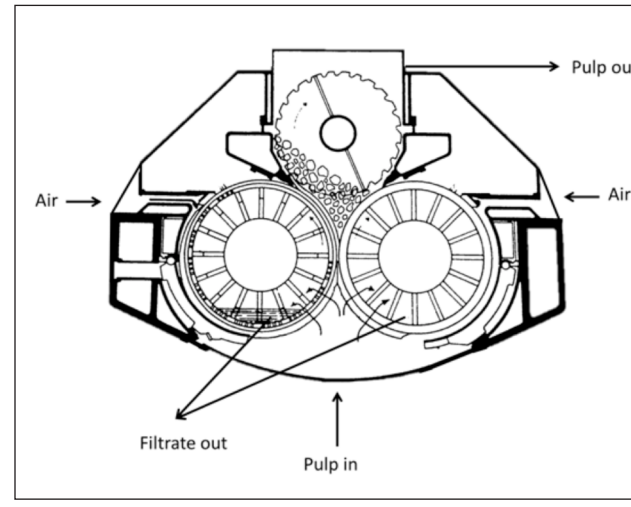
The extraction washing step is accomplished by removing liquid from the pulp/liquor suspension. The net result is a decrease in the volume of the pulp/liquor suspension and a corresponding increase in the consistency [26]. The extraction stage does not change the concentration of dissolved solids in the pulp/liquor suspension, only the volume of liquor in the suspension. As a result, extraction washing reduces the total amount of dissolved solids in the pulp/liquor suspension [26].

Extraction efficiency is dependent on the ratio of incoming consistency/outgoing consistency [13]. Pulp presses are good examples of the extraction washing principle and have a very low consistency ratio with a high washing efficiency. Presses are usually more beneficial in the first stage of washing because they can remove air entrained in the pulp, thus improving the next washing stage [18]. **Figure 3** shows how a press operates.

Dilution/extraction is the first part of the washing process performed in a traditional vacuum drum washer. The pulp is diluted as it is pumped into the washer inlet vat. Next, the pulp mat is formed on the washer drum via extraction of wash water into the droplet and transferred toward the shower bars for the start of the displacement washing process.

Diffusion

Diffusion is a form of washing that is driven by concentration differences between the dissolved solids within the fiber and in the bulk liquid. Diffusion is characterized by the commutation of liquid inside fiber to a cleaner liquid outside of the fiber

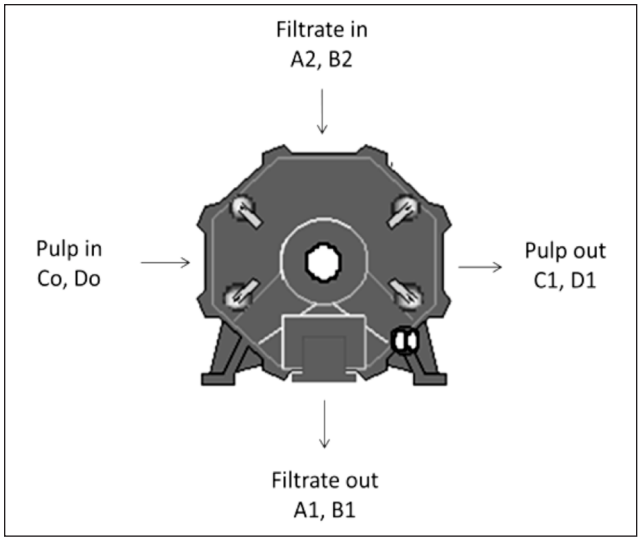


3. Pulp press washing equipment.

[21]. It requires relatively long periods of contact to allow diffusion and leaching of solids from fiber [13,27]. This concept was first used in Kamyr digesters, which provide close to an ideal environment for diffusion of dissolved solids out of the fiber (up to 4 h retention time and elevated temperatures close to 140°C). Another parameter that shows influence during this washing is dilution factor. A higher dilution factor results in higher washing efficiency as a result of solids concentration reduction [13].

WASHER MODELING

The washing system can be modeled using individual washers (**Fig. 4**) or using the entire washing line as a single unit. Some work has focused on modeling washing performance on different parts of a washer drum [28]. Figure 4 shows the minimum number of variables required to model a single stage or a holistic model of an entire washing line. The model includes equipment based on dilution/extraction, displacement, or a combination of all of these principles [21]. A reasonable attempt has also been made to model brownstock washing performance without using flow measurements [29]. It is important to determine the washing efficiency of the entire washing line, treating the entire line as a single unit, but it is equally



4. Example of individual washer modeling. Co and C1: filtrate with pulp entering and leaving (ton/a.d. ton); Do and D1: pulp filtrate dissolved solids entering and leaving (wt%); A1: filtrate leaving washer (ton/a.d. ton); A2: shower filtrate entering the washer (ton/a.d. ton); and B1 and B2: filtrate dissolved solids in the shower water and exiting filtrate (wt%).

important to determine the performance of each washing device to pinpoint potential problem areas that may be improved.

Standard modeling programs, such as WinGEMS [30] or Aspen [31], may be used to prepare material and energy balances. These programs work quite well for the material balance aspects, but great care is needed when attempting to perform energy balances around brownstock washing systems. Brownstock washing systems tend to have significant amounts of surface area between the hoods, filtrate tanks, and piping, which contribute to a significant amount of heat loss. Standard material and energy balance programs do not take these forms of heat loss into account and frequently over-predict the resulting stock and filtrate temperatures.

Brownstock modeling has been performed in dynamic [19,32] and steady state models [33,34]. Several models have focused on the displacement aspect of pulp washing [35,36]. Frequently, the steady state models have been combined with economic data to determine the effect of rapidly fluctuating and decoupled energy and raw material costs [33].

The results from these models tend to give divergent optimization responses, depending on the species of wood, pulping techniques, and type of equipment used in testing [37]. Hence, a washing model that is consistent with the specific mill being evaluated or at the minimum, a model that has been experimentally tuned to the mill in question, should be used when attempting to optimize brownstock washing through modeling techniques [37].

WASHING EFFICIENCY CALCULATIONS

The main purpose of brownstock washing is to separate spent cooking chemicals and wood reaction products (dissolved organics) from the pulp being sent forward for further processing. Ideally, this separation process will be accomplished with a minimal amount of added wash water or processing chemicals. As a result, the efficiency of a washing system in its most basic form can be calculated as the ratio of dissolved solids going to evaporation to the amount of dissolved solids initially present in the washing system. For a mill with batch digesters, the initial dissolved solids present in the system would be those in the blow tank. In a continuous digester, the initial dissolved solids would be determined in the washing zone. The percent washing efficiency calculation is as follows: % efficiency = (dissolved solids to evaporation (weight)/ton pulp) / (dissolved solids to system (weight)/ton pulp).

Under ideal washing conditions, each pulp fiber will be uniformly treated with its share of wash water. When process or mechanical conditions prevent this from happening, reduced washing efficiency occurs. As a result of these decreases in efficiency, researchers have developed several different ways to determine washing efficiency calculations. The most common methods are displacement ratio, equivalent displacement ratio, Norden's method [20], and solids reduction ratio.

Displacement ratio

Displacement ratio (DR) was first developed by Perkins, Welsh, and Mappus [38] to compare the amount of dissolved solids removed from the pulp mat to the maximum amount of solids that could be removed from the pulp mat if the displacement of dirty water in the vat with cleaner shower water was 100% effective. The displacement ratio is a dimensionless number between 0 and 1. If the DR is 1, that means that perfect displacement occurred. If the DR is zero, no displacement occurred. The minimum amount of possible solids in the mat is the amount of dissolved solids present in the shower water (cleanest water added). When shower water is added to the pulp mat (Fig. 2) it displaces (pushes) the dirty water washing out of the mat, replacing it with the cleaner shower water. DR is commonly used to compare the washing efficiency of similar types of equipment [20, 21]. DR is calculated according to the following equation:

DR = [(solids in vat)-(solids in mat)]/[(solids in vat)-(solids in shower water)]
or
DR = (Sv-Sm) / (Sv-Sw)

where:
Sv = solids concentration in the vat
Sm = solids concentration in the mat leaving the washer
Sw = solids concentration in shower water

Equivalent displacement ratio

As washing devices have changed, new and improved efficiency calculations had to be invented to accommodate the new washing methods and to compare washers of different designs. When the first compaction baffle washers were de-

veloped, there was no good method to determine the DR and compare it to the traditional DR used for rotary washer drums. Therefore, new methods were developed to calculate an equivalent displacement ratio.

The equivalent displacement ratio (EDR) is used to compare the actual washer with a hypothetical one, operating at a standard inlet consistency of 1% and outlet of 12%. For the hypothetical washer, EDR is calculated with the following formula:

$$(1 - EDR) = (1 - DR)(DCF)(ICF)$$

where:
DCF = discharge correction factor = Ld /7.333
ICF = inlet correction factor = 99.0(Li+DF)/[Li (99.0+DF) – Ld (99.0–Li) (1–DR)]
Ld = Amount of liquor in the discharged pulp, [(100 – discharge consistency)/discharge consistency] reported as mass of liquor/mass of pulp
Li = Amount of liquor inside the vat or inlet, [(100 – inlet consistency)/inlet consistency]
reported as mass of liquor/mass of pulp
DR = displacement ratio
DF = dilution factor

The term equivalent means that the hypothetical washer has the same dilution factor as the actual one, the solid loss being the same in both cases. EDR is a useful mathematical tool for comparing washers of different designs. The washer with the highest EDR value for the same dilution factor will be the most effective one [39].

Norden method

Norden number/method describes washer effectiveness comparing the washer to a series of dilution extraction washers operating with an inlet consistency of 1% and a mat discharge consistency of 10% with no liquor displacement. Modified Norden numbers use different mat discharge consistencies and have a subscript after the N to let the reader know what the discharge consistency actually is. For instance, an N_{12} number would have a mat discharge consistency in the theoretical dilution/extraction washer of 12% instead of 10%. The method was developed by Norden, et al. in 1966 [20] and defines the number of dilution/extraction washing stages that will give the same washing efficiency as the washer in consideration. Equipment such as vacuum drums and single stage diffusers present the lowest Norden numbers indicating low washing efficiency. Properly operating Kamyr digesters with extended washing zones (up to 4 h) present the highest Norden numbers and consequently the highest washing efficiency [13]. The Norden number may be calculated with the following formula:

$$Nn = \ln((V1 (W1 - X0)/V0(W0 - X1)) / \ln (Y1/V0)$$

where:
N = Norden number
V1 = flow of liquor to the vat
W1 = weight fraction of alkali (Na_2SO_4) in the vat
X0 = weight fraction of alkali in the filtrate to filtrate tank
V0 = flow of liquor out with the mat
W0 = weight fraction of alkali (Na_2SO_4) out with the mat
X1 = weight fraction of alkali in the shower water
Y1 = flow of liquor in the shower water
Ln = natural log

The Norden number or Norden efficiency factor as it is sometimes called is an excellent method of comparing washing devices that discharge at different mat consistencies. The device with the higher Norden number has the better washing.

Solids reduction ratio

Because of its calculation complexity, solids reduction ratio is impractical to use in operating systems. The method was developed by Perkins, Welsh, and Mappus to relate the solids content of the mat liquor leaving the final washer to the solids content of the liquor before any washing. The concept was a good way to demonstrate solids content reduction as a function of the solids content of the liquor entering the stage, as well as to re-emphasize washing systems as fractionating devices. For details on the solids reduction ratio calculations, the reader is referred to Perkins [26].

WASHING SYSTEM VARIABLES

When evaluating a brownstock washing system, it is best to examine the system as a holistic unit. Even when looking at the entire washer system, the number of variables that need to be evaluated are considerable. The main variables will be discussed below. Several of the ancillary system variables will be left for the reader to determine for their specific washing line.

Stock consistency to the vat and sheet formation

When operating a washing device that relies on dilution/extraction as one of its main washing principles (e.g. rotary vacuum washers), the stock inlet consistency is of extreme importance. Ideally, the inlet consistency for a rotary vacuum washer should be about 1.0%– 1.5%. These washers can operate at much higher inlet consistencies, but the quality of washing suffers. When the inlet consistency is increased significantly, to the 2%-3% range, these devices tend to become more of a pulp conveyor, which moves pulp from one stage to another with very little washing. The highest washing efficiency is obtained when stock consistency to the vat is maintained as low as possible, preferably in the 1.5% range. Low vat consistency typically results in good, uniform sheet formation across the washer, which results in a uniform displacement of the dirty liquor. The low vat consistency and uniform mat formation allow each fiber to be exposed to its share of

wash water, resulting in uniform and efficient pulp washing. The high amount of water in the stock also results in better solids removal, overall [10]. Improved sheet formation can also be a function of washer design [10]. It is important to place stock pipes and dilution water in such a manner as to maximize mixing before the vat [40,41]. Stock and dilution lines placed in a Y configuration often result in poor mixing. A 90º joint between the two results in a more turbulent flow with better mixing ability [18].

The drawback of operation in low consistency is the reduced production rate across the washer. As stated by Smith [18], vat consistency is almost a square root of washing capacity. An increase of 100% in consistency (consistency from 1% to 2%) implies in washer capacity increased by 52%. Nevertheless, one should be aware of the negative washing effects of running a washer at high inlet consistency.

Drum speed

Drum speed is another important variable when one is trying to achieve improved washing efficiency. Drum speed should vary as a function of vat level or sheet formation. It is always an improvement when the pulp mat is maintained to a certain thickness across the washer. If the mat is too thick, it will carry over more of the dirty liquor because the shower water will not be able to fully displace the dirty liquid retained in the mat when it was formed on the drum. On the other hand, a washer operating with an extremely thin pulp mat can be challenging to run. The thin mat will not provide good resistance to air penetration of the sheet into the liquor and the drum will tend to seal over, resulting in no drainage and no liquor displacement.

Some washers use drum speed as the vat level control. In these types of washers, a higher drum speed maximizes water removal from the drum vat, which reduces the vat level. The opposite is also true. When considering the production rate, a 100% increase in cylinder speed (from 2 rpm to 4 rpm) will result in a 42% increase in production. The combination of drum speed and vat consistency should be the best available option when one is looking for a productivity increase [18].

Entrained air in the pulp and liquor

Prevention and elimination of entrained air is also of importance when it comes to maximizing brownstock washing [11]. Air/bubble formation can occur in the drum vat when the vat level is low, resulting in a more turbulent system. Filtrate tank design and level set point can contribute to air entrainment in the liquor used to dilute the pulp between stages. Drop-leg seal pots inside the filtrate tanks should be designed to allow air removal from the liquor. The filtrate level should not be above the top of the centerline of the horizontal run of the dropleg, and definitely not above the standpipe or seal pot. Air trapped in the pulp also increases the drum speed by decreasing stock drainability and reduces displacement ratio [10]. Basically, entrained air bubbles in the pulp mat behave as solids and plug the drainage channels within the mat, resulting in a decrease in the displacement ratio. It is important to note that under-washing in one area of the mat cannot be compensated by over-washing in another area, making elimination of air entrainment and good sheet formation over the drum a requirement for optimum washing [10].

Dilution factor

One of the first and most important variables to be considered during brownstock washing is the dilution factor (DF) [14,42-45], defined as the amount of excess liquor added to a washing system. DF is important for determining the overall system material balance and performance. The DF should be minimized to reduce steam usage during black liquor evaporation [10]. DF can be defined as liquor added to pulp in terms of air-dried pulp (a.d.) or oven-dried (o.d.) pulp [21]. Typically, the DF varies from 2-4.5 m^3/o.d. ton [14,46,47].

In theory, the DF should be maintained constant at each stage of washing; in reality, it rarely is. Extra water input into the washing system (e.g. seal water, fresh water hoses placed into the system, filtrate tank level control water, etc.) will result in changes in the DF between stages. A negative DF implies that less water than the amount present in the discharged sheet was added to the system [8]. DF may be calculated by the following equation:

$$DF = WS - C1$$

where:
WS = washing shower (ton liquor/ton pulp)
C1 = liquor discharged with pulp (ton liquor/ton pulp)

Wash liquor distribution and temperature

The golden rule of pulp washing is that "each fiber should get the same amount of washing liquor." Washing liquor should be gently and uniformly applied all the way across the washer [10]. Shower header design and set up will determine the liquor distribution and flow rate. With fewer shower headers, liquor flow rates need to be increased to achieve the desired displacement [18]. Also, an improper shower bar set up can result in pulp mat disruption (holes), which will reduce vacuum and washer efficiency. It is common to have five shower bars arranged in a symmetrical manner on top of the drum [48].

When it comes to washing, liquor temperature plays an important part by influencing the viscosity of the washing liquor. Higher temperature results in lower viscosity, and consequently better diffusion of liquor into the mat, resulting in better washing. Washing temperatures of 145ºF and 155ºF are the optimum point for vacuum drum washers running pine and hardwood, respectively [18]. Typically, operating a vacuum drum washer line with higher applied wash water temperature on the last washing stage results in liquor flashing in the first washer drop leg. When flashing occurs, washing efficiency decreases and, in extreme cases, the resulting vapor bubble can mechanically damage the washer.

Discharge Consistency (%)	Mass Filtrate/ Mass Fiber	Soda Loss per O.D. Ton Pulp (lb)
8	11.5	240
10	9.0	188
12	7.3	153
14	6.1	128
16	5.3	109

I. Impact of discharge consistency on soda loss assuming 10 g soda per liter of filtrate.

Pulp discharge consistency

A higher discharge consistency will provide the system with a better displacement ratio, and consequently, better washing [10]. The impact of discharge consistency tends to be more important when the discharge consistency is low. Once the discharge consistency increases beyond about 14%, the effect of increasing discharge consistency on washing efficiency has been found to be less important [18]. To better illustrate this example, **Table I** shows the effect of discharge consistency on soda loss, assuming a constant dissolved soda concentration of 10 g/L and discharge consistency varying from 8% to 16%. The results in Table I clearly show that once the discharge consistency gets much above 14%-16%, the effect of discharge consistency clearly diminishes. **Table II** presents a summary of the variables influencing solids removal during washing [13].

DETERMINING SOLIDS LOSSES IN WASHING SYSTEMS

Modern washing systems do a good job of chemical recovery. Even so, achievement of 100% efficiency in dissolved solids recovery is nearly impossible. Existing methods allow one to quantify and track those losses and improve the washing system.

One of the most common and widely used ways to quantify chemical losses is the so-called saltcake or soda loss determination. Other techniques, such as dissolved solids and COD, also are used. Although most commonly used in mills, these techniques have been challenged by on-line measurements that claim to be more representative of the real losses [49-55].

Soda loss determination can be reported as the amount of water-washable sodium that can be extracted from the pulp [56,57]. It can also be determined as the amount of sodium extracted from the pulp by using hydrochloric acid. Saltcake can be expressed as $NaSO_4$, NaOH, or Na_2O. Both methods are fast and accurate, making this method the most preferable among the industry.

Dissolved solids is a simple method to measure how much of the solids are being carried over with the pulp and not participating in the recovery cycle. It is performed by collecting a liquor sample from the mat and placing it under heat for water evaporation. The dry solids are the dissolved solids and can be reported as percent dissolved solids carried over from washing.

	Dependency
Pulp characteristics	Pulping process
	Drainability
	Wood species
Shower liquor	Temperature
	Distribution
	Arrangement
Sheet formation	Specific load
	Vat consistency
	Drum speed
Operational	Dilution factor
	Pulp temperature
	Air entrainment
	Black liquor solids content
	Wire mesh characteristics
	Washer incrustations
	Discharge consistency

II. Summary of variables influencing solids removal during washing.

COD is another method used to determine solids losses in a washing system. The drawback of performing this test on a routine basis is its complexity and extended time of reactions. The biggest advantage is the independency of the method in terms of adsorption effects [10].

WASHING EQUIPMENT

For many years, rotary vacuum drums dominated washing systems worldwide. Rotary drum washers still wash more tons of pulp than any other type of washer, but nowadays, a number of different systems and equipment combinations are available to challenge vacuum drum efficiency [13]. Over the years, several studies on filter washing, diffusers, and press washing have been published [6,38,45,42-44,57-75]. Of interest in this review are rotary vaccum drums, rotary pressurized drums (compaction baffle [CB] and displacement drum [DD] washers), horizontal belt washers, extraction presses, atmospheric diffusers, and pressurized diffusers.

Rotary vacuum drums

Rotary vacuum drums are the most common device used in brownstock washing. It applies the drop leg principle to create vacuum and remove dirty liquid from pulp. Rotary

vacuum drums operate at a consistency range from 0.8% (inlet) to 18% (outlet) with a production capacity of 5-12 moisture-free tons/m² and a system DR that is considered low (0.65-0.80). Vacuum washers have limitations in terms of temperature (barometric leg), with an upper limit at 85ºC. The main washing principals in this technology are dilution/extraction and displacement. Low retention times result in limited amounts of diffusion. Air entrainment and foaming are usually the biggest source of trouble when running these washers [42,44]. Face wire pluggage may also result in significant washer upsets.

Compaction baffle

The CB washer follows similar principles to the rotary vacuum drum washer, with the advantage of higher temperature limits (90ºC-95ºC). Additionally, the hydrodynamic baffle imparts pressing to the pulp mat, enabling the removal of part of the filtrate carried with the pulp. It also handles a higher inlet consistency (2%-5%) and delivers higher discharge consistencies (12%-20%) with higher tonnage capacity (30 moisture-free tons/m²). Another advantage is the smaller area required for installation with smaller filtrate tank requirements. CB washers do not require the minimum 30-ft vertical drop that vacuum drum washers require as the pressure differential across the washer drum is supplied via the pressurized washer instead of the barometric leg vacuum generated in the drop leg of a vacuum washer.

Displacement drum

DD washers are multistage devices (two to four stages) on a single drum. They are capable of operating at high temperatures (85ºC-95ºC) and high inlet (5%-12%) consistency to provide higher retention time and displacement. DD washer filtrate systems operate in a hydraulically full manner and are pumped through the entire washer system, thus reducing the amount of entrained air in the system. The washer runs at loads of up to 20 moisture-free tons/m².

Horizontal belt washers

With a very low dilution factor (about 1), this washer can still obtain high solids removal. It is basically a fourdrinier section of a paper machine with the presence of five or more displacement stages along the belt. It has limitations in terms of operation temperature. The belt washer is an excellent device for removing dissolved inorganic solids. It does appear to have some limitations in the removal of dissolved organic material, especially the material within the fiber.

Extraction presses

Extraction presses apply the principle of dilution/thickening of the pulp. They have the advantage of removing liquor from the fiber lumen in a more efficient and quicker manner as compared to displacement and/or diffusion washing [1]. Presses also remove foaming interferences during washing [1]. They operate at inlet consistencies that vary from 2.5% to 6.0% and discharges that can achieve 40% consistency. It requires a smaller installation area and filtrate tank than several of the other washers. A press can achieve up to 40 o.d. tons/day/m² of press roll surface area. Usually the washing system is used with pulps where the principle of displacement is not effective.

Pressurized and atmospheric diffusers

As the name states, diffusion is the main washing principal taking place during this washing operation. It is characterized by the long period of contact between pulp and washing liquor. No air is allowed in the system that requires total submersion of the pulp into the liquor. The rate of flow determines diffuser washing capacity and is limited by pressure gradient, pulp mat resistance and liquor viscosity [6]. The optimum pressure differential during the washing process was found to be in the range of 1.5-2.0 kp/cm² [52].

Pressurized diffusers are characterized by their simple operation with a small required installation area. It has a washing period ranging from 90-120 min. The system provides high washing efficiency. Atmospheric diffusers have the disadvantage of not handling temperatures above 100ºC.

THE ROLE OF ANTIFOAM ADDITIVES

In a kraft mill, the use of antifoam additives allows for more efficient screening and washing of the pulp. This is achieved by preventing entrapped air from forming in the system, which allows for an easier flow of stock through the screens and washers.

For many years, the kraft industry has used mineral oils or kerosene-based antifoams. At the time, these products allowed for significant increases in production and minimization of chemical losses in the recovery cycle and minimized carryover to the bleach plant [76]. The use of oil-based antifoam also resulted in some negative effects for the industry, especially in the paper machine with pitch deposits of high molecular weight fractions of oil and waxes [77]. Environmental impacts were also a concern because dioxin and furan precursors could be found in antifoam products [78] and oil-related sheens often could be detected on the surface of receiving waters. Another negative of its use was price volatility because it depended on petroleum supply and demand.

Since 1943, the use of silicone has steadily increased and a vast array of products have been developed and used in the pulp and paper industry [79]. By the late 1980s, environmental concerns over antifoam additives (oils and waxes) provided greater motivation toward the use of silicone-based antifoam in brownstock washing. Silicone antifoam products demonstrated effectiveness at very low dosages, allowing for foam prevention and improvements in washer drainage, with substantial gains in chemicals for recovery and bleach plants.

Silicone terminology is commonly applied to polymeric materials with Si-O- as the main repeated unit. Covalent bonds of inorganic/organic substituents also may be present in the molecule.

Effective silicone antifoam products have to perform well

in the challenging environment of the pulp and paper industry. To do so, some key features are necessary, such as access to bubbles on the surface with low product application (product inter- and intra-molecular forces need to be low). The product molecule needs to be able to rotate, allowing for the proper orientation on the bubble surface. The product molecule also needs to be incompatible with black liquor to prevent product solubilization and loss of effectiveness (hydrophobicity), stable in terms of viscosity at different temperatures, and able to easily distribute over the surface (low surface tension) [76]. Aqueous silicone emulsions are the most preferred choice in the pulp and paper industry [80].

Although product features (proper formulation) are important, feed points in the process are also a key to successful application. Feed points are usually where foam is most problematic and can be easily identified by locations where air entrainment to the system is most severe [80]. Silicone technology is indeed less problematic than mineral oil. Nevertheless, deposits will still occur if product formulation and/or application are incorrect [77].

Some examples of problematic situations in pulp mills were explored by Hoekstra 2007 [77]. The author describes a situation in a pine bleached kraft mill that switched from mineral oil to concentrated silicone when it installed a new washer system. After transitioning, the mill ran for approximately 20 h and encountered severe deposition of silicone material. The mill fought silicone deposits for months, averaging 5000 tons of unsalable pulp per month. Finally, a new formulation of silicone antifoam with no deposition tendency was introduced and great improvement in pulp quality was obtained. The new formulation was a more effective antifoam product that reduced the application rate to the system. Also stabilizers that reduced deposition were added to the new formulation. Black liquor characteristics and hemicellulose content were found to be directly related to low dispersability of previous antifoam products allowing for deposit formation. High hemicellulose content in black liquor was found to increase deposition likelihood. Temperature increase also appears to contribute to deposit formation, as does high calcium concentration in the system.

In another mill producing unbleached kraft pine pulp, the change in antifoam product allowed an increase of 4% in mat consistency (better drainage), reduction of 4% in solids carryover, reduction of 7% in shower water usage, and a 75% reduction in antifoam usage (on a pound per ton of pulp basis).

To avoid or minimize potential problems when transitioning from one antifoam formulation to another, a mill should perform laboratory experiments that allow deposit potential and product effectiveness to be determined. A simple test consisting of the use of pulp mill black liquor samples heated to process temperatures with the addition of antifoam should be performed. Shear is applied to the sample once process temperature is reached. The sample is then set aside and observed for antifoam separation and deposit formation. The same test can be conducted at different temperatures and pH to test different possible scenarios encountered in the pulp mill [77].

CONCLUSIONS

Several different operational parameters have been discussed and the potential impact on operational efficiency has been reviewed. These include inlet consistency, discharge consistency, stock temperature, shower water flow, drum speed, and antifoam application. The different types of washing, dilution/extraction, displacement, and diffusion have also been reviewed. The tendency for modern washing devices to enhance one, or a few, of these washing types at the expense of others has also been discussed. Methods to compare the efficiency of different washing devices, such as Norden number or EDR, have also been reviewed. Finally, the application of various dynamic and steady state modeling methods has been highlighted.

In general, it is important to understand individual mill specific washing devices to optimize the operation of a specific set of brownstock washers. The mill specific needs, wood species, pulping technologies, and energy considerations need to be incorporated into the model to optimize a specific mill system. When all of the mill specific considerations are taken into account, it is possible to balance soda loss considerations with the evaporator, production, quality, and environmental impacts required to optimize a specific mill. **TJ**

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ABOUT THE AUTHORS

Brownstock washing is one of the major unit operations within the pulp manufacturing business. Poorly operating washers have the potential to significantly and negatively affect most every other area of a pulp and paper mill, including the mill's environmental performance. As such, it is important to periodically review the work that has been performed in brownstock washing to ensure complete understanding of the process.

Hart served as the co-chair of the TAPPI Brownstock Washing Short Course for many years. Since the course has not been offered in a while, the current work was prepared by combining some of the key aspects of that course with the more current literature work available.

The authors were surprised at the amount of modeling theses published about different aspects of brownstock washing and the shear lack of practical operating or applications efforts that have been published in recent years.

Because brownstock washing is one of the key aspects of a well-running integrated mill, review and understanding of brownstock washing fundamentals is important for all mill operations personnel. Good understanding of the fundamentals and current research will help a mill optimize this important unit operation.



Santos



Hart

The next step in this effort would be to expand the current literature review into an updated textbook covering the design and operation of brownstock washing in greater detail. The expanded effort would also review the liquor cycle, bleach plant carryover, and environmental impacts of brownstock washing in much greater detail.

Santos is applied technology specialist, MWV Corp., Covington, VA, USA, and Hart is manager, New Technology, MWV Corp., Atlanta, GA, USA. Email Hart at peter.hart@mwv.com.

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