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Oscillatory Flow Mixer for Pulp Bleaching

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This paper reports the results of an investigation on the use of oscillatory baffled column as a mixer for pulp bleaching. Unbleached hardwood kraft pulp was bleached using hydrogen peroxide. Variables studied were oscillation frequency, oscillation amplitude, and pulp consistency. The mixing process was achieved by oscillating pulp suspension in a periodically baffled column at a certain frequency and amplitude. The mixing quality of pulp bleaching was quantified using mixing index. The results showed that mixing quality improved with oscillation frequency and amplitude, but decreased with pulp consistency. This typical device is very promising as a mixer for pulp bleaching.

Keywords: baffled column, mixing index, oscillation, peroxide bleaching, kappa number.

INTRODUCTION

Mixing of chemicals and pulp is one of the most important operations involved in pulp bleaching. Efficient mixing provides homogeneous bleaching conditions, reduces consumption of chemicals and energy, improves product quality, and reduces the environmental load. When mixing is not uniform, some region of the pulp receive chemicals in excess of those required, some of which is consumed in less desirable side reactions. Other regions receive insufficient chemicals and are not adequately bleached. The net effect is that additional chemical is required to obtain a desired degree of bleaching, and pulp of less than optimal strength is produced (Torregrossa, 1983). Various types of mixers have been used over the years to achieve these objectives such as stirred tanks and static mixers. The existing technology in stirred tanks suffers from pulp degradation or damage by the shearing action of the impeller. While in a static mixer high flow rate of pulp suspension is required to achieve good mixing, which implies high energy consumption. Oscillatory baffled columns have been reported in numerous publications as a very promissing way to improve mixing in columns (Hewgill et al., 1993; Mackley, 1987, 1991). The radial velocity component is comparable to the axial velocity component enhancing mixing in both axial and radial directions (Brunold et al., 1989; Dickens, 1989).

The use of oscillatory baffled columns as bioreactors and polymerization reactors have been studied by several researchers (Harison and Mackley, 1992; Ni et al., 1998). Its application as a mixer for pulp bleaching has not been investigated until now. Therefore, the objectives of this paper were to study the potential of baffled

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column combined with oscillatory flow as a mixer for pulp bleaching, and to examine the bleached pulp quality.

THEORY

Characteristics of Mixing

In a continuous oscillatory flow baffled column, the characteristics of mixing have been studied well from the residence time distribution (RTD) perpective, i.e. the changes of tracer concentration are measured as a function of time as the mixing takes place in such system, and a single parameter known as the axial dispersion coefficient, was evaluated from RTD curves. Then, this coefficient was used to quantified characteristics of mixing in the system (Dickens et al., 1989; Howes and Mackley, 1990).

In a batch oscillatory baffled column, two measurements are generally used to quantify mixing characteristics, namely, the mixing time required to create a predetermined level of uniformity at a specified scale, and the uniformity of a mixture following a given treatment (Ni et al., 1998b; Taslim and Takriff, 2001). However, the uniformity of a mixture following a given treatment has not been studied well.

In batch-operated mixers for pulp bleaching processes, assessment of mixing quality is based on the measurement of product quality at the end of the process such as residual chemical content, pulp brightness, and pulp viscosity (Bennington, 1989). Generally, mixing quality is quantified using an index based on weighted standard deviation of the measured variation over the mean.

Peroxide Bleaching

Hydrogen peroxide (H_2O_2) is a versatile bleaching agent that has been applied to bleaching of mechanical pulp in the industry for a long time. Recently, under the pressure to decrease the use of chlorine-containing bleaching chemicals, its use in the bleaching of chemical pulp has increased significantly. Bleaching is done to increase the brightness of the pulp by removing residual ligninital and other color-containing impurities. For delignification of kraft pulp, the conditions (temperature, peroxide concentration, alkali concentration) are usually much harsher than in peroxide brightening of mechanical pulps, so that lignin removal becomes possible. Also, the nature of residual lignin after chemical pulping promotes delignification by several hydrogen peroxide reaction mechanisms, while native lignin in mechanical pulp lends itself better to brightening reactions (Lachenal, 1996; Gierrer, 1997; Anderson and Amini, 1996). The degree of reaction which takes place depends on the nature and the amount of lignin in the pulp, and on the rate of peroxide decomposition.

The content of lignin must be tracked during bleaching in order to gauge the chemical efficiency of the bleaching process. The residual lignin can be determined from the kappa number test by the following relationship (Tappi, 1991; Reeve, 1996):

$$\%\ \text{lignin} = 0.15 \times \text{kappa number} \qquad (1)$$

EXPERIMENTAL WORK

A schematic diagram of the apparatus is shown in Figure 1. The experiments were conducted in a vertical stainless steel column of 0.105 m diameter and 1.4 m length. The device was flanged to a metal frame to insure a vibration-free environment. Baffle plates with spacing of 0.157 m (1.5 times the column internal diameter) in between plates supported by two 6 mm diameter stainless steel rods were installed in the column. Each baffle has a central hole with 50 mm diameter. The oscillation of pulp suspension was achieved by oscillating the baffle setup. A motor equipped with a gear box was mounted at the top of the experimental apparatus to oscillate the baffle setup. The speed of the motor was controlled by a variable speed controller to provide oscillation frequencies in the range of 0.5 to 2.5 Hz. Oscillation amplitude can be varied by adjusting the length of the connecting rod linking the baffle setup and the driver unit. Details of the apparatus used are presented in Table 1.

Unbleached kraft pulp of kappa number 22.8 from a Malaysian commercial kraft mill was used in this experiment. Pulp consistency and chemical reagents at certain concentrations were prepared as shown in Table 2 and introduced into the mixer. All concentrations are expressed in weight percent per oven-dry weight of pulp. The pulp suspension was oscillated at a certain oscillation frequency and amplitude, and the column was heated to a desired temperature. At the end of the experiment, the content of the column was quickly discharged into cold water at room temperature. The pulp slurry was then filtered and washed completely. The washed pulp was dried in the air for one day before testing. The kappa number test was conducted according to TAPPI standard testing methods (Tappi, 1991).

In this study, mixing quality was quantified using the mixing index, M, which is simply the coefficient of variation of kappa number distribution, given by the following equation:

$$M = \frac{S}{\bar{x}} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}}{\bar{x}} \qquad (2)$$

where x_i is the measured kappa number of the i^{th} sample, $\bar{x}$ its mean, and S the standard deviation. In this case, M = 0 corresponds to each fiber receiving the same quantity of bleaching agents.

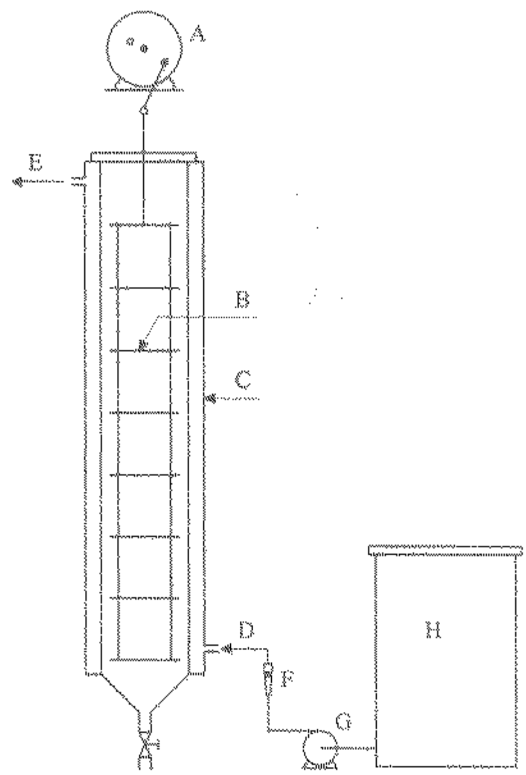
RESULTS AND DISCUSSION

Effect of Pulp Consistency on Mixing Quality

The first set of experiments was carried out to determine the effect of pulp consistency on the mixing index at a fixed oscillation frequency and

Table 1. Details of apparatus used in this work.

Details	Value
Inside column diameter, D	0.105 m
Column height	1.400 m
Baffle inner diameter, D_o	0.050 m
Baffle outer diameter	0.092 m
Baffle spacing	0.157 m
Baffle thickness	0.002 m
Diameter of supporting rod	0.006 m
Number of baffles	8



A. variable speed motor,
B. orifice baffle plate,
C. jacket,
D. hot water from heater tank,
E. hot water to heater tank,
F. flow meter,
G. pump,
H. heater tank.

Figure 1. Schematic diagram of experimental apparatus.

Table 2. Details of experimental conditions.

Details	Range
Oscillation frequency, Hz	0.5-2.5
Oscillation amplitude, cm	3.75, 0.50
Pulp consistency, % on o.d. pulp	3.0-10.0
Hydrogen peroxide, % on o.d. pulp	3
Sodium hydroxide, % on o.d. pulp	3
Magnesium sulfate, % on o.d. pulp	0.1
EDTA, % on o.d. pulp	0.2
Bleaching time, minute	60, 120
Temperature, °C	60

amplitude. The experiments were conducted for a range of pulp consistencies at constant temperature and initial chemical concentrations. The effect of pulp consistency on kappa number is shown in Figure 2. This figure shows that the kappa number distribution widen with pulp consistency. The basic mechanism of mixing is to induce physical motion of the ingredients. In this work, the movement of pulp suspension is produced by the action of oscillation. At low pulp consistency (3%), pulp suspensions exhibit a range of fluid-like behavior, spreading from the motion of flocks (fiber networks) relative to one another through the motion of individual fibers to one another. Vortex formations due to the interaction of pulp suspension and baffles are more pronounced under this condition. Suspension with higher consistencies (5-7%) changes the mixing mechanism and reduces the intensity of vortex formed in the column. The vortex formation is disrupted by fiber networks. Pulp suspensions are actually continuous fiber networks that possess structure and strength resulting from interaction between neighboring fibers. Network strength varies depending on the number of fiber contacts. At high pulp consistency (10%), the strength and non-uniformity of fiber networks are further increased. As the consistency of the suspension increases, the number of fiber/fiber interaction increases, and this, in turn increases network strength. Under this condition, the task of mixing becomes more difficult, which leads to a wider distribution of kappa number observed, resulting in higher mixing indices as shown in Table 3.

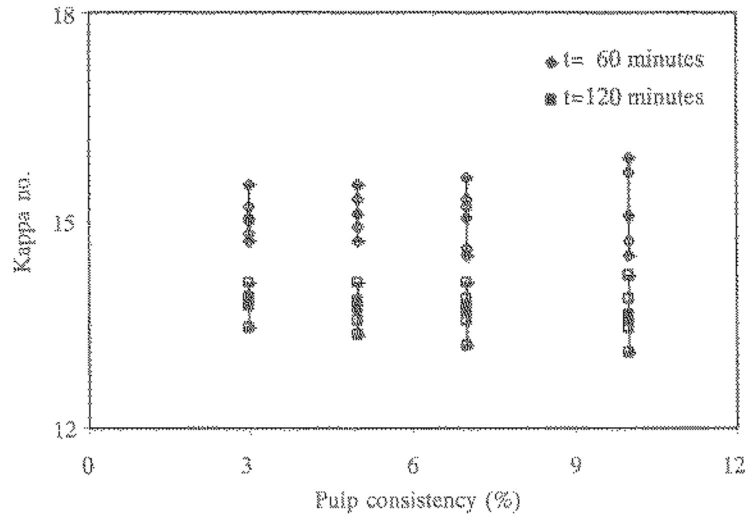


Figure 2. The effect of pulp consistency on kappa number at 60°C, 3% H_2O_2, 3% NaOH, 3.75 cm oscillation amplitude, and 2 Hz oscillation frequency. Filled symbols show the average kappa numbers

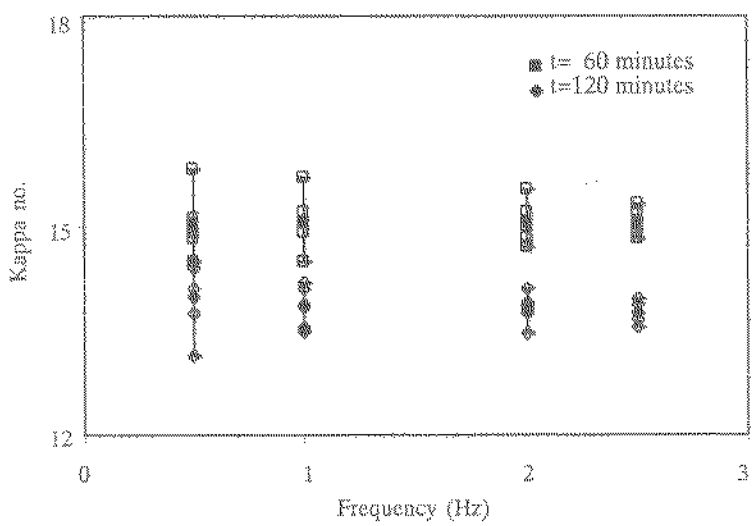


Figure 3. The effect of oscillation frequency on kappa number at 60°C, 3% H_2O_2, 3% NaOH, 3.75 cm oscillation amplitude, and 3% pulp consistency. Filled symbols show the average kappa numbers

Effect of Oscillation Frequency on Mixing Quality

The second set of experiments was conducted to investigate the effect of oscillation frequency on mixing index at a fixed oscillation amplitude, constant temperature and initial chemical concentrations. At a lower range of oscillation frequency being applied to pulp suspension, mixing occurs at the zone between flocks. As the intensity of oscillation is increased, the relative motion between flocks increases and flocks themselves are destroyed. This phenomenon is substantially accelerated by the increase in interaction between flocks and fibers, inducing a uniform mixing. Figure 3 shows kappa number against oscillation frequency. It can be seen that the mixing quality improves with oscillation frequency. More intense motions between flocks are formed at higher frequencies, giving better mixing and consequently a narrow distribution of kappa number is obtained. This is also shown in Table 3; the mixing indices decrease with increasing oscillation frequency. In addition, lower mixing indices reflect better mixing. For example at pulp consistency of 3% and 60 minutes, the mixing index at 2.5 Hz is half of that at 2.0 Hz. Table 3 also shows the mixing efficiency as judged by the mixing index decreases with pulp consistency. The mixing index which at 10% pulp consistency is 5 times of that at 3% and 3.5 times of that at 5%. In bleaching operations, good mixing is normally achieved at M ≤ 0.1 (Bennington, 1996; Backlund et al., 1989).

Effect of Oscillation Amplitude on Mixing Quality

Further experiments were performed by selecting different oscillation amplitudes at a fixed

Table 3. Mixing quality of oscillatory flow mixer.

Time (min.)	Pulp consistency (%)	Frequency (Hz)	Amplitude (cm)	$\bar{x}$	S	Mixing index (M)
60	3	0.5	3.75	15.02	0.4868	0.0234
60	3	1.0	3.75	15.04	0.4442	0.0295
60	3	2.0	3.75	15.04	0.3209	0.0213
60	3	2.5	3.75	15.02	0.2168	0.0172
60	3	2.0	5.00	15.02	0.1301	0.0087
60	5	2.0	3.75	15.08	0.3162	0.0119
60	7	2.0	3.75	15.10	0.4712	0.0314
60	10	2.0	3.75	15.06	0.6841	0.0454
120	3	0.5	3.75	13.98	0.5474	0.0391
120	3	1.0	3.75	13.90	0.3152	0.0228
120	3	2.0	3.75	13.81	0.2381	0.0172
120	3	2.5	3.75	13.76	0.1581	0.0115
120	3	2.0	5.00	13.72	0.1170	0.0086
120	5	2.0	3.75	13.73	0.2870	0.0209
120	7	2.0	3.75	13.70	0.3386	0.0247
120	10	2.0	3.75	13.63	0.4171	0.0306

oscillation frequency. These runs were also carried out at constant temperature and initial chemical concentrations. Figure 4 plots kappa number versus oscillation amplitude obtained for two different amplitudes. This figure shows the distribution of kappa number decreases with oscillation amplitude. At higher oscillation amplitude, the flock motions are displaced further at each stroke, inducing rupture in the flocks. The interaction of pulp suspensions and baffles also becomes more significant, thus enhancement in mixing. As a result, narrower distribution of kappa number was achieved. Hence, lower mixing indices are obtained at higher oscillation amplitude.

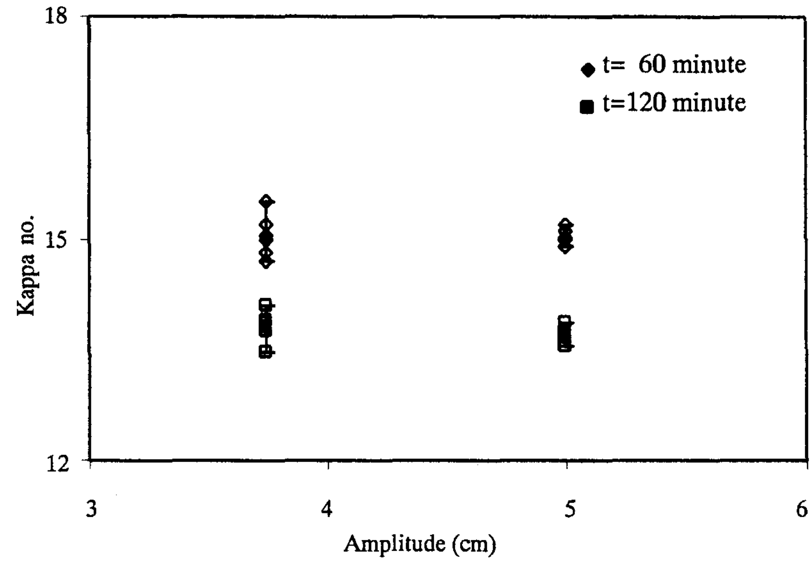


Figure 4. The effect of oscillation amplitude on kappa number at 60°C, 3% H_2O_2, 3% NaOH, 2 Hz oscillation frequency, and 3% pulp consistency. Filled symbols show the average kappa numbers

Results obtained in this work indicate that oscillation frequency and amplitude are the main variables which control mixing efficiency. A combination of these two variables must be selected carefully to achieve optimal mixing. The pulp consistency appears to be the limiting variable in this device. Higher pulp consistency produces a network of fiber with greater strength. Mixing in oscillatory flow in a baffled column is achieved from the vortex formation due to the interaction between oscillating pulp suspension and the baffles. The fiber networks may disrupt vortex formation and dampen its intensity, this reduces mixing efficiency in the column. The results of this study also indicate that oscillatory baffled column has excellent potential for application in the pulp and paper industry. Further research however is required to determine the optimal conditions for application of this device in the pulp and paper industry.

CONCLUSION

The findings of this study indicate that an oscillatory baffled column is very promising as a mixer for pulp bleaching to improve mixing quality. The oscillation amplitude and frequency appear to be the controlling parameters which dictate the mixing efficiency in the oscillatory flow pulp bleaching column. The mixing quality increases with oscillation frequency and amplitude. However, the pulp consistency limits the mixing efficiency. Mixing quality decreases with pulp consistency at constant oscillation frequency and amplitude.

NOTATIONS

M	Mixing index
n	Number of sample
S	Standard deviation
x_i	Kappa number of i^{th} sample
$\bar{x}$	*Arithmetic mean of all measured kappa number*

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Taslim received his BEng (Chem. Eng.) from Universitas Sumatera Utara, Indonesia in 1989, and his MSc (Chem. Eng.) from Institut Teknologi Bandung in 1996. He joined Universitas Sumatera Utara as a tutor in 1990 and was later appointed as a lecturer in 1996. Currently, he is a research assistant and PhD student at Universiti Kebangsaan Malaysia (UKM). His research focuses on the transport phenomena in oscillatory flow in a baffled column and on the development of a novel oscillatory flow reactor for pulp bleaching.

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