Desalination and Water Treatment
www.deswater.com

34 (2011) 389–393
October

doi: 10/5004/dwt.2011.2885

Zero discharge fermentation plant design

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Received 3 September 2010; Accepted 3 January 2011

ABSTRACT

In recent years, there has been an increasing thrust towards zero-discharge operation of wastewater treatment plants. This has been driven by increasingly stringent discharge standards, as well as financial benefits stemming from the recycling of water around such facilities. The molasses-based fermentation industry is associated with high consumption of water and a high generation of high-strength effluent, due to the widespread use of molasses feeds. Traditional biological treatment for this effluent is incapable of meeting stringent discharge and reuse standards; therefore it must be supplemented with tertiary treatment options. The main options for water recovery are reverse osmosis (RO) membrane filtration and evaporation. The main problems for these treatment options is the high energy consumption associated with their use and the requirement for pre-treatment leading up to the RO stages. This paper will compare potential treatment options for high water recovery from the high-strength effluent generated by distilleries and yeast production plants on an economic basis, incorporating both operating costs and capital costs. Treatment options are considered for several different effluent sources. This includes a comparison of the use of both reverse osmosis and evaporation technology for water recovery on end-of-line effluent streams. The potential for a salt recycle from the end-of-line streams to pre-fermentation stages is explored as well as decolourisation of the molasses feed. This paper will also demonstrate the potential for energy integration between the biological treatment stages and the tertiary "polishing" stages. The biogas produced in the anaerobic digestion stage can be used to generate enough electricity to power the following treatment stages, while maintaining a high water recovery (>80%). This paper builds upon the work of Ryan et al. [1]. In their paper, the authors overestimated the levels of TDS reaching the RO stages. They failed to account for the ability of both the aerobic digesters and the nanofiltration treatment stages to remove TDS from the effluent. This paper then focuses on the potential for water recovery from a molasses-based fermentation plant and compares treatment technologies for this water recovery.

Keywords: Fermentation plant; Membrane filtration; Microfiltration; Nanofiltration; Reverse osmosis; Water recovery; Zero-discharge

1. Traditional treatment of fermentation plant effluents

The fermentation industry produces large amounts of effluent. It has been reported that the production of effluent from a bioethanol plant can be 12–15 L/L of ethanol [2], or 6–20 L/L of ethanol [3]. Although these figures are decreasing over time, increasing global ethanol production leads to an increase in the production of effluent from this industry.

Fig. 1 shows the traditional processes employed for the treatment of fermentation plant effluent. Due to the biological nature of the fermentation process, the effluent produced contains high levels of BOD as well as bio-recalcitrant COD and TDS. As a result,

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Presented at the AMS6/IMSTEC10, The 6th conference of the Aseanian Membrane Society in conjunction with the 7th International Membrane Science and Technology Conference, Sydney Australia, November 22–26, 2010

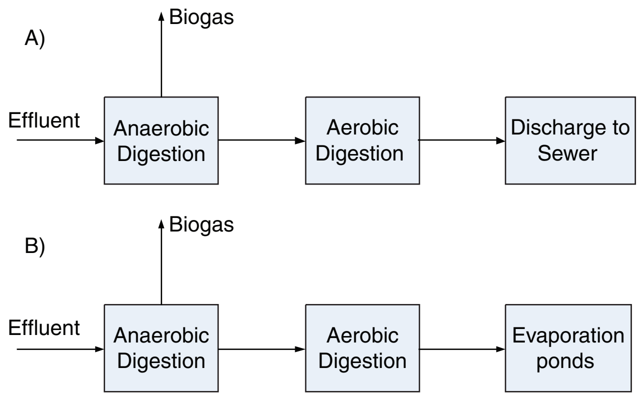

Fig. 1. Traditional treatment options for A) tolerant discharge limits, and B) stringent discharge limits.

biological treatment is the first stage in most treatment plants. Due to the simple design and low costs, anaerobic digestion has become an important initial stage in the treatment of high organic load effluents [1]. The use of anaerobic digestion has the additional benefit of producing biogas at 0.35 N.m^3/kg COD [3], which can be utilised as an energy source in the plant. The effluent is then treated by aerobic digestion, to further reduce the levels of BOD, COD and TDS. Both forms of biological treatment have been assessed at length in recent years [2,4,5].

Combined anaerobic/aerobic treatment processes are often capable of reducing effluent BOD, COD and TDS to acceptable standards for sewer discharge in countries with established sewage systems, such as Australia. In such sewage systems, particularly near big cities, these compounds are diluted when the industrial wastewater is added to sewage or even storm water to be treated. However, they are unable to sufficiently decolourise the effluent. The dark brown colouring of fermentation effluent is attributed to the presence of melanoidins and phenolic/humic compounds. In the past, post-aerobic effluent was then diluted and discharged. Due to more stringent environmental regulations, these practices are now prohibited and the industry must now tackle difficult choices regarding treatment options to meet these new standards cost-effectively.

There is also an increased push towards water reuse. The US EPA has introduced regulations requiring corn-based ethanol plants to recycle water [6]. However, the wastewater is lacking in nutrients for the yeast and carries an abundance of stress agents, such as organic acids and salts [6]. The wastewater generated by the molasses-based fermentation industry would have similar problems. These contaminants, therefore, must be removed from the water before it can be reused in the process. Mavrov et al. have demonstrated that membrane filtration is an effective method of treating effluent from the food industry for reuse [7,8].

2. Membrane filtration

Membrane filtration, from microfiltration to reverse osmosis, has become more widely used in industry for wastewater treatment. This is partly due to the technologies ability to produce permeate of a "reliable" quality.

RO is increasingly being used to recover high quality water from industrial effluents, which can then be reused, and by using multistage processes the water recovery can approach 100% [9]. However, to achieve such high recovery rates, these processes must operate at very high pressures; 70 bar for some distillery effluents [10]. Direct filtration of industrial effluents can also lead to excessive fouling and the need for frequent cleaning. To combat these problems, NF, ultrafiltration (UF) or MF processes are used as pre-treatment stages to prevent solids and/or organic compounds fouling the RO units.

NF is often used as a pre-treatment stage for RO processes in the treatment of high strength industrial wastewater. MF and UF membranes are effective at removing suspended solids and large organic molecules from the effluent; however, they are incapable of removing the smaller organic molecules and therefore cannot completely remove the COD and colour .

The use of NF and RO in the removal of distillery effluent has been reviewed in the past. Rai et al. [11] used NF to remove more than 90% of COD and colour, while maintaining a permeate flux greater than 1 $m^3/m^2/h$. Nataraj et al. [10] achieved similar results using an combined NF-RO process to remove COD, colour and TDS.

3. Energy requirements

Due to the production of biogas, anaerobic digestion has become a ubiquitous stage in the treatment of high strength organic effluents, such as those sourced from fermentation plants. With high levels of COD and BOD, fermentation effluents have a high biogas production capacity. With good digester performance, the amount of biogas produced could be used to provide enough energy to supply the subsequent treatment stages–aerobic digestion and membrane filtration. As a demonstration of this, a case study was run using data from literature [1,2,4,5,10–13] to demonstrate the potential for water recovery in a distillery effluent treatment plant. Based on a flow rate of 250 m^3/h and a COD reduction from 150,000 mg/l to 48,500 mg/l [4] and a thermal efficiency for a biogas run engine of 25%, the electrical power harnessed from the biogas produced amounted to 13,815 kW. The anaerobic digestion also reduces TDS from 120,000 mg/l to 31,000 mg/l, consisting mainly of salts and organic compounds.

Following anaerobic digestion, the effluent passes on to the aerobic digester. For energy requirement calculations, the anaerobic effluent stream undergoes aerobic digestion, reducing the COD levels to 5,000 mg/l. From literature, the energy requirements for aerobic digestion was taken to be 1 kWh/kg COD removed [12]. The energy required by the aerobic digester to meet the specified COD reduction was 10,922 kW. This represents the largest single source of energy consumption within the plant and consumes 79% of the energy generated from burning the biogas. The aerobic digester also reduces the TDS levels to 9,500 mg/l [11]. This TDS consists of salts and recalcitrant COD, both of which contribute to the osmotic pressure of the effluent.

The energy consumption of the following membrane filtration stages is dominated by the pumping power required to pressurise the effluent to the necessary operating pressures. The biologically treated effluent still contains high levels of suspended solids (TSS). NF and RO systems are highly susceptible to membrane fouling and are usually preceded by pre-treatment to remove TSS. The chosen pre-treatment for this plant was microfiltration (MF). MF is capable of removing 97% TSS, while operating at a water recovery of 97%. The energy required for MF pre-treatment was calculated to be 4.6 kW. While removing TSS, MF was assumed to have minimal effects on the levels of COD and TDS.

$$\textit{Power required} = \Delta P \times \textit{volumetric flowrate}$$

Following MF pre-treatment, the effluent is treated by nanofiltration. The NF stage is operated at 5 bar [11], removing 96% COD and 85% TDS [11]. NF is capable of removing multivalent ions from solution, while allowing monovalent ions, such as Na^+, K^+ and Cl^-. The energy requirement of the NF stage, operating at a water recovery of 90%, was 43.5 kW.

Following nanofiltration, the effluent is then treated by reverse osmosis (RO). Ryan et al. assumed minimal TDS removal in the aerobic digestion stage [1]. However, Rai et al. found that aerobic digestion was capable of reducing the TDS levels to 9,500 mg/l from high strength distillery effluent [11]. Due to the reduction in TDS from the aerobic digestion and NF stages, a four stage RO system was chosen to maximise total water recovery. The osmotic pressures for the effluent at each RO stage were estimated based on the TDS levels of the effluent using a conversion factor of 85 Pa/(mg/l TDS). Each stage of RO treatment was assumed to operate with a water recovery of 50%. Stage 1 was calculated to operate at 8 bar and required 62.7 kW. Stage 2 was calculated to operate at 10 bar with an energy requirement of 7.8 kW. Despite having a higher TDS, the energy requirement for stage 2 is substantially lower than stage 1. This is due to the effluent retentate from stage 1 still being pressurised, so that the change in pressure is significantly lower. The flow rate of the feed to stage 2 is also half that of the feed to stage 1. Stage 3 was calculated to operate at 15 bar and requires 9.8 kW. Finally, stage 4 was calculated to operate at 25 bar and requires 14.7 kW.

The retentate from stage 4 is then sent to evaporators to concentrate the residual effluent and recover water. The evaporation process was simulated in HYSYS as a 3 stage feed-forward evaporator system. The simulation found that 0.9 t steam/t water recovered of high pressure steam is required to recover 58% of the remaining water.

The treatment process outlined above treats high strength fermentation effluent and has been summarised in Fig. 2. As a result of the process, over 80% of the water is recovered treated to reuse standards. The energy required to run the treatment process up to the end of the RO system was calculated to be 11 MW. The biogas produced in the anaerobic digester can be utilised to generate 13.8 MW of electrical power. Therefore, this effluent treatment plant is capable of high water recovery, while maintaining a net production of energy.

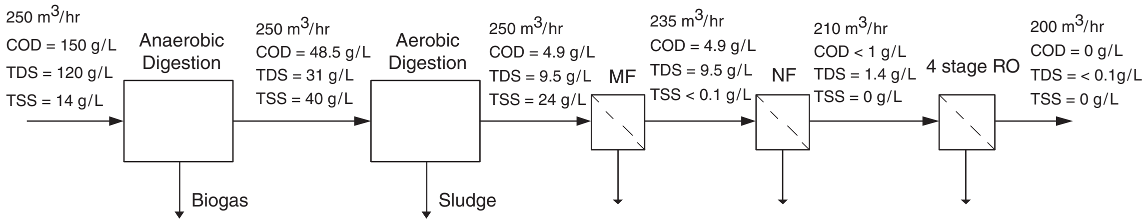

Fig. 2. Process flowsheet.

4. Membrane replacement costs

Another cost associated with the use of membranes is the replacement costs of the membrane elements. Membrane elements have a lifespan between 3–5 y [14]. Assuming a lifespan of 3 y, one third of the elements will need to be replaced each year. Costing data for MF and NF was based on AMI membranes [15]. The number of elements required was calculated based on the stated capacities of the AMI membranes. For RO costing, Hydranautics design software, IMSDesign, was used to estimate the number of elements required for a defined process. In each case, the number of elements required was increased to account for cleaning time. It was assumed that elements would require chemical cleaning once a week [14]. Chemical cleaning can take up to 14 h for a full chemical clean of one membrane treatment train [14], therefore, for every seven elements an extra element is required. As a result, the number of elements for each membrane filtration stage is increased by approximately 14%.

Due to the large number of elements required by each stage of the process, the membrane replacement costs represent a significant amount of the overall operating costs for the membrane filtration systems. The membrane lifespan is influenced by the fouling potential of the effluent. As shown in Table 1, if the membrane lifespan can be increased from 3 to 5 y, the replacement costs drop dramatically. The lifespan can be increased by effective monitoring and management of membrane fouling.

5. RO vs. evaporation

The two options for water recovery – reverse osmosis and evaporation – are both highly energy intensive technologies. In the treatment process outlined above, a 4 stage RO system (using a pump for each stage) followed by a 3 stage evaporator was used to recover water economically. This configuration was chosen as a result of a case study comparing the costs of recovering water using RO and evaporators. The results of the case study are outlined in Table 2. The operating cost of the RO system was estimated by the cost of electricity consumed. The operating pressures of the RO stages were estimated by calculating the osmotic pressure as a function of the TDS in the effluent. The operating cost of the evaporators was estimated by the cost of producing the high-pressure steam used in the evaporators [17].

From Table 2, it is clear that water recovery using RO is more economical than using evaporation. The total operating costs calculated in this case study decrease dramatically as additional RO stages are added. This is due to the decreasing amounts of effluent sent to the evaporators. However, adding extra RO stages onto the system would only result in marginal increases in water recovery.

Table 1
Operating costs of membrane filtration

	Number of elements required	Cost of elements ($AU)	Annual membrane replacement costs ($AU/y) (3 y lifespan)	Annual membrane replacement costs ($AU/y) (5 y lifespan)	Annual pumping costs ($AU/y)
MF	64	$416 [15]	$8,875	$5,300	$4,800
NF	816	$300 [15]	$81,525	$46,000	$34,000
RO	474 [16]	$2,000	$316,000	$189,600	$99,000

Table 2
Operating costs of RO/evaporation water recovery system

No. of RO stages	Pumping costs of RO system ($AU/y)	Operating costs of evaporators ($AU/y)	Total operating costs ($AU/y)	Total water recovery
1	$65,000	$5,990,000	$6,050,000	69%
2	$73,000	$2,890,000	$2,950,000	79%
3	$84,000	$1,30,000	$1,400,000	83%
4	$99,000	$650,000	$750,000	85%

6. Conclusions/Future work

The fermentation effluent treatment plant detailed in this paper demonstrates the potential of membrane filtration technology for recovering water economically, when run in conjunction with existing treatment technology. The treatment plant operated at a total water recovery of 85%. The anaerobic digesters, coupled with piston engines, can produce enough electricity to power the subsequent treatment stages.

The membrane replacement costs were identified as a major cost item. As the lifespan is affected by the degree of fouling encountered by the membranes, effective management of fouling becomes an important factor in cost minimisation for such a plant.

The next step in our work will be to conduct pilot scale testing on industrial effluent in order to ascertain the operating parameters of targeted effluent streams within a fermentation plant. This will also allow us to determine the potential for water recovery from various sources of these plants and to determine what extent of water recovery is practical.

Acknowledgements

This paper represents part of the research funded by *ARC Linkage LP100100310*: Measurement and Prevention of Membrane Fouling for Water Reuse in Biorefineries. This grant has also funded an APAI scholarship for Tim Handelsman.

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