THERMO-ECONOMIC ANALYSIS OF A THERMOPHILIC BIOGAS PLANT INTEGRATED WITH MEMBRANE DISTILLATION

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ABSTRACT

This study assessed the thermo-economic performance of membrane distillation (MD) for concentrating nutrients and recover process water from digestate at a thermophilic biogas plant. The input data were derived from mapping the Uppsala Vatten och Avfall biogas system, present knowledge on anaerobic digestion process management and technologies for biogas system operating conditions in Sweden. The study evaluated the potential for recovering waste heat from the digestate effluent and boiler flue gas for use in the MD system. The thermal energy requirement, size, and separation efficiency of the MD unit were based on a previous laboratory study. The study assessed the overall energy efficiency and costs estimation of a full-scale co-digestion plant with thermally integrated MD.

Presented results shows that the proposed model of integrated MD system has the best thermal performance. The recovered waste heat contributed total thermal energy demand of MD and additionally it could save 19% boiler energy by heating incoming slurry. The results showed that the MD product water permeate was 3.5 L/(m^{2}h) at 65°C digestate inlet temperature. Specific heat demand for MD was 100 kWh/m^3 with internal heat recovery. Cost estimation showed that the unit cost of MD permeate water was 3.6 €/m^3 at a digestate feed temperature of 65°C. The economic assessment indicated that thermal integration of a biogas plant with MD could be economically feasible. However, long-term continuous studies are needed to determine impact of fouling and membrane lifetime.

Keywords: biogas plant; digestate; membrane distillation; concentrated nutrients and water recovery; thermo-economic analysis

1. INTRODUCTION

Digestate from wet co-digestion biogas plants contains large volumes of water, causing high transportation and handling costs. Even though digestate is rich in plant nutrients, its value as a fertilizer is low due to its high water content of 90 to 95% [1]. To overcome this problem, the digestate can be processed for volume reduction allowing a more economic and resource efficient ways of handling the product. However, even though digestate treatment offers many advantages, it also causes many problems. For complete processing, complex methods and technologies are currently available with various degrees of technical maturity, high energy input, and high investment and operating costs [2]. The rate of biogas production can increase significantly by thermophilic digestion but there is a high demand of reaction heat, and a previous study has shown that a considerable amount of heat could be recovered by preheating the substrate feed with the effluent slurry [3]. Thus, it is crucial to use the waste-heat effectively in order to decrease the amount of external heat input to improve the energy balance.

Hence, there is a need to develop innovative, energy-efficient, and robust digestate separation technologies with high separation efficiency that can easily be integrated with an existing plant, in order to achieve better energy and cost effectiveness compared to conventional technology [4-7].

MD (membrane distillation)-based water recovery unit operations are proposed due to advantages such as high stability, low energy consumption, robustness, and easy operation [1,8]. MD is a thermally driven separation/concentration process where water vapor is transported through a hydrophobic microporous membrane by temperature gradient-induced vapor

pressure [8]. To date, no comprehensive study has examined the feasibility of MD separation of digestate, which is a challenging and complex feed solution due to relatively high fiber and total suspended solids concentration.

The overall objective of the study was to assess the thermo-economic performance of integrated digestate separation and concentration by MD at a thermophilic biogas plant. The aim was to assess the digestate separation/concentration system integrated in an existing AD plant (Uppsala, Sweden) co-digesting municipal food waste, liquid and slaughterhouse wastes to produce process water and concentrated nutrients. For the proposed integrated system the mass, nutrient and energy balances were calculated and the nutrient and process water recovery, mass reduction, waste heat recovery and energy efficiencies were determined based on typical thermophilic co-digestion plant values from full scale studies.

2.   MATERIALS AND METHODS

This study was performed by mapping the current operating conditions for the Uppsala Vatten och Avfall biogas plant, which operates a semi-continuous thermophilic process with mainly sanitized organic waste (Fig. 1(a) and Table 1). The basic characteristics of the plant and different unit operations in terms of mass and energy balance were assessed to provide input data for calculations on thermal integration of the biogas production system and a typical industrial MD system based on the digestate, and the boiler flue gas system as a provider of waste heat. The thermal energy requirement, size, and separation efficiency of the MD unit were calculated based on the performance of a laboratory-scale unit determined in a previous study [1]. In order to evaluate whether thermal integration is a cost-effective option, general economic analysis was performed based on the methodology used in a previous study [4] for the integrated system.

2.1   Biogas plant and digestate characteristics

The biogas plant Kungsängens gård, owned by Uppsala Vatten och Avfall AB, produces biogas and digestate from a mixture of organic wastes, comprising the source-sorted organic fraction of municipal solid waste (SS-OFMSW, about 82 wt%), food waste (about 3 wt%) and slaughter house waste (about 15 wt%), which is digested under thermophilic conditions (52°C). All of the SS-OFMSW and food wastes are pretreated in a Haarslev waste food depacker and mostly separates plastics and other inorganic wastes, where water is

added for dilution and reduce the particle size to <10 mm. The slaughterhouse waste then passes through pulpers. Thereafter, the substrate enters the buffer tank and subsequently the sanitation (pasteurization) process (Fig 1(a)). The heat for pasteurization and the digester tank is supplied by steam from a pellet boiler. After the pasteurization step, the suspension is cooled with the incoming substrate suspension to achieve the temperature required, which is 52°C for thermophilic processes. Part of the sanitized sludge heat is recovered by using it to heat the input feed sludge with heat exchangers.

The characteristics of the digestate is shown in Table 1. The digestate has a N:P:K-ratio of 9:1:3 and is used as an organic fertilizer in the agriculture.

Table 1. Main characteristics of the Uppsala Vatten och Avfall biogas plant.

Parameter	Units	Value
Organic waste supply	ton/day	130-150
Digester inside temperature	°C	52-55
Digestate (TS 4%)	ton/day	150-170
Digestate temperature	°C	52
Digestate pH		8.11
TOC	mg/Kg	14,034
Total N in digestate	mg/Kg	4567
Total P in digestate	mg/Kg	509
Total K in digestate	mg/Kg	1506
Total S in digestate	mg/Kg	294

2.2 Membrane distillation (MD) and its performance

MD permeate water characteristics used in the assessment are based on data from the previous laboratory study [1]. Data on the separation efficiency, flux (water permeate), production rate of digestate, and specific thermal energy demand for the laboratory-scale MD unit used in the calculations were taken from previous studies [1,8]. For a detailed description, see Khan and Nordberg [1]. Previous experimental studies [1,8] showed that the MD process exhibited a high rate of rejection of all nutrients present, thereby effectively concentrating these nutrients in the digestate. With these data, the amount of water purified for a given thermal energy recovery level in the biogas system integrated with the MD unit was determined. In the present study, the sizing of the MD module was based on the heat recovery achieved at the Uppsala Vatten och Avfall biogas plant.
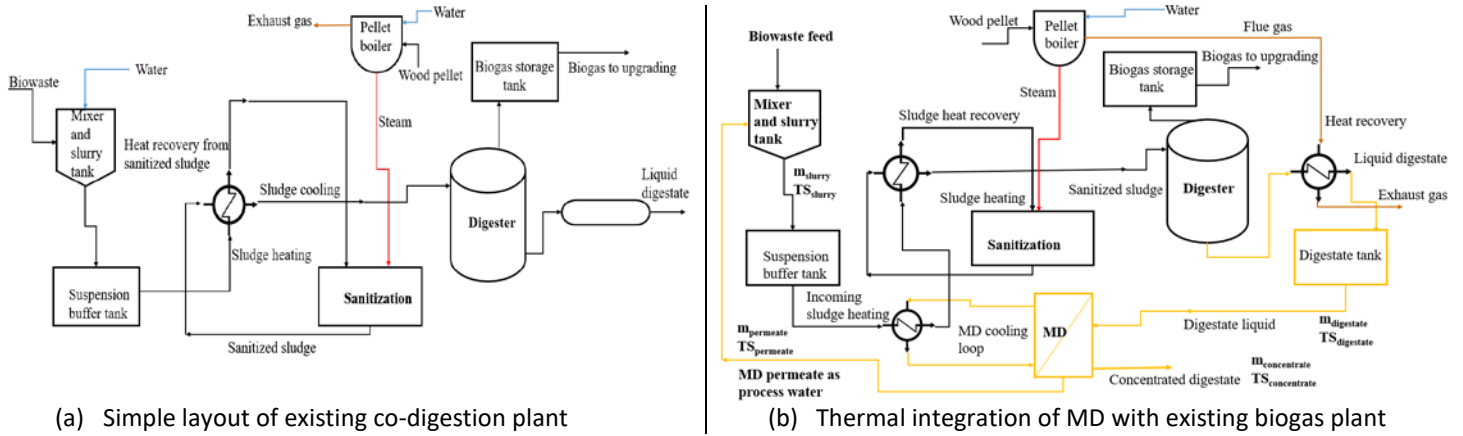
(a) Simple layout of existing co-digestion plant	(b) Thermal integration of MD with existing biogas plant

Fig. 1. Simplified schematic diagram of existing (a) and proposed (b) layout of co-digestion plants.

2.3 Thermal integration of AD plant with membrane distillation

The proposed integrated system is shown in Fig 1(b). The integrated approach was intended to improve the thermal energy efficiency and the water balance at the plant by:

1) Recover flue gas heat from the pellet boiler via a heat exchanger to heat the digestate from 52 °C to 65 °C before MD.

2) Recover waste heat from the MD cooling channel via a heat exchanger to preheat the substrate suspension

3) Replace the substrate dilution tap water with permeate from the MD unit, which will have a relatively higher temperature than the tap water.

The thermal characteristics of the MD system (sink for waste heat) and the prospect of waste heat energy recovery were assessed by the temperature differences for the main streams of the systems [4], using the following equation:

$$T_{heat\ recovery,min} > T_{waste\ heat} > T_{sink} + T_{min} \qquad (1)$$

where $T_{heat\ recovery,min}$ is the lowest temperature necessary in the effluent digestate for waste heat utilization (to heat the incoming feed to MD), $T_{waste\ heat}$ is the temperature of the available waste heat rejected from the effluent digestate system, T_{sink} is the temperature of the MD feed system, and T_{min} is the lowest temperature difference required for heat transfer between the incoming digestate and the waste heat line.

In the present study, the two-stage cascaded MD module arrangement presented elsewhere [9,10] was considered, with 10 cassettes per module (two or more cassettes are placed in parallel), with total thermal energy input, feed digestate, and coolant flow rates adjusted proportionally. For a specified temperature difference across the MD module, the total number of cassettes was estimated by the amount of available thermal energy. The feed digestate was considered to be concentrated two-fold by MD, i.e. mass of the digestate was reduced to 50% after the MD treatment.

The capacity method was used for estimating the full-scale costs of the integrated system. The costs estimation methodology has been used from a previous study [4]. The economic assessment of the anticipated large-scale MD system was mainly based on the prices estimates supplied by Xzero AB (subsidiary company of Scarab Development AB) [11], and the economics of pilot-scale MD plants used in previous studies [4,8]. The cost and benefit changes due to thermal integration of MD included waste heat utilization, replacing tap water with MD permeate, and concentration of nutrients from the digestate (reducing the volume with 50 %).

2.4 Results

The heat analysis showed that most of the available low-grade waste heat (about 90%) can be recovered by effective integration of the MD process (Fig 1(b)). The recovered waste heat contribution to the MD process was about 100% of total thermal energy demand, which shows the importance of thermal integration and waste heat recovery. Thermal integration of the biogas plant-MD not only increased waste heat utilization, but also reduced internal energy consumption (1825 kWh/day) through the thermal integration and overall plant cooling duty. However, the total heat energy demand for MD was still 5500 kWh/day, and pumping power (about 200 kWh/day) for feed digestate circulation. A specific thermal energy demand (STED) value of 60-140 kWh/m³ can be achieved by integrated MD system with heat recovery from the MD cooling side, depending on

digestate flow rate, feed digestate inlet temperature, coolant inlet temperature, and flow rate. If no heat recovery is made from the MD cooling side, STED is in the order of ~950-1200 kWh/m^3 at a feed digestate inlet temperature of about 65°C. However, the average STED value was considered to be 100 kWh/m^3 in the present thermo-economic analysis. The maximum capacity of feed digestate flow for the MD was 2.7 m^3/h/module and the total number of modules was 233. The total permeate water production was about 3.5 L/m^{2}h (in total 55 m^3/day) in full-scale operation and the total thermal energy demand was about 5.5 MWh/day.

The cost analysis calculation indicated that the total investment costs for a full-scale MD installation were about 443,000 €, with the MD modules (about 31% of total capital investment) and heat supply line (about 23% of total investment) accounted for the main proportion of capital investment, followed by other costs. The analysis showed that lower operating and maintenance costs (40 t€/year) are achieved in the integrated system than in the system without heat recovery, as waste heat is utilized in the complete operation. Thus waste heat recovery could affect the operating costs significantly. Waste heat recovery from effluent digestate and boiler flue gas could save 125,000 € thermal energy cost yearly, which represents about 3 fold more than the total operating and maintenance costs of the integrated system.

In the present case study, the unit cost of MD permeate water for a system with heat recovery was 3.6 €/m^3 at a digestate feed temperature of 65°C. This unit cost of permeate water (process water) production by MD was lower than the 4.7 €/m^3 reported by Woldemariam et al. [9] for a pilot-scale test rig deployed at Hammarby Sjöstadsverk, Stockholm (MD feed was pharmaceutical contaminants sewage water). But the cost of permeate 2.2 €/m^3 reported by Kullab and Martin [10] for a test rig deployed at Idbäcken Cogeneration Facility, Nyköping, Sweden (MD feed was flue gas condensate), which is lower than this study, probably the lower cost must be due to lower specific thermal energy demand, and operation and maintenance costs because the characteristics of the treated liquid is different.

The economic analysis indicate that thermal integration of an AD biogas plant and MD can be feasible in terms of cost and revenues. A net annual costs reduction of 150,000 € could be achieved for the Uppsala Vatten och Avfall biogas plant through thermal integration of a MD unit.

2.5 Discussion

Thermal integration relies mainly on the operating circumstances of the biogas plant, especially the substrate/sludge sanitization process and ambient conditions. In long-run operation of the integrated system, it is very important to bear in mind that the amount of digestate which needs to be distilled by MD must be determined in combination with a suitable TS content for the digester process water, as well as the investment and operating costs of the designated integration system. In this case study, the most common investment cost models, which are simplified approaches that rely on actual experiences from former projects and the principle of economies of scale, were considered. The digestate from a biogas plant is a very challenging feed due to particles and high TS concentration and the operating and maintenance costs for handling the sludge are higher than for other feeds to MD. Ultimately, the aim should be to optimize an integrated system that is of appropriate size to maintain the digestate TS content at an optimum level. For further improvement of waste heat recovery by the integrated biogas-MD system, thermal energy optimization approaches can be applied. By optimizing the assembly techniques for MD modules, the overall investment costs for water production could possibly be decreased. The net thermal energy demand could be optimized with appropriate MD-biogas plant integration, which could lead to a lower specific thermal energy demand and ultimately decrease the MD water production cost. In the laboratory experiments with MD, the membrane surface was cleaned with H$_2$SO4 acid, with decent outcomes [1]. However, experience on cleaning MD membranes after treatment of real digestate process water is limited, and more work is needed to demonstrate effective cleaning for longer period operation. Moreover, long-term studies are needed to evaluate the impact of membrane fouling in continuous operation.

2.6 Conclusions

This study showed that a thermophilic AD process based on solid organic waste can be effectively integrated with thermal energy-driven MD for treatment of the digestate, in order to recycle process water, recover low-grade waste heat, and concentrate the nutrients for bio-fertilizer use with a factor two. The main conclusions are:

- The recovered waste heat from the effluent digestate and boiler flue gas (about 7325 kWh/day) contributed the total thermal energy demand of MD and

furthermore it could save 19% of pellet boiler energy by heating incoming slurry.

- The MD product water permeate was 3.5 L/(m^{2}h) at 65°C digestate inlet temperature.

- The specific thermal energy demand for the MD system was assessed to 100 kWh/m^3 of product water when heat was recovered from the cooling side of the MD system.

- Cost assessments showed that the unit cost of MD permeate water was 3.6 €/m^3 at a digestate feed temperature of 65°C.

- The economic assessment also indicated that the revenues could exceed the total costs, mainly due to the MD can be operated only on recovered heat.

- There is a need for long-term continuous studies on performance of the membranes to determine the impact of fouling and the membrane lifetime.

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