Assessment of Mixing Quality for an Industrial Pulp Mixer Using Electrical Resistance Tomography

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The quality of mixing of a pulp suspension and chlorine dioxide by a static mixer in an industrial chlorine dioxide bleaching stage was evaluated using electrical resistance tomography (ERT) as a function of process operating conditions, including chemical flow rate, suspension flow rate, and suspension mass concentration. The uniformity was quantified by a mixing index based on the coefficient of variation of the individual conductivity values in each image pixel. An increase in the mixing index, indicating lower mixing quality, was observed when the chemical flow rate increased. In addition, the mixing quality decreased with a decrease in suspension flow rate. On the other hand, a decrease in the suspension mass concentration at a constant volumetric suspension flow rate gave better mixing quality. The results show that ERT can be used to evaluate industrial-scale mixer performance and to monitor the changes in the mixing quality as a function of process operating conditions. The results are in good agreement with those in the literature based on other measurement techniques for similar mixer installations.

La qualité de mélange d'une suspension de pâte et d'une solution de ClO2 par un mélangeur statique dans un stade de blanchiment industriel a été évaluée à l'aide de la tomographie par résistance électrique (ERT) en fonction du processus d'exploitation de conditions, y compris le débit de solution, débit de suspension et la concentration de fibre. L'uniformité a été quantifiée par un indice de mélange basé sur le coefficient de variation des valeurs individuelles de conductivité dans chaque pixel de l'image. Une augmentation de l'indice de mélange, indiquant une qualité inférieure de mélange, a été observée lorsque le débit de solution a augmenté. En outre, la qualité du mélange diminue avec une diminution de la vitesse d'écoulement de suspension. En revanche, une diminution de la concentration de fibre dans la suspension à un débit constant de suspension volumétrique a donné un mélange de meilleure qualité. Les résultats montrent que l'ERT peut être utilisée pour évaluer sur le plan industriel le rendement du mélangeur et pour surveiller la qualité du mélange sous différentes conditions d'exploitation. Les résultats sont en bon accord avec ceux de la littérature basée sur d'autres techniques de mesure pour des installations de mélangeur similaire

Keywords: pulp fibre suspensions, bleaching operations, static mixers, mixing index, electrical resistance tomography

INTRODUCTION

Mixing is an essential unit operation in the pulp and paper industry. It is used for blending pulp in stock chests, controlling consistency in pulp processing, attenuating high-frequency variations in consistency before paper machines, and mixing chemicals into pulp suspensions in bleaching stages. Without good mixing, operation costs can be higher due to unstable production and poor product quality. For example, poor mixing in a bleach plant leads to poor chemical contacting, resulting in poor product quality such as lower pulp brightness and cleanliness. This is often offset by using additional chemicals. However, excessive use of bleaching chemicals increases production costs and has a detrimental effect on product strength.

The benefits of improved mixing have been known for many years. Mill experience and laboratory studies have shown that improved mixing leads to reduced chemical usage and more uniform product quality in pulp bleaching operations (Atkinson and Partridge, 1966; Elliott and Farr, 1973; Torregrossa, 1983;

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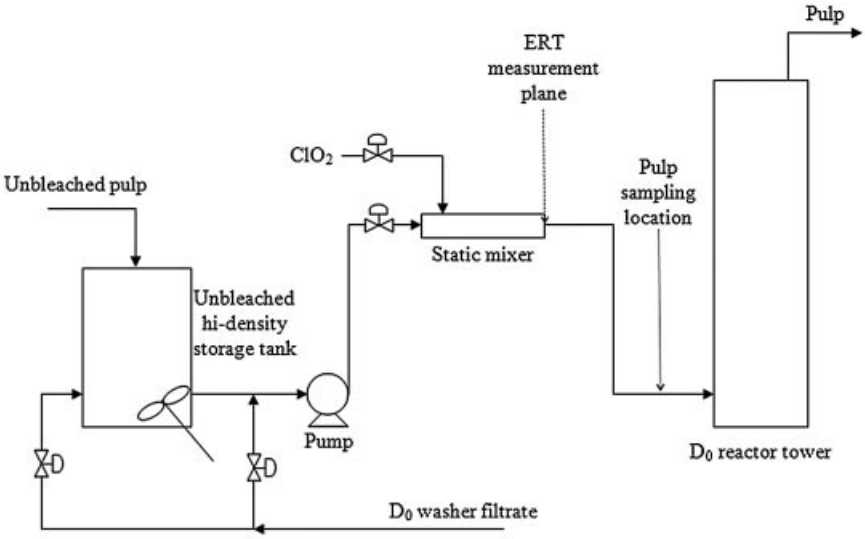

Figure 1. Schematic of D_0 stage at Howe Sound Pulp and Paper.

Kolmodin, 1984; Pattyson, 1984; Sinn, 1984; Backlund and Parming, 1985; Backlund et al., 1987; Robitaille, 1987; Berry, 1990). Several pulp mills that improved mixing efficiency in the process obtained their returns on investment in as little as 3 months (Bennington, 2004). In order to assess the potential benefits of the improved mixing, the mixing quality must be determined by a suitable technique.

As in other industries, assessing mixing quality in pulp and paper processes is a difficult task. Several methods have been applied. Among the most common are indirect measurement techniques based on the final product quality such as kappa number (lignin content), pulp brightness, pulp cleanliness, and pulp strength (Atkinson and Partridge, 1966; Bennington et al., 2001). Poor product quality can be an indication of poor mixing in the production process. However, product quality is an ambiguous indicator of mixing quality since it is unable to specify where the problem occurs. For example, poor product quality could be due to poor washing of pulp rather than poor mixing. Therefore, direct methods to assess mixing quality are highly desirable.

There are a number of direct methods to evaluate mixing quality. For laboratory or pilot scale mixing assessment, these include measurement of the distribution of chemical residuals (Paterson and Kerekes, 1985), inert tracers (Breed, 1985; Bennington et al., 1997; Francis and Kerekes, 1990; Kamal and Bennington, 2000), and radioactive isotopes (Kuoppamaki, 1985; Kuoppamaki et al., 1992). For mill applications, the technique must not interfere with the process or adversely affect pulp quality. Past techniques include measurement of the uniformity of chemical residuals (Paterson and Kerekes, 1986), distribution of inert tracers (Torregrossa, 1983; Backlund et al., 1987), and temperature profiles around process piping (Torregrossa, 1983; Sinn, 1984; Pattyson, 1984; Robitaille, 1987; Rewatkar et al., 2002). However, there is still no effective method to determine mixing quality on the industrial scale at a pulp mill. Most mixing assessment techniques are invasive, tedious, and time consuming. Since they can only give an indication at a sampling point, a large number of samples at different locations are required to give a clear picture of how mixing is occurring. Temperature profiling the surface of a process pipe can be used to infer the mixing quality if a sufficient temperature difference exists between the pulp stream and the added chemical. It does not interfere with the process and can be implemented as an in situ measurement technique. However, this technique only determines mixture quality at the periphery of the pipe and is unable to quantify mixing throughout the suspension volume. The main goals of this study are to develop protocols for measuring mixing quality in pulp suspensions and to implement the technique as a real-time mixing assessment tool on an industrial scale.

In this work, electrical resistance tomography (ERT) was used to assess mixing quality for an industrial pulp mixer. ERT is a non-invasive technique that has been utilised extensively to assess mixing quality in various processes (William et al., 1996; West et al., 1999; Li and Wei, 1999; Kaminoyama et al., 2005; Vlaev and Bennington, 2005; Kim et al., 2006; Stephenson et al., 2007). ERT measures the distribution of electrical conductivity in the region of interest from voltage measurements at the vessel periphery (Mann et al., 1997). If a suitable conductivity difference exists between the suspension and the added chemical, the spatial homogeneity of conductivity can be measured, and mixing conditions can be evaluated and quantified.

The mixing quality of pulp suspensions downstream of a static mixer in the first chlorine dioxide bleaching (D_0) stage at Howe Sound Pulp and Paper Ltd (HSPP), Port Mellon, BC was evaluated for various operating conditions. The D_0 stage operates with low-consistency pulp suspensions, $C_m = 3$–$4\,\%$, treated with chlorine dioxide, ClO_2 (1.5–2.0 wt.% on pulp) for 20 min at temperatures from 50 to 60°C. These conditions are referred to as normal operating conditions in this study. Bleaching begins by contacting pulp with ClO_2 in a brief (1–2 s) period inside a static mixer. The pulp is then transferred to a reaction tower with sufficient retention time to complete the reaction. The process flow diagram for the D_0 stage is illustrated in Figure 1. The ClO_2 solution (10 g/L) is introduced in the pulp suspension at a T-junction through a small drilled pipe sparger that distributes the chemical throughout a cross-section of the static mixer. The mixture then flows through the static mixer to contact the pulp suspension with the added chemical and to ensure radial uniformity of composition. The static mixer is important to ensure efficient contacting between chemical and pulp in the tower, an essential requirement for achieving the greatest lignin removal and optimal use of the bleaching chemical.

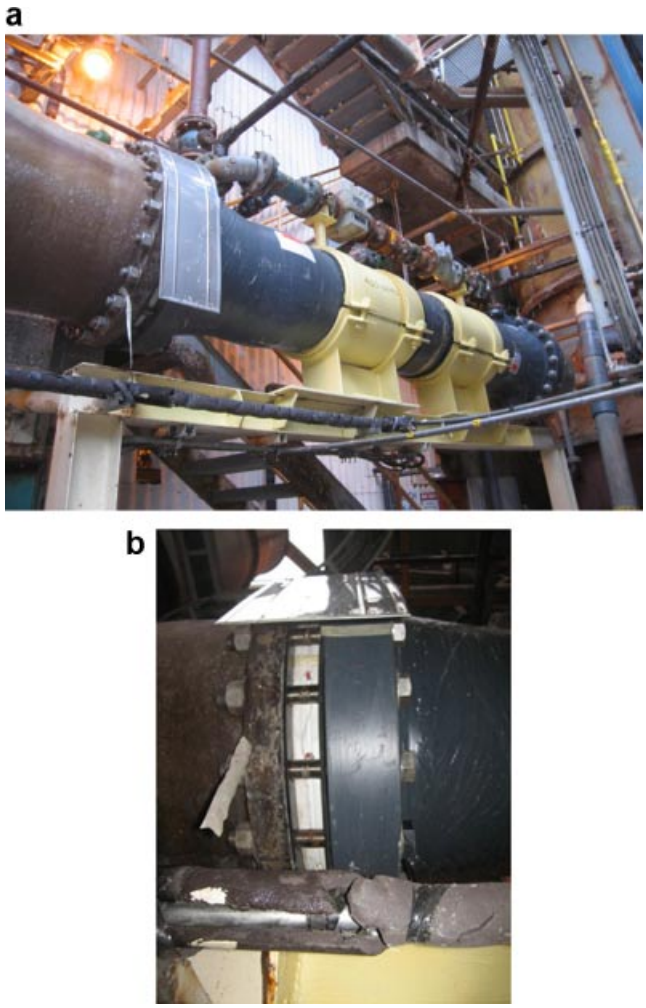

Figure 2. ERT sensor plane (a) located at outlet of static mixer where pulp suspensions flow from right to left; (b) inserted between flanges after static mixer.

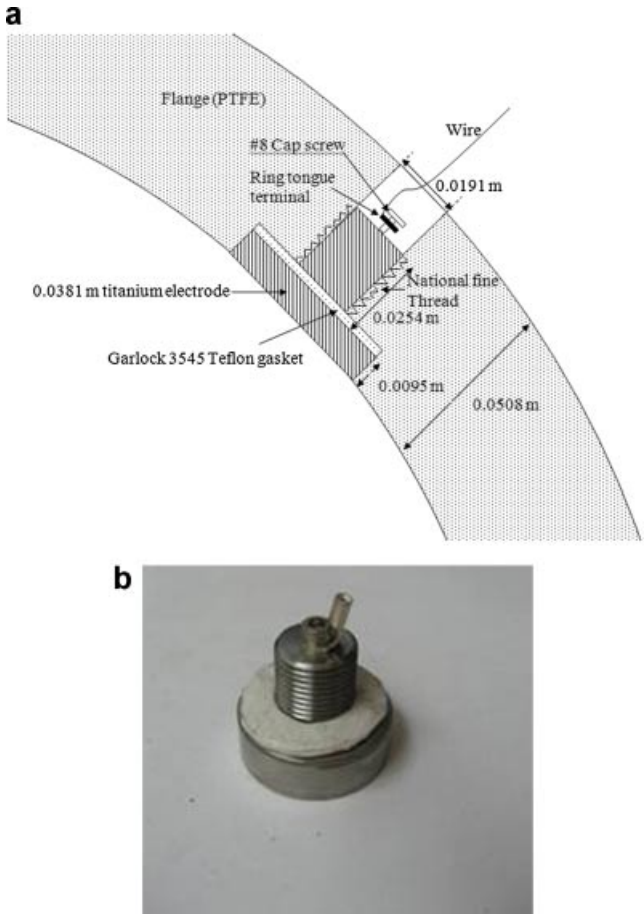

Figure 3. ERT sensor design details (a) schematic of ERT sensor; (b) image of electrode.

EXPERIMENTAL

The ERT technique was applied to assess the quality of mixing of pulp suspension with chlorine dioxide by measuring the distribution of electrical conductivity in a cross-section of the pipe. A 610 mm ID PTFE gasket was inserted between the flanges after the static mixer. It served as an ERT measurement plane as shown in Figure 2. The measurement plane consists of 16 circular titanium electrodes (38.1 mm diameter), equi-spaced at 22.5° intervals around the periphery. Each electrode (sensor) was threaded into the PTFE gasket to be flush with the internal wall of the plane. Thus, the electrodes do not alter the flow of pulp suspension in the pipe, and the measurement technique is non-intrusive. A screw was tapped into the end of each electrode to attach the coaxial cables, which carried input and output electrical ERT signals. Details of the sensor design are shown in Figure 3. The sensors were arranged around the pipe periphery, with the first electrode at the top of the pipe. A ground electrode of the same size as the sensor electrode was positioned between electrodes 8 and 9 at the bottom of the sensor plane. All electrodes were connected to an ITS Z8000 system (Industrial Tomography Systems, Manchester, UK) via 2.5 m long coaxial cables.

The ITS Z8000 system applies a constant AC current to a pair of electrodes and measures the voltage differences between the other electrode pairs using an adjacent-pair strategy (ITS, 2007). The frequency of the injection current was 80 kHz. The sampling interval was maintained at 100 ms, and hence data were acquired at a rate of 10 Hz. A linear back projection algorithm was employed for image reconstruction using ITS Z8000 software. In general, the Z8000 system has excellent temporal resolution (maximum sampling rate of 1000 Hz), but achieves a spatial resolution of only 5–10% of the pipe diameter (equivalent to 30–60 mm in this study). The local conductivity values obtained from ERT measurement were temporally averaged for 100–150 frames (representing 10–15 s of operation) for further analysis.

The degree of uniformity in a measurement plane as a function of time was characterised by the coefficient of variation (CoV) of the image pixels, defined as the mixing index:

$$M_{\mathrm{m}} = \frac{\sigma}{\overline{y}} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(y_i - \overline{y})^2}{n-1}}}{\overline{y}} \tag{1}$$

where σ is the standard deviation of the conductivity values, y_i is the local mixture conductivity determined from ERT measurements, $\overline{y}$ is the average conductivity, and n is the total number of pixels in the measurement plane (316 pixels). The mixing index decreases when the mixing quality improves and is zero for perfect mixing.

In order to account for differences in conductivity due to inherent heterogeneity in the pulp suspension and system noise, the

mixing index defined by Equation (1) was corrected as:

$$M = \sqrt{M_m^2 - M_s^2} \quad (2)$$

where M_m is the measured mixing index under the given operating conditions and M_s is the system mixing index measured in the absence of ClO_2.

RESULTS AND DISCUSSION

New Mixer Installation at HSPP

Komax static mixers have been used in the D_0 stage at HSPP since 1989. Increasing chemical usage through 2007 and early 2008 led the mill to inspect the old mixer, and its performance was found to be unsatisfactory. It was replaced by a new static mixer during the October 2008 mill maintenance shutdown. At this time, it was found that mixer elements in the old mixer were completely missing as shown in Figure 4. The new Komax static mixer consists of four mixer elements with adjacent mixing elements rotated by 90°. It was designed to improve the performance by reducing the diameter from 610 to 508 mm to give higher velocities and hence higher energy for mixing from a higher pressure drop. During the mixer installation period, we had the opportunity to install the ERT sensor plane between flanges after the mixer. This allowed the performance of the new mixer to be assessed based on the new measurement technique and the results to be compared with mixing measurements which utilised other techniques in previous studies for similar mixer installations.

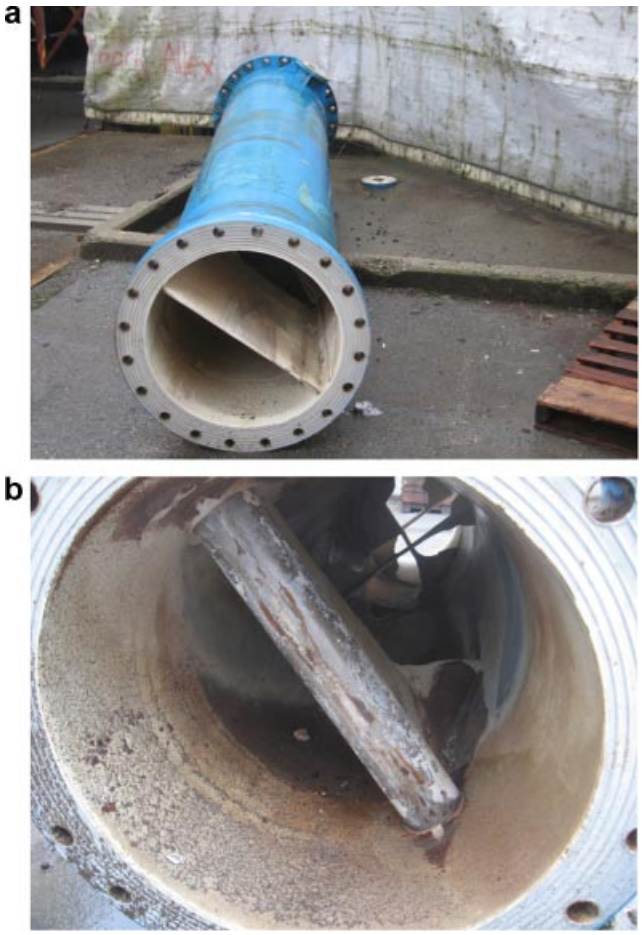

Figure 4. Photographs of (a) old static mixer; (b) its mixer elements.

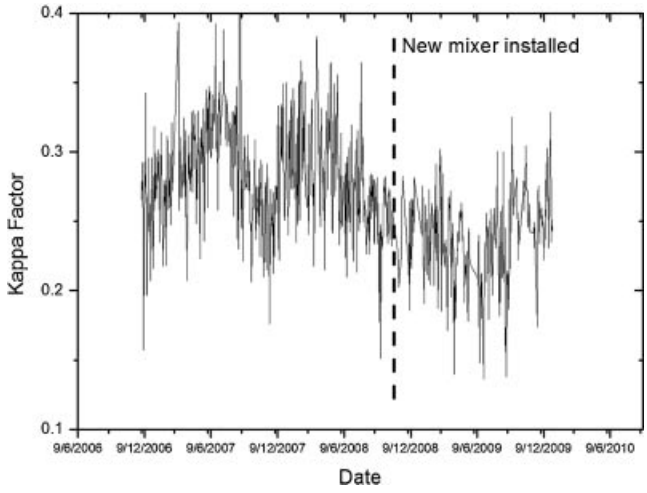

Figure 5. Kappa factor representing chemical use before and after mixer installation.

The chemical use before and after mixer replacement was compared based on the kappa factor (ratio of the amount of chemical applied to the process to the amount of lignin in the pulp entering the process). The kappa factor was found to significantly decrease from 0.29 to 0.24, as shown in Figure 5, resulting in chemical savings of approximately $1 600 000 per year. Comparison showed that the mixing quality improved significantly when the new mixer was installed.

The variation of kappa factor in Figure 5 is quite large on a daily basis, mainly due to variations in process conditions. The chemical use is strongly affected by the performance of brownstock washers ahead of the static mixer. The evaporator sometimes reached its upper limit, so that there was not enough fresh water to properly wash pulp, resulting in higher chemical demand. In addition, chemical use depends on the composition of the wood entering the process, and this changed during some periods of time. However, this variation did not affect the ERT measurements. Each ERT measurement period lasted <5 min, while the time scale for variation of the kappa factor was about a day. Hence the impact of this variation on the ERT measurements was very small.

Reaction of ClO_2 with Pulp

Chlorine dioxide added to the pulp for bleaching operation can itself be treated as a tracer in the mixing studies carried out in this work. This is possible because the electrical conductivity of ClO_2 (1.76 mS/cm) differs significantly from the conductivity of pulp suspension (4.8 mS/cm). In a typical conductivity tomogram, the regions of low conductivity thus correspond to ClO_2-rich regions. However, the extent of reaction needs to be considered since the tracer reacts with the process fluid. Chlorine dioxide delignification is a combination of an initial fast reaction and a subsequent slow reaction (Tessier and Savoie, 1997; Chandranupap and Nguyen, 1998). The pulp suspension and chlorine dioxide are in contact for approximately 2 s (based on a typical flow velocity of 1.5 m/s in the 508 mm ID pipe, corresponding to a production rate of 1000 t/d or a suspension flow rate of 300 L/s) when the mixture arrives at the ERT measurement plane. If there were to be plug flow of the mixture through the pipe, the extent of reaction is estimated to be about 20% at the measurement

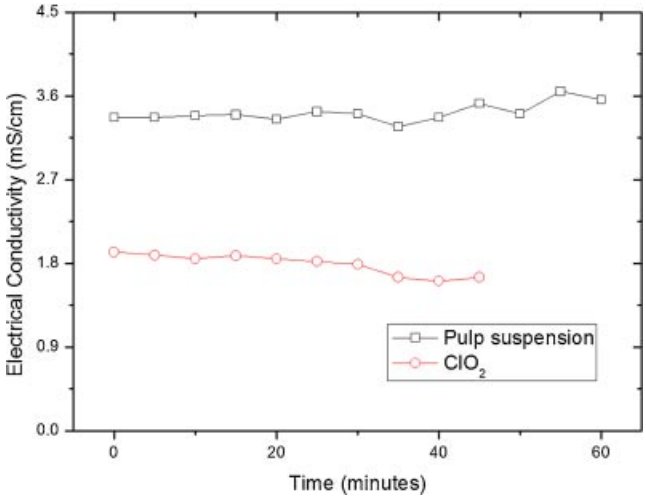

Figure 6. Temporal variation of electrical conductivity of pulp ahead of mixer and ClO_2 solution.

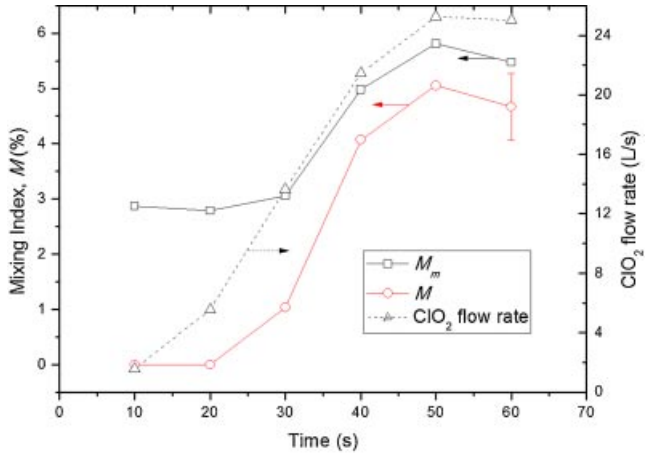

Figure 7. Mixing index as a function of time after the ClO_2 valve was opened from shut-off position.

plane, based on reaction kinetics of pulp suspension with chlorine dioxide (Chandranupap and Nguyen, 1998). The measured ClO_2 concentration at a distance of approximately 12 m downstream of chemical injection (corresponding to a residence time of 10 s) also showed high chemical consumption, roughly 80%. Unfortunately, there is no sampling port for taking samples immediately after the static mixer, but the extent of reaction is expected to be significant at the measurement plane. The reaction of a tracer with pulp reduces the tracer concentration, possibly changing the chemical distribution in the pulp suspension and thus the measured mixing quality in the process. The reaction also changes the electrical conductivity of the mixture. The conductivity of the mixture approximately 12 m downstream of chemical injection was found to be 10% higher than that of the pulp suspension before the mixer. The change in conductivity in the mixture due to reaction therefore does not affect the interpretation of the regions of low conductivity, which can still be referred to as ClO_2-rich regions.

Variability of Conductivity with Time for Pulp Suspension and ClO_2 Feed to Mixer

Figure 6 illustrates the temporal variation of electrical conductivity for pulp suspension before the static mixer and ClO_2 solution. There was little variability of conductivity in a period of an hour for both fluids, while the ERT measurement period was <5 min. This ensures that the errors in ERT mixing quality measurement caused by variation in the electrical conductivity of the feeds are negligible.

Flow Regime

For Newtonian fluids, Reynolds numbers are used to estimate the flow regime for each operating condition. In the case of pulp suspension flow through pipes, however, characterising flow regimes such as laminar, transitional, or turbulent is impossible. This is because pulp suspensions mainly flow in a plug flow manner through the pipe, except near the walls where shear-dominated flow exists. Therefore, it is difficult to obtain a Reynolds number in a conventional sense, since the apparent viscosity of pulp suspension is a strong function of the shear rate and the shear is confined to a very small region near the pipe walls. The flow of pulp suspension exhibits more complexities than that of a single-phase non-Newtonian fluid characterised by apparent viscosity. The complex rheology of pulp suspension and its impact on the flow regime, floc formation, dispersion, etc. is the subject of ongoing investigation (Kerekes, 2006). For pulp suspension flow through pipes, it is customary to identify the flow regime as plug, mixed, or turbulent based on the criterion given by Robertson and Mason (1957). This analysis indicates that the pulp suspension was mostly in the plug flow regime for the operating conditions of this study.

Mixing Quality as a Function of Process Operating Conditions

The mixing index in the absence of ClO_2, designated M_s, was found to be 2.87%. Figure 7 illustrates the measured mixing index and corrected mixing index when the ClO_2 valve was opened from the shut-off position. The ClO_2 valve had been closed for approximately 20 s before being opened to the normal position. The corrected mixing index significantly increased after the ClO_2 valve was opened, with the average mixing index when ClO_2 was present being 4.86%, which is considered to be the mixing index for normal operation. Tomographic images for the same condition are shown in Figure 8. The first image illustrates the temporal-averaged conductivity tomograph over the first 20 s with no ClO_2 present, whereas the other image shows the average conductivity distribution with ClO_2 present. The second image shows the low conductivity region on the right of the image due to the presence of the added chemical, which has lower conductivity. Although some ClO_2 was likely consumed by the initial fast reaction, the amount of tracer was high enough for ERT to detect the ClO_2-rich region. However, the conductivity of this region (4.0–4.6 mS/cm) is higher than the measured ClO_2 conductivity (1.76 mS/cm) and close to the conductivity of pulp suspension (4.8 mS/cm), mainly due to the dilution of ClO_2 in pulp suspensions. This was confirmed by a mass balance ($m_p = 289$ kg/s and $m_c = 20.9$ kg/s), where the estimated conductivity of the mixture for perfect mixing conditions (assuming the conductivity to be linearly related to concentration) was 4.59 mS/cm.

Figure 9 shows the effect of a step change in suspension flow rate on mixing quality of the pulp suspensions at a constant mass concentration of 3.5%. The suspension flow rate decreased from 390 to 225 L/s, and the mixing index increased continuously as the flow rate decreased. The reduction in mixing quality was due to the lower energy for mixing when the flow rate through the static

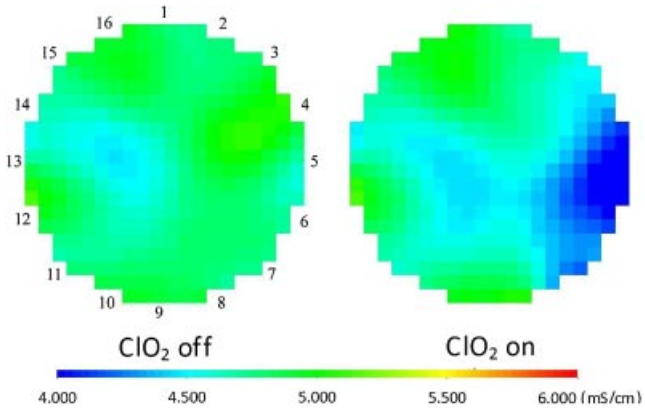

Figure 8. Tomographic images before and after ClO_2 was introduced.

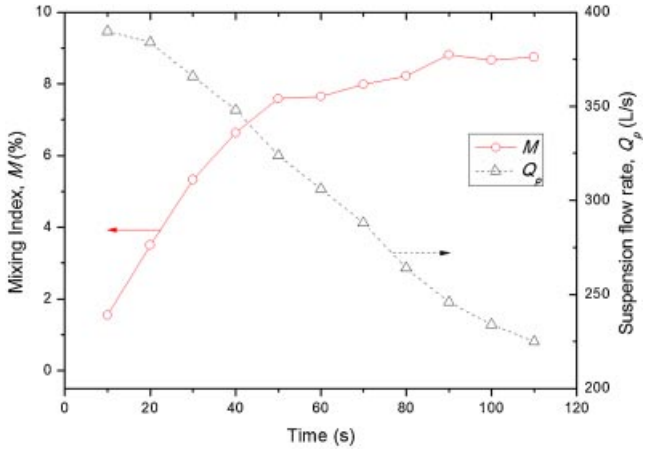

Figure 9. Temporal variation of mixing index as suspension flow rate changed from 390 to 225 L/s at $C_m = 3.5\%$.

mixer decreased. The mixing energy is derived from the pressure drop across the mixing elements of the static mixer when the process fluid passes, and thus depends on the flow rate of the process fluid. The tomographic images for the same condition are illustrated in Figure 10. The images are in time series and were averaged over 10 s for each image. The images show the

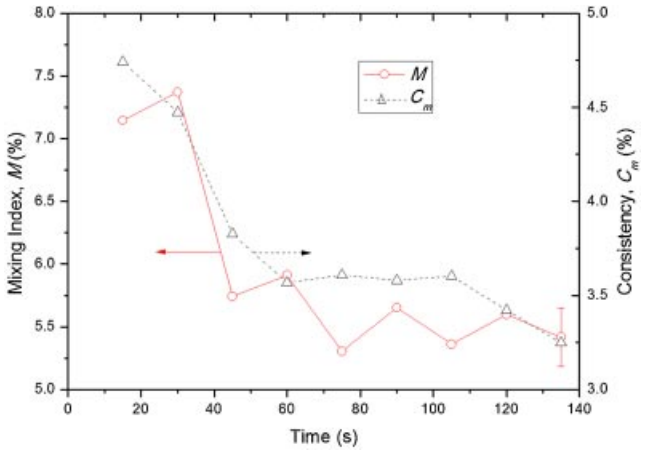

Figure 11. Temporal variation of mixing index as consistency changed from 4.7% to 3.2% at $Q_p = 325$ L/s.

lower conductivity region at the bottom of the image (blue in the colour reproductions), which is probably the region of high concentration of ClO_2, occurring when the mixing quality decreases at lower suspension flow rate. The high-conductivity region (yellow and red in the colour images) probably corresponds to the product of the reaction, consistent with the observed increase in size of this region as the suspension flow rate decreases, since one would expect an increase in the extent of reaction with increasing residence time of the suspension in the pipe. The reason for the side-to-side asymmetry in this region is unclear and needs further investigation.

Figure 11 illustrates the change in mixing quality of the pulp suspensions when the consistency decreased from 4.7% to 3.2% at a constant suspension flow rate of 325 L/s. The mixing index was found to decrease (and hence the quality of mixing improved) with a decrease in suspension consistency, likely due to a less densely packed fibre network, enhancing the distribution of the chemical. The region of low conductivity (blue in the colour images), which is likely to be the ClO_2-rich region, is also smaller when the suspension consistency decreases as illustrated in Figure 12. The images were in time series with each image averaged over 15 s. The third image ($t = 45$ s) illustrates a decrease in the

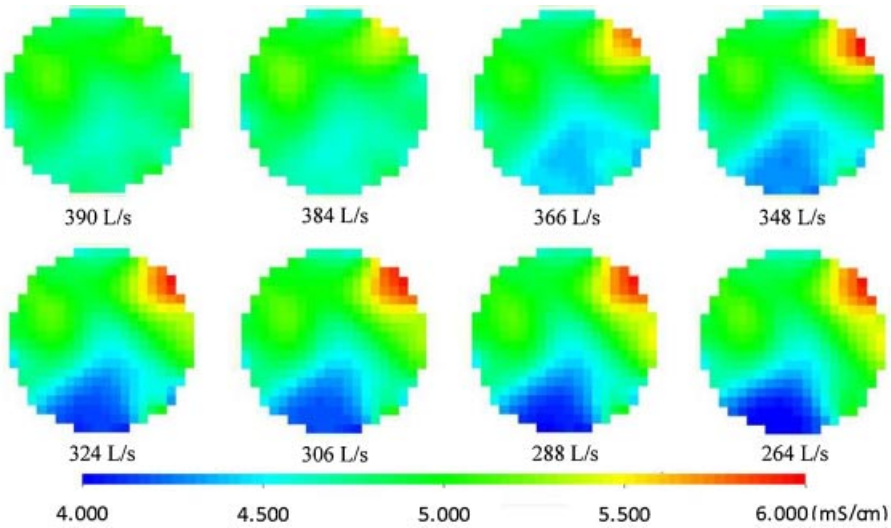

Figure 10. Tomographic images in time series when the suspension flow rate decreased from 390 to 264 L/s at $C_m = 3.5\%$.

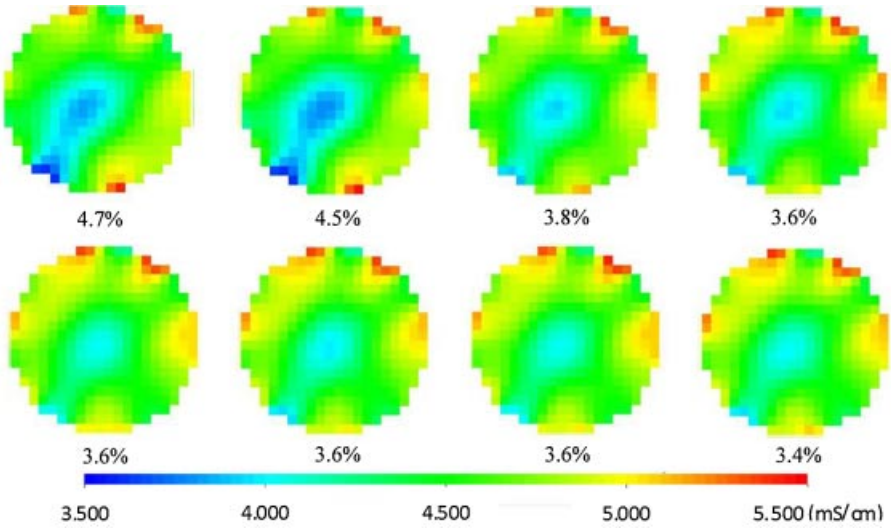

Figure 12. Tomographic Images over time as the consistency decreased from 4.7% to 3.4% at $Q_p = 325$ L/s.

low-conductivity region, that is, an increase in the degree of uniformity compared to the first and second images ($t = 15$, 30 s), corresponding to the trend in Figure 11 when the consistency began to decrease significantly.

Table 1 shows the assessment of mixing quality of industrial pulp mixers based on various measurement techniques. Each of these studies employed the coefficient of variation to quantify the degree of mixing. The flow regime in each work has also been estimated based on the data available in the literature. For most of the previous work cited, the flow was in the plug flow regime, except for the study which utilised the radioactive tracer technique (Kuoppamaki, 1985) where relevant data are unavailable. The mixing indices were compared and good agreement was observed between the ERT measurement and other techniques. The mixing index measured by the ERT technique for normal operation was 4.86%, showing that good mixing quality was obtained, and this corresponded to a significant reduction in chemical use after the new mixer was installed. The good agreement with other techniques also indicates that the reactive tracer can be effective and that the extent of reaction did not significantly affect the measured mixing quality. In addition, the ERT technique has advantages relative to other techniques since it is non-invasive, not tedious, and able to quantify the mixing throughout the entire suspension volume. The results also show that ERT was reasonably successful in monitoring the industrial process changes and in determining the mixer performance. This technique therefore has potential as an online, real-time mixing assessment tool for industrial pulp mills.

While ERT has several benefits over other techniques, it also has some drawbacks. ERT has a spatial resolution of only 5–10% of the pipe diameter; thus it provides less accuracy of measurement on an industrial scale where the pipe diameter can be large. In addition, a custom sensor array has to be built, and there are constraints on its placement since the installation must be between flanges. Once the sensor array is installed, it cannot be easily moved to test other mixers. The array in our case was installed between flanges after the mixer, which is closer to the mixer than would be optimal since the turbulence from the last mixing element continues to cause mixing for several pipe diameters downstream of the mixer exit, beyond the ERT sensor plane. However, turbulence generated in the static mixer decays very quickly due to the network strength of pulp fibre suspensions, when the power dissipation required to sustain the turbulence is not sustained (Bennington et al., 1989). Therefore, mixing occurring downstream of the last mixing element of static mixer is expected to be very small. Finally, this technique requires a significant electrical conductivity difference between the fluids being mixed.

Table 1. Comparison of mixing assessment of industrial pulp mixers (bold for present case)

Mixer type	Consistency, C_m (%)	Measurement technique	Mixing index, M (%)	Refs.
Static	Low[a]	Radioactive tracer	0.5–12	Kuoppamaki (1985)
	2.5	Chemical residuals	5.3	Paterson and Kerekes (1986)
	3.5	ERT	**4.86**	**This work**
High	9.5–12	Inert tracer (LiCl)	2–5	Kolmodin (1984)
Shear	10.5–12	Temperature	8.5	Pattyson (1984)
	10	Inert tracer (LiCl)	6–8	Backlund et al. (1987)
	Medium[b]	Temperature	2.4	Robitaille (1987)
	8–11	Temperature	10–40	Rewatkar et al. (2002)
Peg	Medium[b]	Temperature	5.8	Robitaille (1987)

[a] Low-consistency application ($C_m < 5\%$).
[b] Medium-consistency application ($8\% \leq C_m \leq 16\%$).

CONCLUSIONS

ERT was successful in assessing the mixing performance of an industrial static mixer and in monitoring process changes in the first chlorine dioxide bleaching (D_0) stage at Howe Sound Pulp and Paper. ERT was able to detect the presence of ClO_2 by showing regions of lower conductivity in the tomogram when ClO_2 was introduced. The mixing quality was quantified from image pixels, and the results showed higher mixing index (lower quality mixing) when the ClO_2 flow rate increased. In addition, ERT was able to monitor the changes in mixing quality as the suspension flow rate or mass concentration changed. At lower suspension flow rate, the tomographic images showed regions of lower conductivity at the bottom of the pipe, indicating a higher concentration of ClO_2 at that location. This is likely due to poor mixing when the energy for mixing decreases at a lower suspension flow rate. The images also showed smaller regions of low conductivity or lower concentration of ClO_2 when the suspension mass concentration decreased, likely due to a decrease in the network strength of fibre suspension improving the chemical distribution. In addition, the quantitative analysis showed an increase in the mixing index when the suspension flow rate decreased, and a decrease in the mixing index when the suspension mass concentration decreased. This demonstrates that better mixing performance can be obtained at a higher suspension flow rate and at a lower suspension consistency. The mixing index of the static mixer under normal operation obtained by the ERT technique was also in good agreement with results obtained by other techniques for similar industrial pulp mixers.

NOMENCLATURE

C_m	suspension mass concentration or consistency (%)
m_c	ClO_2 mass flow rate (kg/s)
m_p	pulp suspension mass flow rate (kg/s)
M	mixing index (%)
M_m	measured mixing index (%)
M_s	system mixing index (%)
Q_p	suspension flow rate (L/s)
n	number of image pixels
t	time (s)
y_i	local mixture conductivity (mS/cm)
$\bar{y}$	average conductivity (mS/cm)

Greek Symbols

σ	standard deviation of conductivity in a tomographic image

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