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Treatment of Evaporator Condensate Using a High Temperature Membrane Bioreactor: Determination of Maximum Operating Temperature and System Costs

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Treatment of
Evaporator Condensate
Using a High Temperature
Membrane Bioreactor:
Determination of Maximum Operating
Temperature and System Costs

SFM Network Project: **Membrane Bioreactors for Contaminant Control in Closed Pulp and Paper Mills**

by

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ABSTRACT

The feasibility of biologically treating the foul fraction of the evaporator condensates from a kraft pulp mill for reuse as process water, using a high temperature membrane bioreactor (MBR), was investigated. Treatment is required because of the high concentration of odorous compounds contained in the foul fraction of the evaporator condensate. Also, increasingly stringent legislation, such as the Cluster Rule, prohibits the reuse of the foul fraction of the evaporator condensates without treatment because of the high concentration of hazardous air pollutants (HAP) the condensate contains. The HAP can volatilize to the atmosphere causing hazardous working conditions. Methanol is the main contaminant of concern. A high temperature MBR was selected for the treatment of evaporator condensate for reuse since it is potentially more efficient and less expensive than steam stripping and conventional biological treatment.

It was possible to develop a mixed culture of thermotolerant methanol-utilizing bacteria, on synthetic foul condensate containing methanol, dimethyl sulphide and dimethyl disulphide, at temperatures ranging from 55 ^{o}C to 70 ^{o}C and a sludge retention time of 20 days. The maximum feasible operating temperature for the biological removal of methanol from condensate using a membrane bioreactor was approximately 60 ^{o}C. A maximum methanol removal rate of 1.4 mg/L$\cdot$min (specific utilization rate of 0.8/day), was observed at 60 ^{o}C. Over 99 % of the methanol was removed from the condensate at operating temperatures of 55 ^{o}C and 60 ^{o}C. Above 60 ^{o}C, the methanol uptake rate declined sharply, significantly reducing the methanol removal efficiencies. The results suggest that high temperature operation is not only possible, but may be more efficient at treating the evaporator condensate for reuse than conventional, lower temperature, biological treatment.

Based on the kinetic information collected and the characteristics of the evaporator condensate at a local kraft pulp mill, a preliminary design for an MBR system was developed. Capital and operating costs were estimated for two operating scenarios. Scenario 1 involved treatment of the fouler fraction of the evaporator condensate only. Scenario 2 involved treatment of the fouler fraction and approximately 50 % of the cleaner fraction of the evaporator condensates. Capital and operating cost estimates were lower for an MBR system compared to a steam stripping system capable of achieving similar treatment efficiencies.

ACKNOWLEDGEMENTS

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INTRODUCTION

Some of the cleaner fraction of the evaporator condensate in a kraft pulp mill is typically reused as process water in brown stock washing and dregs washing. However, the fouler fraction of the evaporator condensate cannot be reused without treatment because of the high concentration of odorous compounds it contains. Also, increasingly stringent legislation, such as the Cluster Rule, prohibits the reuse of the foul fraction of the evaporator condensates without treatment because of the high concentration of hazardous air pollutants (HAP) the condensate contains (Vice and Carroll 1998). The HAP can volatilize to the atmosphere causing hazardous working conditions Garner (1996). The fouler fraction of the evaporator condensate is typically sewered and treated in a combined mill effluent biological treatment system before being discharged to the environment. Some mills steam strip the fouler fraction of the condensate before final treatment and discharge to the environment. As an alternative to combined mill effluent treatment and discharge to the environment, some mills are considering treating the fouler fraction of the evaporator condensate to reuse it as process water in the mill (Bérubé and Hall 1996). In addition to reducing the contaminant load to the existing combined mill effluent treatment system, reducing the raw water requirements and potentially reducing energy requirements, the Cluster Rule proposes a number of incentives for treating and reusing the fouler fraction of the evaporator condensate (Vice and Carroll 1998). Specifically, mills can take credit for HAP emission reductions resulting from the treatment and reuse of the fouler fraction of the evaporator condensate, and apply the credits against HAP emissions in other areas of the mill. In addition, reusing all of the evaporator condensate can potentially generate greater permitting certainty, could reduce the effluent monitoring and inspection requirements and reduce penalties (Vice and Carroll 1998).

A number of treatment technologies, such as steam stripping and conventional biological treatment, can be used to remove some of the contaminants of concern from the foul fraction of the evaporator condensate. However, the low treatment efficiency and the high costs associated with these systems provide a significant incentive to investigate and develop better treatment technologies (Garner 1996; NCASI 1994; Barton et al. 1996; Hough and Sallee 1977).

A study was initiated to investigate a novel technology to remove the contaminants of concern from evaporator condensates. A high temperature biological treatment system (membrane bioreactor - MBR) was selected. This system may prove to be more efficient than steam stripping and conventional biological treatment for the removal of contaminants of concern. Furthermore, cooling of the condensates before treatment may not be required, as is the case with conventional biological treatment. Consequently, the condensates would remain at an elevated temperature and be reused with minimal heating which would result in energy savings due to the recovery of the heating value of the condensates (Sebbas 1988; Durham 1991).

Contaminants of Concern

A literature survey indicated that evaporator condensates contain hundreds of volatile organic compounds and extremely odorous compounds (Blackwell et al. 1979; Sarkanen et al. 1970; Carter and Tench 1974; Werner 1963; Marvell and Wilman 1963). Of these hundreds of contaminants, methanol has been identified as a primary contaminant of concern. It is the most abundant contaminant contained in evaporator condensates, contributing up to 95 % of the total organic content, and it is classified as a HAP (Vice and Carroll 1998; Blackwell et al. 1979; U.S. E.P.A. 1990). The literature survey also revealed that total reduced sulphur (TRS) compounds were also contaminants of concern. TRS compounds such as hydrogen sulphide, methyl mercaptan, dimethyl sulphide and dimethyl disulphide are also classified as HAP and are extremely odorous.

Based on the literature survey, samples of evaporator condensates were collected from a local kraft pulp mill (Western Pulp Partnership, Squamish, Canada) and analyzed for the contaminants of concern. At the Western Pulp mill, the foul and cleaner fractions of the evaporator condensate are segregated. The foul fraction contributes approximately 10 % of the total evaporator condensate flow which is approximately 6.6 m^3/min (11.6 m^3/admt). Samples of the cleaner fraction were collected from the "Combined Condensate Seal Tank" and consisted of condensates from the 6th effect and from the surface condenser in the evaporation plant. Samples of the fouler fraction were collected from the "Contaminated Condensate Seal Tank" and consisted of condensates produced in the 6th effect after heater and in the second stage of the surface condenser in the evaporation plant. Results from the analysis are summarized in Table 1. Also listed in Table 1 are concentrations of the contaminants of concern typically found in combined evaporator condensates. Methanol and reduced sulphur compounds (RSC) contribute approximately 70 % and 6.5 %, respectively, to the total organic content of the condensate from the Western Pulp mill, based on total organic carbon (TOC) measurements. The remaining organic fraction consists of ketones, terpenes, phenolics and resin acids at trace concentrations. The temperature of the condensates is approximately 70 °C. The mill has a 90th percentile pulp production rate of 816 admt of pulp per day.

Under current operating conditions, approximately 30 % to 50 % of the cleaner fraction of the condensate is used as process feedwater. A conductivity probe ensures that no contaminated condensate is reused. All of the foul fraction of the evaporator condensate and the remaining unused portion of the cleaner fraction of the condensate are sent to the combined mill effluent treatment system and thereafter discharged to the environment. This is typical of many kraft pulp and paper mills (Hough and Sallee 1977).

Table 1 - Characteristics of Condensates from Evaporator Plant

Compound	**Western Pulp Foul Fraction** (mg/L)	**Western Pulp Cleaner Fraction** (mg/L)	**Typical Range Combined Condensate** (mg/L)
Methanol	1014 ± 288	425	263 - 960
Hydrogen Sulphide	77 ± 13	10	143 - 730
Methyl Mercaptan	75 ± 18	0.3	31 - 101
Dimethyl Sulphide	33 ± 8	0.8	1.6 - 2.4
Dimethyl Disulphide	10 ± 4	0.4	16

(± defines 90% confidence interval for measurements; Typical values adapted from literature)

Study Objectives: High Temperature Treatment

The possibility of using high temperature biological treatment to remove contaminants from combined kraft pulp mill effluent has been investigated in a number of laboratory scale studies. Tripathi and Allen (1998), Tai (1998), as well as Flippen and Eckenfelder (1994), all reported that the chemical oxygen demand (COD) removal efficiencies decreased at operating temperatures above 35 ^{o}C, while Graczyk (1984), Barr et al. (1996) and Rintala and Lepisto (1993) reported similar or even better COD removal efficiencies at operating temperatures above 35 ^{o}C. Consequently, there is no clear advantage in treating combined kraft pulp mill effluent at elevated temperatures. However, unlike the removal of general COD from combined kraft pulp mill effluent, the biological removal of COD caused by methanol and TRS compounds, has been documented to be more efficient at temperatures in excess of 35 ^{o}C. Using pure cultures grown on methanol as a sole substrate, Brooke et al. (1989) observed a higher growth yield at temperatures exceeding 45 ^{o}C. Similarly, Snedecore and Cooney (1974), observed a higher growth yield at temperatures above 45 ^{o}C for a mixed culture of bacteria grown on methanol as a sole substrate. Also, bacteria capable of biologically oxidizing RSC have been reported to thrive at temperatures exceeding 50 ^{o}C (Brock 1978). Unfortunately, there is very little information available regarding the removal kinetics of methanol from condensate (Barton et al. 1996).

Since methanol is the main contaminant of concern, the high temperature biological treatment of evaporator condensate for reuse appears promising. The feasibility of biologically removing the methanol from condensates at a high temperature was investigated in the present study. The two main objectives of the study were as follows:

1. To determine the maximum feasible operating temperature for an MBR treating synthetic evaporator condensate. An operating temperature range from 55 ^{o}C to 70 ^{o}C was selected for this study since this approximates the expected temperature range for the evaporator condensate.

2. To determine the economic feasibility of treating the evaporator condensate for reuse using a high temperature MBR.

Experimental Set-up

The MBR used (Figure 1) consisted of a 20 liter stainless steel reactor, with an 8 liter working volume, a ceramic tubular membrane ultrafiltrafiltration system (Membralox 1T1-70 bench scale filtration unit: 7 mm ID, 0.0055 m2 surface area, 500 angstrom pore size) and a progressing cavity pump (Moyno Model SP 33304).

The MBR was fed semi-continuously by adding a mixture of synthetic condensate and nutrients once every 3 hours. A constant volume was maintained in the MBR by recycling some of the treated effluent back to the reactor tank. Semi-continuous feeding was chosen because it can yield more information about removal kinetics than experiments performed under strict continuous flow conditions. Synthetic condensate was used in this study. The synthetic condensate contained methanol, dimethyl sulphide and dimethyl sulphide, in tap water, at concentrations similar to those observed in the foul fraction of the evaporator condensate from the Western Pulp kraft pulp mill at the start of the study (methanol: 500 mg/L; dimethyl sulphide 37 mg/L; dimethyl disulphide 25 mg/L). It should be noted that the methanol concentration in the foul fraction of the condensate increased significantly (doubled) when the furnish to the mill was changed from coastal, to interior wood species, early in 1998. The concentration of TRS compounds remained relatively constant throughout the study. The synthetic condensate did not contain hydrogen sulphide and methyl mercaptan because of the difficulty of solubilizing these gaseous TRS compounds to specific concentrations in liquid. The synthetic condensate was stored at a temperature of 4 ^{o}C. The nutrient solution was selected to provide sufficient nutrients for the biological removal of contaminants form the condensates (Kargi and Roberston 1984; Kargi 1987; Shrives and Brock 1973; Metcalfe and Eddy 1991). The maximum expected concentrations for methanol, RSC and other organic contaminants, contained in real condensates, were used to determine the nutrient requirements. This was done so that a consistent nutrient solution could be used when investigating the contaminant removal kinetics from synthetic and real condensates. The nutrient solution addition produced the following concentrations in the reactor tank at the start of each 3 hour feed cycle: NH_4NO_3 1000 mg/L, KH_2PO_4 165 mg/L, $MgSO_4.7H_2O$ 1280 mg/L, $MgCl_2.6\ H_2O$ 270 mg/L, $CaCl_2.2\ H_2O$ 70 mg/L, $FeCl_3.6\ H_2O$ 20 mg/L, $MnCl_2.4\ H_2O$ 1.8 mg/L, $Na_2B_4O_7.10\ H_2O$ 4.5 mg/L, $ZnSO_4.7\ H_2O$ 0.22 mg/L, $CoCl_2.6\ H_2O$ 0.05 mg/L, $Na_2MoO_4.2\ H_2O$ 0.03 mg/L. The reactor was operated with a 12 hour hydraulic residence time and a 20 day sludge retention time (SRT). The SRT was maintained by wasting 50 ml of mixed liquor from the reactor tank at the start of every batch feed cycle. The ultrafiltration membrane was operated with a cross-flow velocity of approximately 3 m/s and a trans-membrane pressure of approximately 2 atmospheres (207 kPa; 30 psi). The pH of the mixed liquor was maintained above 6, using a pH meter/controller which added sodium hydroxide as required. The aeration rate, through a fine bubble stone diffuser, was 1.58 l/min. This produced non-limiting dissolved oxygen conditions and a minimum dissolved oxygen concentration of approximately 1.1 mg/L. The temperature of the mixed liquor was controlled by a hot plate and temperature sensor/controller.

The MBR was inoculated with material obtained from four different locations. During start-up, the MBR was inoculated with sludge from a lab scale activated sludge system treating kraft mill effluent at 45 ^{o}C Tai (1998), waste sludge from a full scale activated sludge system treating kraft mill effluent (Western Pulp, Squamish, BC, Canada), waste sludge from a pilot scale activated sludge system (UBC-Civil Engineering Pilot Plant, Vancouver, B.C., Canada) and with water and soil samples collected from Harrison Hot Springs (Harrison, B.C., Canada). Approximately 500 ml of inocula from each location were added directly to the MBR. This was repeated twice during the first two weeks of the acclimatization period. In an ongoing study, the MBR was shut down and re-inoculated with waste sludge from the Western Pulp mill only. A similar bacterial population and methanol removal kinetics were observed after inoculation from a single source. The operating temperature and pH of the MBR were set to 55 ± 2 ^{o}C and 6 - 6.5, respectively, during the acclimatization period. The mixed culture was assumed to be acclimatized when the concentration of mixed liquor volatile suspended solids (MLVSS) and the rate of methanol removal in the MBR were constant. Steady state conditions were reached after approximately 6 weeks of acclimatization.

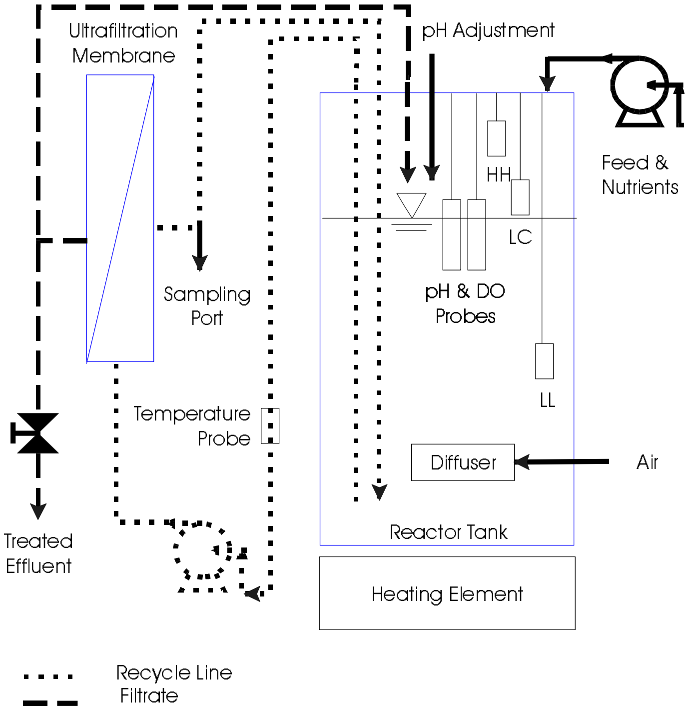


Figure 1: Schematic of bench scale MBR system.

The rate of methanol removal was determined by measuring the change in the concentration of methanol in the MBR with time. Samples were collected and analyzed for methanol at 5, 20, 35, 50 and 65 minutes following selected feedings of the condensate/nutrient mixture. Samples collected for methanol and MLVSS analysis were withdrawn from the return line downstream of the membrane unit. The concentration of methanol was measured by direct injection of filtered (0.45 µm cellulose nitrate syringe membrane filter cartridge) aqueous samples into a gas chromatograph (HP5890, Hewlett Packard Co., Avondale, PA, USA) with a 30 m long wide bore capillary column (DBWAX 0.53 MMID, J & W Scientific, Folsom, CA, USA). The MLVSS concentration was determined according to Standard Methods (APHA et al. 1995). The rate of methanol uptake and the concentration of MLVSS were monitored for a few weeks after reaching steady state operating conditions. The concentrations of TRS compounds in the condensates were measured by direct injection of aqueous samples into a gas chromatograph equipped with a flame photometric detector as described by Bérubé et al. (1998). The concentration of total organic carbon (TOC) was measured by combustion-infrared method using a TOC analyzer (Shimadzu TOC-500, Columbia, USA) according to Standard Methods (APHA et al. 1995). The statistical significance of changes in any measured or calculated values was determined using a 90 % confidence interval.

The effect of temperature on the rate of methanol removal was investigated by progressively increasing the temperature of an acclimatized mixed culture of methanol-utilizing bacteria, from 55 ^{o}C, to 70 ^{o}C, at 5 ^{o}C increments. For each step, the operating temperature was increased by 5 ^{o}C over one feed cycle. The system was then given sufficient time to acclimatize to the new operating temperature. In all cases, pseudo-steady state operating conditions were reached after approximately 1 week following the temperature increase. The methanol removal rate was monitored for two to three weeks following the acclimatization period.

RESULTS AND DISCUSSION

At each operating temperatures examined in the present study, the rate of reduction in the concentration of methanol in the MBR, following batch feeding, was constant with time and with the concentration of methanol as illustrated in Figure 2. The rate of methanol removal followed a zero order rate equation of the form:

$$r_{su} = KX \qquad [1]$$

where:
r_{su}: rate of methanol removal (mg methanol/l.minute)
K: specific methanol utilization rate (/day)
X: MLVSS concentration (mg/L).

Clean water stripping tests indicated that stripping of methanol by the aeration system was negligible at all temperatures examined. At operating temperatures of 55 ^{o}C and 60 ^{o}C, the concentration of methanol in the MBR was reduced to less than 0.5 mg/L (method detection limit) during each batch cycle. The lower methanol removal rates at operating temperatures of 65 ^{o}C and 70 ^{o}C resulted in measurable residual methanol concentrations in the MBR at the end of each batch cycle as illustrated in Figure 2.

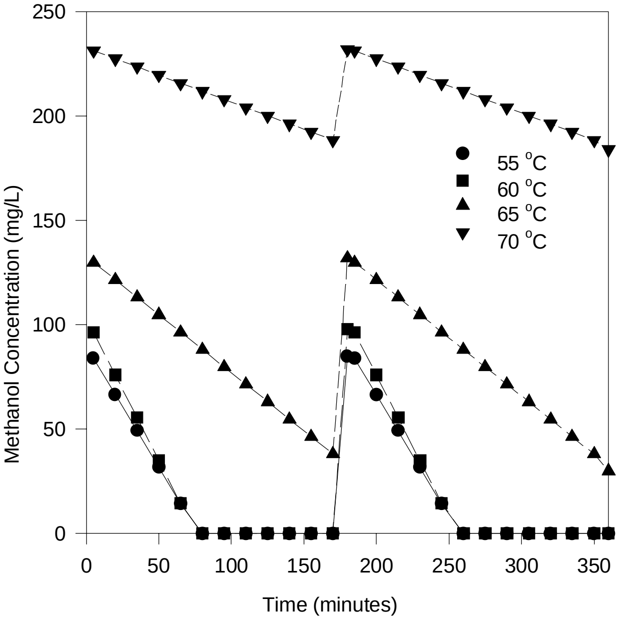
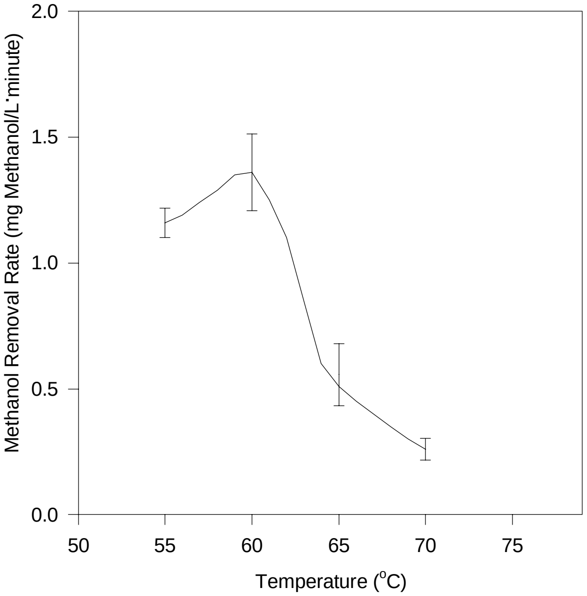


Figure 2: Typical removal of methanol during two batch feed cycles for the four operating temperatures investigated.

The methanol removal rate (r_{su}) was significantly affected by temperature as illustrated in Figure 3. The methanol removal rate increased from 55 ^{o}C to 60 ^{o}C where it reached a maximum of 1.4 mg/L.minute (specific methanol utilization rate (K) of 0.8/day). Beyond 60 ^{o}C, both the methanol removal and specific utilization rates declined sharply. The inhibited growth beyond 60 ^{o}C indicates that the mixed culture was thermotolerant rather than thermophilic. By definition, thermophilic bacteria thrive at temperatures above 60 ^{o}C (Brock 1978). The lower metabolic activity above 60 ^{o}C is likely due to the instability of the enzymes responsible for the oxidation of methanol at these elevated temperatures (Brock 1978; Izumi et al. 1989).

The maximum specific utilization rate of 0.8/day, observed in the present study using synthetic condensates and an operating temperature of 60 ^{o}C, is higher than those reported for biological treatment systems operated at a mesophilic (30 ^{o}C - 35 ^{o}C) or intermediate (35 ^{o}C - 45 ^{o}C) temperature range. Tai (1998) reported specific utilization rates of 0.69 /day and 0.44 /day, for methanol removal from bleached kraft pulp mill combined effluent in a lab scale activated sludge treatment system operating at temperatures of 35 ^{o}C and 45 ^{o}C, respectively. Barton et al. (1996) measured a specific methanol utilization rate of approximately 0.45 /day in a batch treatment system treating combined kraft mill condensates at 33 ^{o}C. The results from the present study suggest that operating at an elevated temperature not only reduces the need for cooling of the condensates before treatment, but may also results in a high contaminant removal rate. In an ongoing study, the effects of real condensates on methanol removal kinetics are being investigated.



(Error bars represent 90% confidence interval for measurements made during steady state monitoring period.)

Figure 3: Influence of temperature on methanol removal rate.

System Costs

Based on the kinetic information collected and the characteristics of the evaporator condensates at the Western Pulp mill, a conceptual design for an MBR system was developed and capital and operating costs were estimated for two operating scenarios. Scenario 1 involved the treatment of the fouler fraction of the evaporator condensate only. Scenario 2 involved the treatment of the fouler fraction and approximately 50 % of the cleaner fraction of the evaporator condensates (i.e. all of the condensates which are typically discharged to the environment following combined mill effluent treatment). The characteristics of the condensate to be treated, for each scenario, are listed in Table 2. Condensate characteristics are for a kraft pulp mill similar to the Western Pulp mill. A 95 % methanol removal efficiency was selected to ensure compliance with the Cluster Rule and to maximize potential HAP reduction credits (Vice and Carroll 1998). A steam stripping system capable of treating the condensates to a similar methanol removal efficiency as the MBR system was also sized and cost estimates determined for comparison.

Table 2: Characteristics of condensates to be treated

Characteristics	Scenario 1	Scenario 2
Pulp Production (admtpd)	816	816
Flow (m^3/min)	0.6	3.6
Methanol Concentration (mg/L)	1,000	500
Temperature (^oC)	70	60 - 70

Capital Costs

The capital cost estimate included equipment, installation, piping, electrical, instrumentation, civil works, engineering, contractor overhead/profits and contingency. Taxes were not included. All costs are expressed in Canadian dollars. A generic capital cost is difficult to estimate because of variations in mill size and layout. To ensure an adaptable capital cost estimate, the following assumptions were made.

1. Condensates to be treated are collected in storage tanks.
2. Condensates are piped approximately 300 meters to the treatment system and the treated condensates are piped approximately 300 meters to the point of reuse (Barton et al. 1996).
3. The treated condensates are collected in a treated condensate storage tank.
4. Waste sludge is piped approximately 150 meters to the existing secondary treatment system (Barton et al. 1996).
5. Vent gases are piped approximately 150 meters to the existing power boiler or lime kiln for incineration (Barton et al. 1996).
6. Steam is piped approximately 300 meters to the stripper system.
7. No cooling is required.

An MBR system, similar to the one used in the present study, was sized according to the design parameters listed in Table 3. The process diagram is illustrated in Figure 4a. The capital cost for the MBR system was estimated based on equipment quotes for each of the MBR components (Stainless steel tank, air blowers, ceramic dome diffusers, ultrafiltration membrane system, pumps, piping, instrumentation). The capital cost estimate for treating the condensates based on scenarios 1 and 2, using a high temperature MBR, is listed in Table 4.

Table 3: MBR design parameters

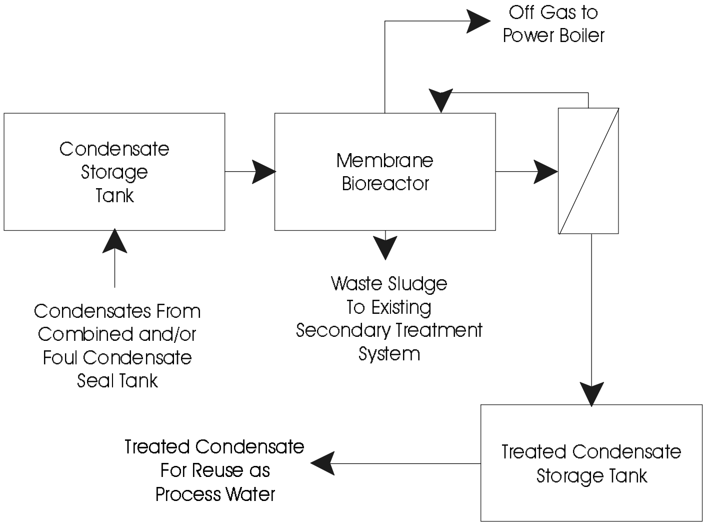
Design Parameter	**Scenario 1**	**Scenario 2**
Methanol Removal Efficiency (%)	95	95
Operating Temperature (^oC)	60	60
HRT (hours)	2.8	1.4
SRT (days)	20	20
MLVSS (mg/L)	10,000	10,000
Specific Utilization Rate (/d)	0.8	0.8
U/F Membrane Flux ($l/m^2.min$)	2.69	2.69

The membrane costs listed in Table 4 are for ceramic ultrafiltration membranes, similar to those used in the present study. Ceramic ultrafiltration membranes have a proven track record for operating under harsh conditions such as elevated temperatures. However, they tend to be more expensive than polymeric membranes. With recent developments in membrane materials, it may be possible to use polymeric membranes at operating temperatures of 60 ^oC. Using submerged hollow fibre polymeric membranes in the MBR system would reduce the capital cost associated with the membrane component by almost 50 %. The resulting total capital cost would be approximately \$3,200,000 and \$8,300,000 for scenarios 1 and 2, respectively. The overall operating cost is expected to be in the same order of magnitude for polymeric and ceramic membranes. The major disadvantage associated with using submerged hollow fibre membranes is that their long term use at elevated temperatures has not been well documented.

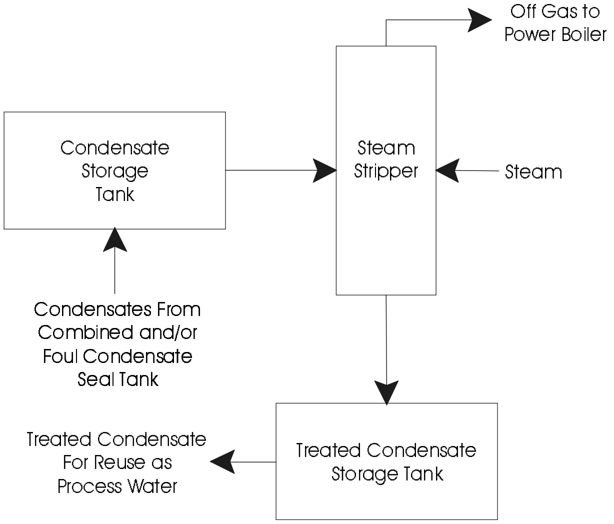
The capital cost for the steam stripping system was estimated based on delivered and installed cost for complete steam stripper systems, provided by established equipment suppliers. The capital cost estimates includes all steam stripper components (pumps, motors and instrumentation). The steam stripper capital costs obtained from two independent suppliers were in the same order of magnitude. The process diagram for the steam stripper is illustrated in Figure 4b. The capital cost estimates for treating the condensate based on scenarios 1 and 2, using a steam stripper system, are listed in Table 4.

Operating Costs

The operating cost estimates for the MBR system are summarized listed in Table 5. The electrical operating costs were estimated based on \$0.1 /kWh. Equipment maintenance costs were estimated based on a yearly operating cost equivalent to 2 % of the installed equipment costs (Barton et al. 1996). The chemical operating costs were adapted from Barton et al. (1996) based on biological oxygen demand (BOD) removal. The labor cost is for four full time personnel equivalents (Barton et al. 1996).



a) MBR System



b) Steam Stripper System

Figure 4: Process schematics.

The operating cost estimates for the steam stripper system are also listed in Table 5. The cost associated with steam generation is highly mill specific and is function of existing steam generating capacity. Based on discussions with local engineering consultants, the cost of providing steam was estimated based on a life cycle cost for a large boiler, fired with gas and wood waste fuel, over a 20 year period. Given local conditions and 9 % financing, the life cycle cost of providing steam is estimated to be $5/1000 lb ($11/1000 kg) steam. Fuel credits are based on a fuel value of 22,700 kJ/kg for methanol and a fuel cost of $3.5/GJ. Labor and equipment maintenance costs were estimated as described above.

Table 4: Capital cost estimate in thousands of dollars

Cost Component	Scenario 1	Scenario 2
Membrane Bioreactor		
Piping	500	900
Storage Tanks & Pumps	180	390
Chemical Addition	65	230
MBR Tank	70	160
Aeration System	1,100	1,649
Membranes	1,300	8,200
Civil/Electrical	660	1,300
TOTAL	**$3,900** **(*$3,200)**	**$12,800** **(*$8,300)**
Steam Stripping		
Yard Piping	600	1,000
Storage Tanks and Pumps	180	390
Steam Stripper	4,700	9,900
Kiln Combustion System	200	300
Civil/Electrical	660	1,300
TOTAL	**$6,300**	**$13,000**

(*Total cost for MBR system using polymeric membranes)

Table 5: Operating costs per air dry metric tonne

Cost Component	Scenario 1	Scenario 2
Membrane Bioreactor		
Power	0.63	2.75
Chemicals	0.25	0.74
Labor	0.60	0.60
Equipment	0.05	0.07
TOTAL	**$1.53**	**$4.16**
Steam Stripping		
Steam	2.32	13.97
Fuel Economy	0.08	0.24
Labor	0.60	0.60
Equipment	0.15	0.37
TOTAL	**$3.00**	**$14.66**

As an alternative, waste heat from a blow heat recovery system could be used to meet the steam requirements for the stripper system (Hough and Sallee 1977; Farr et al. 1993). This could reduce the operating cost for steam by as much as one order of magnitude (Farr et al. 1993). However, significant modifications to existing mill equipment would be required (NCASI 1994). Consequently, waste heat recovery for steam stripping may only be feasible with new mills.

Cost Comparison

The capital cost estimates indicate that biological treatment, using a high temperature MBR, is significantly less expensive than steam stripping, when treating the foul fraction of the evaporator condensate for reuse (Scenario 1). When treating a combination of the foul and cleaner fractions of the evaporator condensate, for reuse (Scenario 2), the costs of both systems are similar. However, if polymeric membranes are used, the capital cost of an MBR system may be significantly less than the cost of a steam stripping system for both operating scenarios.

The operating cost of an MBR system is significantly less than the operating cost of a steam stripping system, particularly for scenario 2. This is similar to previously published cost estimates which indicate that the operating cost associated with generating steam can be prohibitively expensive when steam stripping large flows (Vora 1995).

The cost estimate for the MBR indicates that cost is most sensitive to the volume of wastewater to be treated and not the amount of methanol to remove. Achieving a high methanol removal efficiency, as achieved in the present study (95 %), does not significantly affect the total cost. Consequently, a high methanol removal efficiency should be assumed in a process design to maximize HAP emission credits.

MANAGEMENT APPLICATIONS

The results reported here have been produced in the first phases of a lengthier research project whose objective is to determine whether membrane bioreactors operated at high temperatures may be a feasible technology for internal treatment and reuse of kraft pulp mill condensates. The information should be of interest to forest products companies that operate bleached kraft pulp mills and who are considering options for further internal reuse of condensate, or who wish to reduce the organic loading contributed by contaminated condensates to an existing, external secondary wastewater treatment system.

The results summarized above indicate that preliminary experimental data confirm that the treatment process is technically feasible for operation at elevated temperatures (55 to 60^{o}C). By applying the technology in this temperature range, the economics of the membrane bioreactor treatment approach are substantially improved. A cost comparison to steam stripping confirmed that the membrane bioreactor options could be significantly less expensive than the major alternative technology for this duty.

CONCLUSIONS

1. A maximum feasible operating temperature of approximately 60 ^{o}C was observed.
2. High temperature operation is not only possible, but may be more efficient for treatment of evaporator condensate for reuse, than conventional, lower temperature, biological treatment.
3. The combined capital and operating costs for a high temperature MBR are significantly less than for a steam stripping system for both scenarios investigated, particularly if polymeric membranes can be used.
4. A high temperature MBR appears to be a promising alternative to conventional biological treatment or steam stripping when treating evaporator condensates for reuse.

ONGOING STUDIES

The effect of other contaminants contained in real condensate, on the rate of methanol removal using a high temperature MBR, is currently being investigated. In addition, the removal of contaminants, other than methanol, is also being investigated. Preliminary results indicate similar methanol removal rates when treating real and synthetic condensates. However, the methanol removal rate appears to be more variable. Tests are currently under way to investigate the cause of the variation.

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