



Design methodology for submerged anaerobic membrane bioreactors (AnMBR): A case study



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ABSTRACT

The main objective of this study is to propose guidelines for designing submerged anaerobic MBR (AnMBR) technology for municipal wastewater treatment. The design methodology was devised on the basis of simulation and experimental results from an AnMBR plant featuring industrial-scale hollow-fibre membranes. The proposed methodology aims to minimise both capital expenditure and operating expenses, and the key parameters considered were: hydraulic retention time, solids retention time, mixed liquor suspended solids concentration in the membrane tank, 20 °C-standardised critical flux, specific gas demand per square metre of membrane area, and flow of sludge being recycled from the membrane tank to the anaerobic reactor. An AnMBR WWTP operating at 15 and 30 °C with both sulphate-rich (5.7 mg COD mg⁻¹ SO₄-S) and low-sulphate (57 mg COD mg⁻¹ SO₄-S) municipal wastewater was designed. The minimum cost of the designed plant was €0.097 and €0.070 per m³ when treating sulphate-rich and low-sulphate wastewater, respectively.

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1. Introduction

Anaerobic wastewater treatment has several advantages in comparison with conventional aerobic treatment: (i) lower sludge production because of the low yield of anaerobic microorganisms; (ii) lower energy consumption because no aeration is required; and (iii) potential resource recovery because energy (from biogas production) and nutrients (NH₄⁺ and PO₄³⁻) can be obtained from the anaerobic degradation process. As a result, anaerobic processes are viewed as an attractive choice for sustainable low-strength wastewater treatment (e.g. municipal wastewater). However, anaerobic processes have certain drawbacks that currently prevent them from being used in the full-scale treatment of low-strength wastewater.

As regards the anaerobic treatment of municipal wastewater, the low COD (chemical oxygen demand) of municipal wastewater (typically less than 1 g L⁻¹) means that little methane is produced.

Therefore, an external energy source would be needed to heat the reactor to mesophilic conditions [1]. At low temperatures, the growth rates of anaerobic microorganisms are greatly reduced and long sludge retention times (SRT) are necessary – not only to meet appropriate effluent and sludge standards and produce considerable amounts of biogas, but also to prevent biomass washout [2]. Therefore, the success of anaerobic treatment of municipal wastewater at low temperatures depends on the ability to detach SRT from hydraulic retention time (HRT). In this respect, submerged anaerobic membrane bioreactors (AnMBRs) are considered a feasible alternative for municipal wastewater treatment at low temperatures.

Jeison [3] reported reductions of up to 90% in the sludge produced when AnMBR technology was used, therefore this technology is a promising alternative for the anaerobic treatment of low-strength wastewater. In addition, depending on the operating conditions, the produced sludge could be enough stabilised to be disposed of directly on farmland with no further digestion step (no pathogens and low biological methane production).

On the other hand, when municipal wastewater containing sulphate is anaerobically treated, the sulphate is reduced to sulphide. The production of this end product can cause technical problems such as: (i) hydrogen sulphide is toxic to anaerobic microorganisms; (ii) the amount of biogas produced is reduced because some of the influent COD (approx. 2 g COD per g SO₄-S) is consumed by

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sulphate-reducing microorganisms (SRB); (iii) the quality of the produced biogas is reduced because some of the hydrogen sulphide produced will end up in the biogas; (iv) hydrogen sulphide can cause corrosion in pipes, engines and boilers, entailing higher maintenance and replacement costs; and (v) downstream oxygen demand may be required for oxidising hydrogen sulphide. For municipal wastewater, which can easily present low COD/SO₄-S ratios, the competition between Methanogenic Archaea (MA) and SRB can critically affect the amount and quality of the biogas produced. According to the theoretical methane yield under standard temperature and pressure conditions (350 L CH₄ per kg COD), SRB reduces the production of approx. 700 L of methane per kg of influent SO₄-S (considering reduction of all sulphate to sulphide). Therefore, higher biogas productions would be achieved at low sulphate influent concentrations [4].

As regards filtration, the high SRTs applied in AnMBR technology usually mean high levels of mixed liquor suspended solids (MLSS) which contribute to membrane fouling [5]. In order to minimise any kind of membrane fouling and thereby increase membrane lifespan, the main operating challenge for AnMBRs is to optimise membrane operation and configuration [6–8]. It is therefore necessary to optimise filtration whilst minimising not only capital expenditure but also operating and maintenance costs. Hence the AnMBR design strategy must be carefully selected since depending on the design strategy, different design criteria can be adopted.

The main points of fouling control strategies as regards membrane operation are: optimising the frequency and duration of the physical cleaning stages (back-flush and relaxation) [9,10]; optimising different operating variables such as gas sparging intensity or permeate/influent flow rate ratios; and operating membranes under the sub-critical filtration conditions bounded by critical flux (J_C) [11,12]. Thus, one such design strategy entails operating membranes in sub-critical filtration conditions. Operating membranes sub-critically increases membrane lifespan, which reduces maintenance costs, but it usually increases investment and/or operating expenses (i.e. it increases the membrane area needs and/or the intensity of the gas sparging used for membrane scouring). MLSS and gas sparging intensity (usually measured as specific gas demand per membrane area, SGD_m) have been widely identified as the factors that affect J_C most. As for MLSS, an optimum combination of reactor volume and filtration area must be selected in order to keep MLSS at sub-critical levels for a given SGD_m . In addition, membrane scouring by air/biogas is a key process that allows minimising energy consumption of MBR plants because it is the most energy-consuming process in full-scale MBRs (see, for instance, [12]). Therefore, one of the main challenges when designing an AnMBR plant is to achieve acceptable membrane performances at minimum levels of SGD_m whilst minimising membrane fouling.

Another design criterion entails operating membranes in supra-critical filtration conditions. This strategy means lower initial investment because it requires lower operating volumes (i.e. operating at higher MLSS levels) and/or smaller membrane surfaces than operating membranes at sub-critical filtration conditions. However, maintenance and operating expenses are probably higher. For instance, for a given SGD_m , an increase in MLSS usually means greater membrane fouling, which in turn increases membrane maintenance costs because the membranes are chemically cleaned more often. In addition, increasing the frequency of membrane chemical cleaning affects the membrane lifespan, which also increases membrane replacement costs.

Although AnMBR technology has not been yet applied to full-scale municipal wastewater treatment, recent literature [13–17] has reported increasing interest by the scientific community in the use of AnMBRs for municipal wastewater treatment. However,

a design methodology that holistically considers the key operating factors that affect both biology and filtration is still necessary in order to lay the foundations for the optimum design of full-scale AnMBRs for municipal wastewater treatment. The aim of this paper is to provide guidelines for designing AnMBR technology under different scenarios. To this aim, a design methodology was developed based on the knowledge and operation experience gained from an AnMBR plant featuring industrial-scale hollow-fibre membranes that was fed with sulphate-rich wastewater from the pre-treatment of a municipal WWTP located in Valencia (Spain). The proposed methodology aims to minimise total annual costs, which are defined as the sum of capital and operating expenses (CAPEX/OPEX). OPEX take into account energy requirements, methane production and capture, sludge handling and disposal, and membrane maintenance and replacement. In this respect, the key operating parameters considered when designing the biological process were hydraulic retention time (HRT) and solids retention time (SRT); and, when designing the filtration process, the levels of mixed liquor suspended solids in the membrane tank ($MLSS_{MT}$), the 20 °C-standardised critical fluxes (J_{20}), SGD_m and the recycling sludge flow rate from the membrane tank to the anaerobic reactor (Q_{rec}).

The proposed methodology was used to design an AnMBR WWTP handling municipal wastewater with high and low levels of sulphate (5.7 and 57 mg COD·mg⁻¹ SO₄-S, respectively) at 15 and 30 °C.

2. Materials and methods

As mentioned earlier, the proposed design methodology is based on the knowledge and the results obtained from the operation of an AnMBR plant fitted with industrial-scale membranes that was operated using real sulphate-rich municipal wastewater. The WWTP simulating software DESASS [18], which enables a wide range of wastewater treatment schemes (including AnMBR systems) to be evaluated, was used to simulate the AnMBR WWTP.

2.1. AnMBR plant description

The AnMBR plant consists of an anaerobic reactor with a total volume of 1.3 m³ connected to two membrane tanks, each with a total volume of 0.8 m³. Each membrane tank features one ultrafiltration hollow-fibre membrane commercial system (PURON®, Koch Membrane Systems, 0.05 µm pore size, and outside-in filtration). Each module consists of 9 hollow-fibre bundles of 1.8-m length that give a total of 30 m² membrane surface. In order to scour the membranes, thus minimising cake layer formation, a fraction of the produced biogas is continuously recycled to the membrane tanks through the bottom of each fibre bundle.

As mentioned above, this plant was fed with sulphate-rich municipal wastewater from the pre-treatment of the Carraixet WWTP (Valencia, Spain), which involves screening, degritting and grease removal. Further details of this AnMBR can be found in Giménez et al. [19] and Robles et al. [9].

2.2. AnMBR plant operation

The AnMBR plant was operated for more than 4 years under different operating conditions [4,9]. Regarding the biological process, the plant was operated at four different SRT (20, 30, 40 and 70 days), with controlled HRT ranging from 5 to 30 h, and organic load rates (OLR) ranging from 0.5 to 2 kg COD m⁻³ d⁻¹. The impact of temperature on process performance was evaluated in the 14–33 °C range. During the operating period, the pH in the mixed liquor remained stable around 6.8 ± 0.2. As regards filtration, the

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