

On-line measurement of ozone consumption rate during high-consistency bleaching

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OZONE BLEACHING OF CHEMICAL pulps has been the subject of intensive investigation. The process has been satisfactorily applied in the production of elemental chlorine free (ECF) and totally chlorine free (TCF) bleached pulps, although there is opportunity for improvement (1). Most research on this topic has centered on the effect of the treatment under fixed conditions on brightness and strength properties of a variety of pulps (2–6). Recent research has focused on the kinetic aspects of the process, targeting process design, operation, and optimization (7–9).

Nguyen *et al.* (7) investigated the ozonation kinetics of a kraft eucalypt pulp using a modified rotary evaporator. During the experiments, a mixture of ozone and oxygen was passed through a fluffed pulp of about 40% consistency for a chosen period of time, in the order of 0.5–5 min. The residual ozone leaving the reactor was absorbed in a potassium iodide solution (KI), which was then titrated with a starch solution to determine the amount of ozone not consumed by the pulp. The ozone charge was determined by the same technique. The data were used to characterize the process kinetics. Griffin *et al.* (8) used a similar apparatus to investigate the ozonation of a hemlock kraft pulp at high consistency.

Recently, Carlsmith *et al.* (9) described a laboratory-scale bleaching apparatus capable of measuring ozone consumption at contact times as short as 2 s. The system uses an “evacuate and inrush” technique to-

gether with a batch reactor to achieve the desired ozone pulp contact. The residual ozone is measured using the KI absorption method.

Although KI absorption is a satisfactory technique for measuring the concentrations of ozone in the inlet and outlet streams of the reactor during ozone bleaching, the measurement is slow. With this technique, each reactor run yields only one result corresponding to one contact time. Consequently, numerous test results are required for kinetic studies. For this reason, previous kinetic models of ozone bleaching were established with small sets of test results. If the ozone concentrations and flow rates could be measured continuously, each reactor run would yield one set of kinetic data. This approach would also improve the accuracy of the data by eliminating the variation in the properties of the pulp used in the test runs.

This paper presents the details of a newly installed laboratory apparatus capable of continuously measuring the rate of ozone consumption during high-consistency ozone bleaching. Included are a description of the equipment used, details of instruments, measurement techniques, and the procedure for data analysis. This work is an extension of that commenced by Nguyen *et al.* (7) in early 1992. This apparatus arrangement for kinetic studies has been recently recommended by Carlsmith *et al.* (9).

EQUIPMENT CONFIGURATION

Ozone is produced from high-purity-grade oxygen using an ozone genera-

ABSTRACT

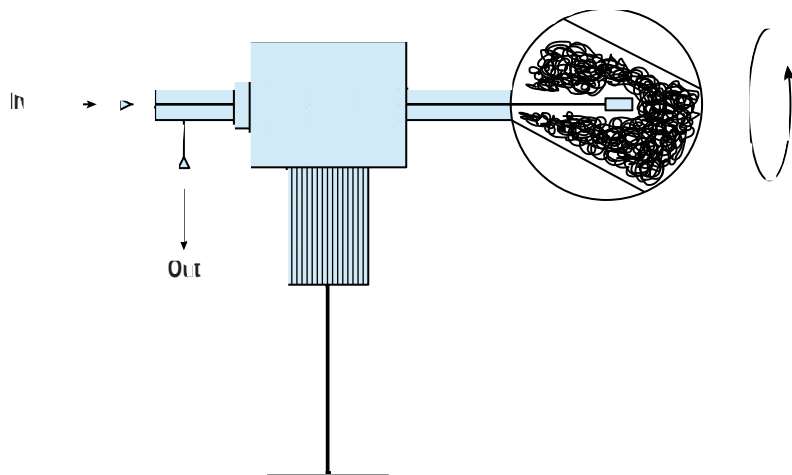
A laboratory-scale flow-through reactor was constructed to enable kinetic studies of ozone bleaching at high consistency. Reaction temperature, pressure, and ozone charge are controlled during test runs. On-line ultraviolet sensors measure ozone concentrations in the inlet and outlet streams. Flow rates for both streams are measured with electronic flow monitors. Each measurement is repeated every 10 s and is integrated with other measurements via a data logger and a computing system. The laboratory apparatus provides accurate, reliable, and rapid on-line measurements of the ozone consumption rate.

Application:

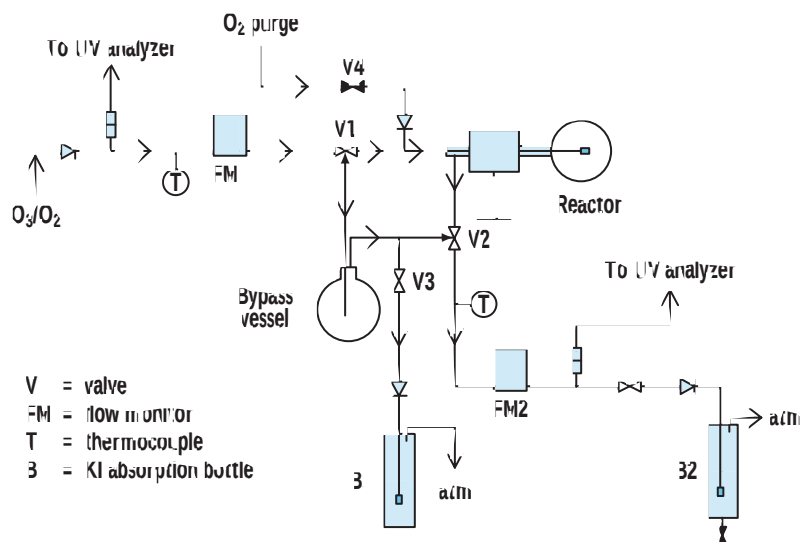
Describes a laboratory apparatus for use in studying the kinetics of ozone bleaching at high consistency.

tor (Ozonias LN 103) that is capable of producing ozone at concentrations of up to 4 wt.% O₃ in O₂ and at flow rates of up to 0.15 g O₃/min. The volumetric gas flow rates are in the range of 3–4 L/min under these conditions. The concentration of ozone produced is dependent upon operating pressure, feed gas composition, total gas flow rate, and the applied electrode voltage. The highest ozone concentrations are produced by utilizing pure oxygen, minimum flow rate, and maximum applied voltage.

The reactor is a modified 2-L rotary evaporator (IKA Labor Technik type RV-05), shown in Fig. 1. The reactor has two baffles pressed into the sides to provide good mixing conditions. Up to 30 g of oven-dry pulp can be charged in each reactor run. Ozone is distributed throughout the pulp via a sparger located near the center of the flask.



1. Reactor for high-consistency ozone bleaching



2. Ozone bleaching apparatus

The mixing characteristics of the pulp can be altered by varying the rotational speed of the reactor. From observing the movement of the pulp in the vessel at different speeds, it was noted that at speeds higher than 50 rpm the centrifugal force held the pulp against the wall of the flask and away from the gas inlet sparger, while at speeds less than 10 rpm there was insufficient movement of pulp in the reactor. The best mixing is achieved at about 30 rpm.

To control the reaction temperature, the reactor is partially im-

mersed in a constant-temperature water bath. The bath temperature is set at a few degrees above the desired reaction temperature to compensate for the heat loss. This method of temperature control is very effective.

Two ozone concentration analyzers (Dasibi 1003-HC) are used to provide a continuous measurement of ozone concentration in the gas streams entering and leaving the reactor. The analyzers are self-contained instruments that measure the absorption of ultraviolet (UV) light in

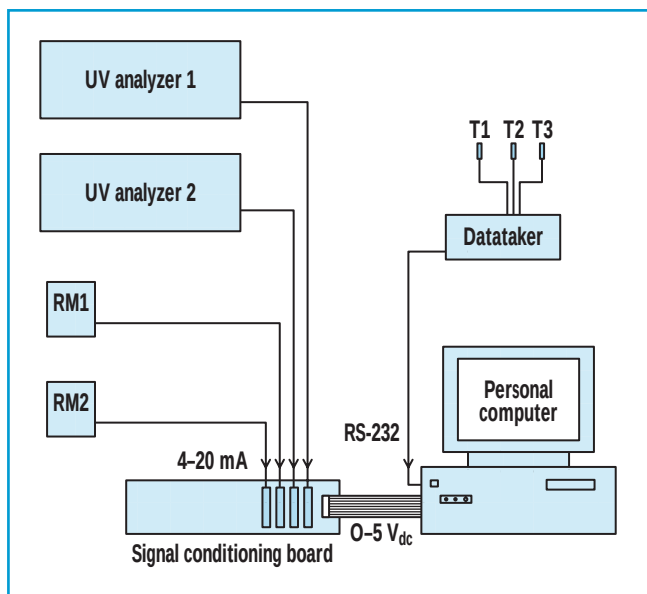
samples of gas flowing through them. Oxygen gas is also supplied to the detectors for calibration. They are capable of measuring ozone concentration in the range of 0–60,000 ppm of ozone in the carrier gas. Factory settings enable each measurement to be initiated every 24 s. However, this time interval can be reduced to 10 s without loss of performance by adjusting the sampling time within the instrument.

On-line corrections to the displayed ozone concentration are performed to account for deviations from Beer's law. The flow to the analyzers relies solely on the supply pressure from the ozone generator. Catalytic scrubbers are used to remove ozone in the exhaust stream from the analyzers prior to venting to the atmosphere.

Two electronic flow monitors (Sierra Top-Track® Series 820) provide continuous measurement of the total volumetric gas flow rates entering and leaving the reactor. The monitors are capable of measuring total flow rates over the range of 0–5 L/min. On-line corrections are made when measuring at conditions other than those for which the instruments are calibrated. The corrected ozone concentration is used in conjunction with the measurement of total gas flow rate to determine the actual mass flow rates of ozone and oxygen to and from the reactor.

For safety reasons, the entire ozone-bleaching apparatus and measuring instruments, excluding the ozone generator, are housed in a fume cupboard. An ozone detector (Ozone Hunter Plus model AET-030P) is employed to detect leaks. The output of this detector is interlocked to the power supply of the ozone generator. In the event of a leak, the detector triggers the power cutout switch to stop the ozone generation.

Potassium iodide absorption bottles are used for scrubbing the resid-



3. Data acquisition hardware

ual ozone in the exhaust gas. They are also used to calibrate the UV ozone analyzers using the standard KI absorption and titration technique (10).

A simplified flow schematic of the ozone-bleaching apparatus is shown in Fig. 2.

The majority of the pipework consists of 0.25 in. o.d. (outside diameter) Teflon® tubing, with small sections of glass tubing used to connect glassware. PFA Teflon and stainless steel (SS316) tube fittings (Swagelok®) are used to connect relevant sections of tubing. Flexible PVC tubing is used to carry the oxygen gas supplies to the ozone generator and analyzers, as well as the generator cooling water supply and return.

All of the major valves, both plug and stopcock valves, are hand operated and can be accessed from outside the fume cupboard. All of the check and relief valves are constructed from SS316 with Swagelok fittings.

INSTRUMENTATION

Data acquisition and logging

A set of data-acquisition hardware/software is employed to continuously record data from the ozone analyzers, flow monitors, and thermocouples.

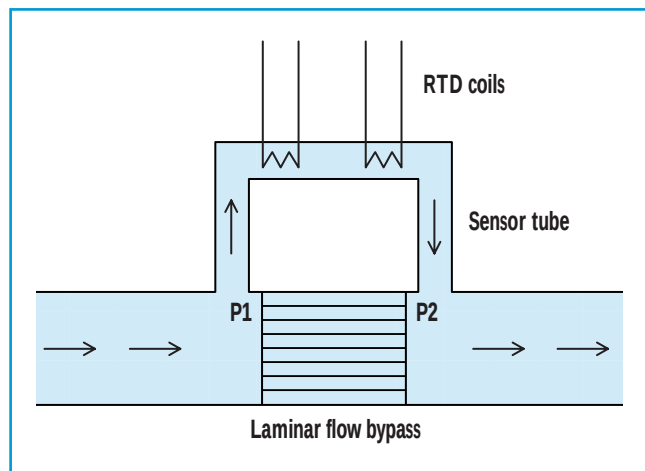
The 4-20-mA output signals from the ozone analyzers and electronic flow monitors are converted to 0-5 V_{dc} signals via a signal-conditioning board. It consists of a series of isolated analog-to-digital converters. The digital signal is then processed by a signal-carrier board that is mounted in one of the PC expansion slots. The output signals from the three type-J thermocouples are transmitted, via a Datataker™, using RS-232 protocol, to one of the serial ports of the PC.

The signals are logged at a frequency of 1 Hz. The data are further processed using the acquisition software to display the values of ozone concentrations and flow rates. The acquisition software, Labtech Notebook, has been selected as the user interface. It has the capability of on-line manipulation of raw data, allowing continuous corrections and calculations to be performed. This facility is used to calculate the instantaneous amount of ozone applied and consumed during reactor runs. The data are logged and stored in a Microsoft Excel® file.

Figure 3 is a diagram outlining the configuration of the data-acquisition system.

Ozone concentration

UV light at a wavelength of 254 nm is



4. Flow path and RTD configuration (12)

used in the measurement of ozone concentration. The amount of UV light absorbed by a gas sample is dependent upon the concentration of ozone in the sample. The ozone analyzer measures ozone concentration from the attenuation of UV radiation by ozone molecules. The amount of attenuation depends on the optical path length, the absorptivity of the ozone, and the concentration. The relationship between all these factors is shown by Beer's law.

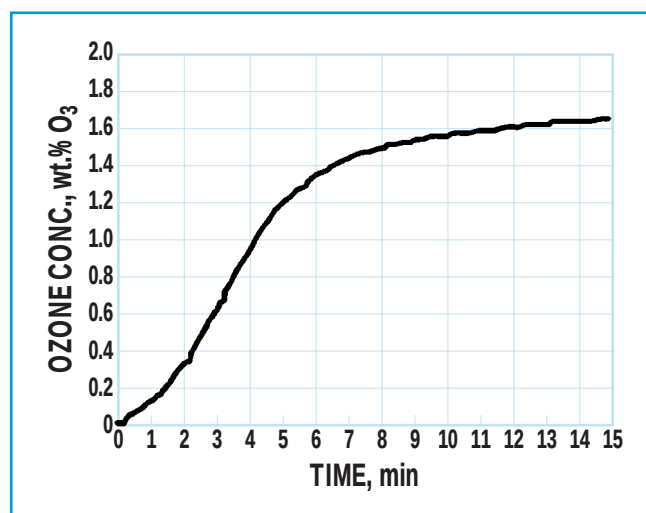
$$\frac{I}{I_0} = e^{-(ALC)} \quad (1)$$

[Note: Definitions for the variables in Eq. 1 (and all other equations) appear in the Nomenclature section at the end of this work.]

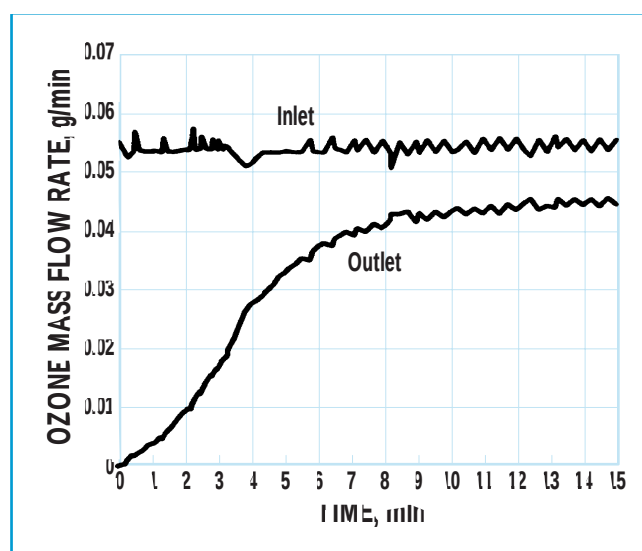
The analyzers use a linearized approximation of Beer's law for displaying the ozone concentration (11). The displayed reading *R* is corrected and converted to the desired units. The calculation procedures, performed on-line, for converting the corrected ozone concentration reading (parts per million) to weight percent are detailed later, in the data analysis section.

Total gas volumetric flow rate

The flow monitors are plumbed directly into the flow path of the gas to be measured. The gas enters the main flow body and separates into two flow paths. The majority of the flow goes through the laminar-flow bypass. This creates a pressure drop



5. Outlet ozone concentration during a reactor run



6. Inlet and outlet flow rate of ozone streams during a reactor run

Instrument reading (R), ppm	Temperature (T), °C	Pressure (P), psig	Calculated ozone conc. ([O ₃]), wt. %
25,000 ± 1%	25 ± 0.5	4 ± 0.5	6.33 ± 4.3%
5,000 ± 1%	25 ± 0.5	4 ± 0.5	0.81 ± 1.2%

7. Error in the calculation of ozone concentration

that forces a small fraction of the flow through a sensor tube. The ratio of these two flows remains constant. Two resistance temperature detector (RTD) coils around the sensor tube direct a constant amount of heat into the gas stream. The amount of heat carried from the upstream to the downstream coil results in a temperature difference that is detected by the RTD coils and gives rise to the output signal. A flow schematic is shown in Fig. 4.

The flow monitors were factory calibrated, using nitrogen as the calibration gas, at 1 atm and 21°C. During a reactor run, they measure the gas flow rate at the reaction temperature and pressure. This reading must therefore be corrected accordingly.

DATA ANALYSIS

Measurement of ozone concentration and mass flow rate

In kinetic studies, it is convenient to have the units of ozone concentra-

tion and flow rate expressed on a mass basis. The Appendix at the end of this article outlines the procedure used to convert the reading from the ozone analyzers from ppm to weight percent (11). The Appendix also presents a general outline of the algorithm used to calculate the actual ozone mass flow rate from the measurement of total gas flow rate obtained from the flow monitor (12).

Although raw data are collected from the instruments every second, the ozone analyzers are only capable of updating the measurement of ozone concentration every 10 s. For this reason, outlet ozone concentration readings were taken either when the new reading differed significantly (±1%) from the previously selected reading or a period of 10 s had elapsed. All subsequent calculations were based on the resulting time periods and selected readings.

Figure 5 shows the outlet ozone concentration profile, based on selected readings, for an oxygen-delig-

nified kraft pulp (initial kappa number = 11.3) when ozonated at an inlet ozone concentration of 2.0 wt.% O₃. The results shown in Figs. 5, 6, and 7 show the format of the results obtainable using the experimental apparatus.

Because of fluctuations in the gas flow rates (≈10% of total flow), both into and out of the reactor, the values of ozone mass flow rate recorded over the time periods between each of the selected outlet ozone concentration readings were averaged over that period. Figure 6 shows the resultant average inlet and outlet ozone mass flow rates.

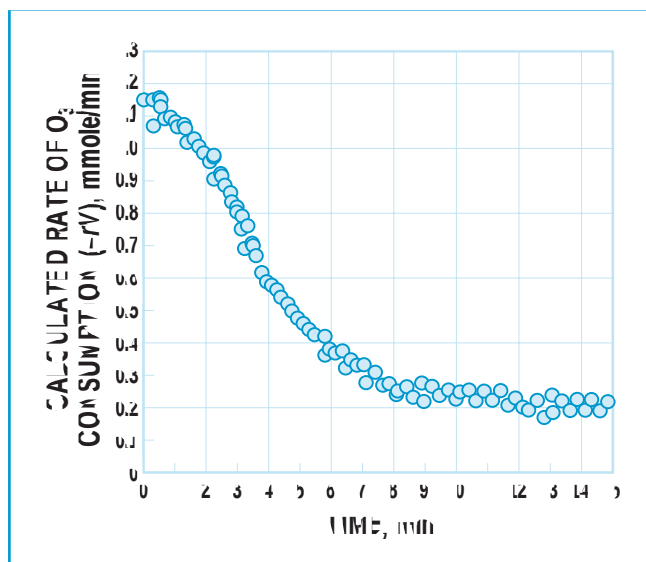
Determination of the ozone consumption rate

The rate of ozone consumption was calculated based on the selected outlet ozone concentration readings and the corresponding averaged mass flow rates. It was determined by applying the following mass balance equation to the reactor for each successive time period:

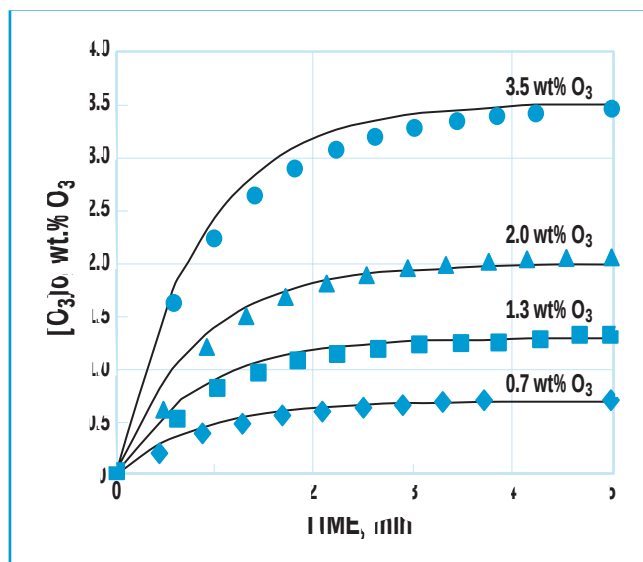
$$\text{In} = \text{Out} + (-rV) + V \frac{d[\text{O}_3]}{dt} \quad (2)$$

The rate of ozone consumption, $-rV$, for any selected time period can be calculated by rearranging Eq. 2:

$$-rV = \text{In} - \text{Out} - V \frac{d[\text{O}_3]}{dt} \quad (3)$$



7. Calculated rate of ozone consumption during a reactor run



8. Comparison of observed outlet ozone concentration profiles with those predicted by Eq. 5

Total volumetric gas flow (F_T), std. L/min	Instrument reading (R), ppm	Calculated O_3 flow, g/min
3.0 ± 0.1	$25,000 \pm 1\%$	$0.22 \pm 1.1\%$
1.0 ± 0.1	$5,000 \pm 1\%$	$0.01 \pm 0.1\%$

II. Error in the calculation of ozone flow rate

Figure 7 shows the calculated rate of ozone consumption as a function of time.

Error analysis

The error associated with the determination of ozone concentration from the reading obtained using the UV ozone analyzers depends on errors in readings of pressure, temperature, and ozone concentration. Typical errors of the readings and the resultant error in the calculation of the ozone concentration are shown in Table I.

The error associated with the calculation of ozone flow rate is estimated using the same approach. Typical errors of the readings and the resultant error in the calculation of the ozone flow rate are shown in Table II.

Table III shows the values and the differences (expressed as a percent) between measurements of ozone concentration and flow rate using UV and KI techniques. The comparison shows that the discrepancies be-

Measure	UV	KI	Difference, %
$[O_3]_i$, wt.% O_3	4.99	5.20	4
O_3 flow, g/min	0.18	0.20	10

III. Differences in measurements of ozone concentration and flow rate using UV and KI techniques

tween the two techniques are within acceptable experimental limits.

Reactor character

Equation 2 suggests that it is essential to characterize the reactor used in test runs before the kinetics of the process can be determined. If a well-mixed condition is achieved, the concentration of ozone in the outlet stream is the same as the concentration in the reactor. Hence (without pulp):

$$\frac{d[O_3]_o}{dt} = v_i[O_3]_i - v_o[O_3]_o \quad (4)$$

The following conditions are assumed:

- Constant gas density
- Constant reactor volume
- $v_i = v_o$
- $[O_3]_i = \text{constant}$

and the following initial condition is applied:

$$t = 0 \text{ and } [O_3]_o = 0$$

Ozonation time, min	ZE kappa number
0	11.3
2	3.0
4	1.1
6	1.1
8	1.0
10	1.0

IV. Variation of kappa number during a test run

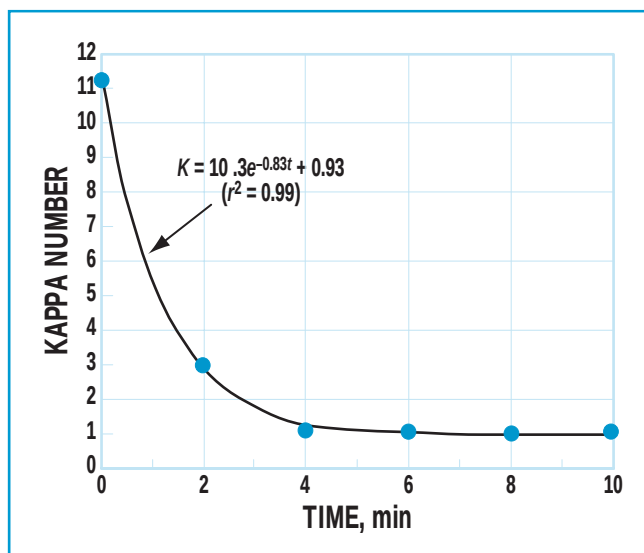
The relationship between the inlet and outlet concentrations is

$$[O_3]_o = [O_3]_i \left(1 - \exp \frac{-vt}{V} \right) \quad (5)$$

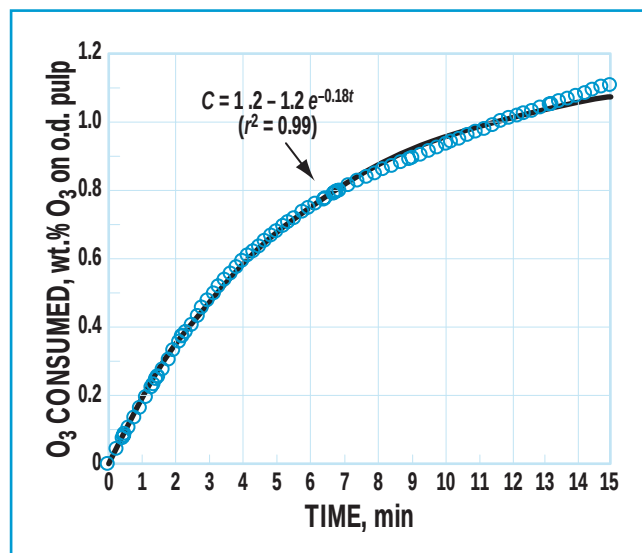
The experimental results obtained from runs with different initial ozone concentrations (0.7, 1.3, 2.0, 3.5 wt.% O_3) are shown in Fig. 8. These results fit well with those predicted by Eq. 5. It is anticipated that the presence of fluffed pulp improves the degree of mixing in the reactor. For this reason, it is quite reasonable to assume that the reactor behaves like a continuously stirred tank reactor during the test runs.

ANALYSIS OF RESULTS

Table IV shows the variation of kappa number over time during a test run. The dependence of kappa



9. Variation of kappa number during a test run



10. Variation of ozone consumption during a test run

number on the ozonation time can be empirically represented by Eq. 6.

$$K(t) = j_1 e^{-j_2 t} + j_3, \quad r^2 = 0.99 \quad (6)$$

where

$K(t)$ = kappa number at time t
 j_1, j_2, j_3 = constants for a given set of conditions

The comparison between the measured kappa number and Eq. 6 is shown in Fig. 9.

The kinetics of the delignification process can be expressed with the following empirical equation:

$$\frac{dK}{dt} = -j_1 j_2 e^{-j_2 t} \quad (7)$$

The total amount of ozone consumed during the course of the ozonations was determined by integrating the rate of ozone consumption, $-rV$, over each of the successive selected time periods. The variation of ozone consumption is shown in Fig. 10. The total ozone consumption $\int (-rV) dt$ can be empirically represented by Eq. 8.

$$C(t) = j_4 - j_5 e^{-j_6 t}, \quad r^2 = 0.99 \quad (8)$$

where

$C(t)$ = total ozone consumption at time, t

j_4, j_5, j_6 = constants for a given set of conditions

A kinetic model describing the ozone bleaching process is yet to be determined at this stage. However, it is anticipated that with the results obtained using the laboratory reactor, previous models (7–9) can be further refined.

FINAL REMARKS

A laboratory reactor has been designed and installed to study the kinetics of high-consistency ozone bleaching. On-line sensors and data-logging facilities are provided for measurements and data processing. The accuracy of these measurements is extremely high.

Ozone consumption has been found to be an exponential function of time. Measurements of kappa number during the tests suggest that the delignification rate is also an exponential function of time.

APPENDIX

Calculation of ozone concentration

Step 1. Calculate the units conversion factor.

$$k = \frac{k_1}{k_2} \quad (9)$$

Step 2. Calculate the analyzer span number, a setting used so that

the concentration data are displayed at ambient conditions.

$$S = \frac{k_1 CF_{TP}}{AL} \quad (10)$$

where

$$CF_{TP} = \frac{T}{273.15P} \quad (11)$$

Step 3. Correct the reading R from the analyzer for the nonlinearity in Beer's Law.

$$\frac{C}{R} = \frac{S}{R} \ln \left(\frac{1}{1 - \frac{R}{S}} \right) \quad (12)$$

Step 4. Convert the corrected reading from ppm to weight percent ozone.

$$c = \frac{C}{k} \quad (13)$$

Example 1:

Assume that a reading of 5000 ppm is obtained during the course of measurement. The sample temperature and pressure are 25°C and 1.27 atm, respectively. It is desired to correct this reading and convert it to weight percent ozone.

$R = 5000$ ppm

$T = 298.15^\circ\text{K}$

$P = 1.27$ atm

$k_1 = 10^6$ ppm/atm

$$k_2 = 150 \text{ wt.\% O}_3/\text{atm}$$

$$A = 308.3 \text{ cm}^{-1} \cdot \text{atm}^{-1}$$

$$L = 0.0762 \text{ cm}$$

Step 1. Calculate conversion factor k .

$$k = 6666.67 \text{ ppm/wt.\% O}_3 \text{ (from Eq. 9)}$$

Step 2. Calculate the analyzer span number S .

$$S = 36,527 \quad \text{(from Eq. 10)}$$

Step 3. Calculate the corrected reading C .

$$C = 5377.05 \text{ ppm} \quad \text{(from Eq. 12)}$$

Step 4. Convert the corrected reading from ppm to weight percent ozone.

$$c = 0.81 \text{ wt.\% O}_3 \quad \text{(from Eq. 13)}$$

The ozone analyzers require a period of 10 s to measure and display consecutive readings. Thus the concentration of ozone in the gas sample, as indicated by each new reading, is assumed to be the average concentration during this 10 s.

Calculation of ozone mass flow rate

Step 1. Calculate the density of the gas mixture at the actual temperature and pressure.

$$\rho = (m_1/m_T)\rho_1 + (m_2/m_T)\rho_2 \quad (14)$$

Step 2. Calculate the specific heat of the gas mixture at the actual temperature and pressure.

$$C_p = F_1 C_{p1} + F_2 C_{p2} \quad (15)$$

where

$$F_1 = (m_1 \rho_1)/(m_T \rho) \quad (16)$$

$$F_2 = (m_2 \rho_2)/(m_T \rho) \quad (17)$$

Step 3. Calculate the correction factor for the number of atoms in the gas molecules.

$$N = (m_1/m_T)N_1 + (m_2/m_T)N_2 \quad (18)$$

Step 4. Calculate the “ k -factor” for the gas mixture.

$$k_m = \frac{N}{\rho C_p} \quad (19)$$

Step 5. Calculate the volumetric flow rate of the actual gas mixture at the instrument calibration conditions (STP).

$$Q_c = \frac{Q_{i,m}}{k_c} \quad (20)$$

where

$$k_c = 3.1955$$

Step 6. Calculate the volumetric flow rate of the actual gas mixture at the actual temperature and pressure.

$$Q_a = \frac{P_c T_a}{P_a T_c} Q_c \quad (21)$$

Step 7. Calculate the density of ozone in the gas mixture using the information from the ozone analyzer along with the relevant concentration conversion factors.

$$\rho_{2,m} = [\text{O}_3] \frac{k_3}{k_4} \quad (22)$$

Step 8. Calculate the mass flow rate of ozone in the gas mixture.

$$m_{2,m} = \rho_{2,m} Q_a \quad (23)$$

Example 2:

Following on from Example 1, assume that at the same time the associated flow monitor is giving a reading of 3.00 L/min. What is the actual ozone mass flow rate in the particular gas stream?

Step 1. The density of the mixture is

$$\rho = 1.433 \text{ g/L} \quad \text{(from Eq. 14)}$$

Step 2. The specific heat of the mixture is

$$C_p = 0.220 \text{ cal/g} \cdot \text{K} \quad \text{(from Eq. 15)}$$

where

$$F_1 = 0.988 \quad \text{(from Eq. 16)}$$

$$F_2 = 0.012 \quad \text{(from Eq. 17)}$$

Step 3. The correction factor N is

$$N = 0.999 \quad \text{(from Eq. 18)}$$

Step 4. The k -factor for the gas mixture is

$$k_m = 3.169 \quad \text{(from Eq. 19)}$$

Step 5. The volumetric flow rate of the gas mixture at STP is

$$Q_c = 2.98 \text{ L/min} \quad \text{(from Eq. 20)}$$

Step 6. The volumetric flow rate of the gas mixture at the actual temperature and pressure is

$$Q_a = 2.55 \text{ L/min} \quad \text{(from Eq. 21)}$$

Step 7. The density of ozone in the gas mixture is

$$\rho_{2,m} = 11.56 \times 10^{-3} \text{ g/L} \quad \text{(from Eq. 22)}$$

Step 8. The mass flow rate of ozone in the gas mixture is

$$m_{2,m} = 29.49 \times 10^{-3} \text{ g/min} \quad \text{(from Eq. 23)}$$

TJ

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NOMENCLATURE

A = absorption coefficient of ozone, $\text{cm}^{-1} \cdot \text{atm}^{-1}$
 C = ozone concentration as partial pressure, atm
 c = ozone concentration in desired units
 C_p = specific heat of the gas mixture, cal/g·K
 C_{p1} = specific heat of oxygen, cal/g·K
 C_{p2} = specific heat of ozone, cal/g·K
 CF_{TP} = temperature and pressure correction factor
 F_T = total volumetric gas flow, std. L/min
 I = transmitted UV intensity for sample gas cycle
 I_0 = transmitted UV intensity for calibration gas cycle
 j_n = constants for a given set of conditions
 K = kappa number
 k = concentration conversion factor, ppm/wt.% O_3
 k_1 = concentration conversion factor, ppm/atm
 k_2 = concentration conversion factor, wt.% O_3 /atm
 k_3 = concentration conversion factor, $\text{g/m}^3 \cdot \text{atm}$
 k_4 = concentration conversion factor, wt.% O_3 /atm

k_c = conversion factor for calibration gas at calibration conditions
 k_m = factor used to correct for difference between calibration gas and actual gas mixture
 L = optics bench path length, cm
 m_1 = mass flow rate of oxygen, g/min
 m_2 = mass flow rate of ozone, g/min
 $m_{2,m}$ = mass flow rate of ozone in the gas mixture, g/min
 m_T = total mass flow rate of gas mixture, g/min
 N = correction factor for the molecular structure of the gas mixture
 N_1 = correction factor for the molecular structure of oxygen
 N_2 = correction factor for the molecular structure of ozone
 $[O_3]$ = ozone concentration, wt.% O_3
 $[O_3]_i$ = inlet ozone concentration, wt.% O_3
 $[O_3]_o$ = outlet ozone concentration, wt.% O_3
 P = pressure, atm
 P_a = actual gas mixture pressure, atm
 P_c = calibration pressure, atm
 Q_a = flow rate of gas mixture at actual temperature and pressure, L/min

Q_c = flow rate of gas mixture at calibration temperature and pressure, L/min
 Q_i = reading obtained from flow monitor, L/min
 R = instrument reading, ppm
 r = rate of ozone consumption during selected time period, mole/min·cm³
 S = instrument span number
 T = temperature, K
 T_a = actual gas mixture temperature, °C
 T_c = calibration temperature, °C
 t = time, min
 V = volume of reactor, cm³
 v = gas flow rate, L/min
 v_i = total gas flow rate into reactor, L/min
 v_o = total gas flow rate out of reactor, L/min
 In = average mass flow rate of ozone into reactor during selected time period, g/min
 Out = average mass flow rate of ozone out of reactor during selected time period, g/min
 ρ = density of the gas mixture, g/L
 ρ_1 = density of oxygen, g/L
 ρ_2 = density of ozone, g/L
 $\rho_{2,m}$ = density of ozone in the gas mixture, g/L

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