Energy Conversion and Management 102 (2015) 131–139

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Investigation of thermal integration between biogas production and upgrading ☆

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ARTICLE INFO

Article history:
Available online 30 March 2015

Keywords:
Anaerobic digestion (AD) biogas production
Biogas upgrading
Amine based chemical absorption
Thermal integration
Energy saving
Cost analysis

ABSTRACT

Thermal integration of anaerobic digestion (AD) biogas production with amine-based chemical absorption biogas upgrading has been studied to improve the overall efficiency of the intergraded system. The thermal characteristics have been investigated for industrial AD raw biogas production and amine-based chemical absorption biogas upgrading. The investigation provides a basic understanding for the possibilities of energy saving through thermal integration. The thermal integration is carried out through well-defined cases based on the thermal characteristics of the biogas production and the biogas upgrading. The following factors are taken into account in the case study: thermal conditions of sub-systems, material and energy balances, cost issues and main benefits. The potential of heat recovery has been evaluated to utilise the waste heat from amine-based upgrading process for the use in the AD biogas production. The results show that the thermal integration has positive effects on improving the overall energy efficiency of the integrated biogas plant. Cost analysis shows that the thermal integration is economically feasible.

1. Introduction

Biogas as a clean and CO_2-nutral energy carrier can make an important contribution to increase renewable energy's share in energy supply. One key driving force for biogas production is the reduction of greenhouse gas (GHG) emissions by the substitution of fossil fuels. Biogas is commonly produced from anaerobic digestion (AD) of various digestible organic substrates and wastes or from landfills. For the AD systems, the biogas production and gas composition highly depend on the feedstock (digestible substrates) and the operation conditions [1]. Four main stages are normally involved in the AD process including hydrolysis, fermentation, anaerobic oxidation and methanogenesis. Raw biogas mainly consists of methane, carbon dioxide, moisture, and minor components such as H_2S, H_2, NH_3, O_2, N_2 [17]. Utilisation of biogas as energy resources is most common applications. Removal of some of contaminates are generally required depending on specific applications. Biogas upgrading is to separate CO_2 from raw biogas in order to increase the heating value of biogas. Biogas upgrading developments in Sweden and Germany represent the state-of-art technologies for biogas utilisations for vehicle fuel and injection to NG grid [3]. In recent years more chemical scrubbing biogas upgrading plants have been operated in Germany and Sweden [3], which may reflect the current trend in biogas upgrading technologies to achieve high purity bio-methane and very low methane emissions [15,13]. According to recent IEA Bioenergy report [22] for IEA bioenergy member countries (19 nations), the total number of biogas plants are more than 13,000 and the biogas upgrading plants are more than 260 that represent of the bio-methane production capacity is larger than 100,000 Nm^3/h.

Energy conversion efficacy is the most important issue for energy production processes, which can significantly enhanced by using better energy recovery and thermal integration cross different processes or plants in an industrial area [21]. Both the AD biogas production and biogas upgrading based on chemical scrubbing require additional thermal energy in their operation. In a typical AD biogas plant, approximately 10–15% of the produced energy is internally used for heating substrates [20]. Whereas, in the amine-based chemical scrubbing process, the thermal regeneration of CO_2 rich solvent to release captured CO_2 consumes a large

☆ This article is based on a four-page proceedings paper in Energy Procedia Volume 61 (2015). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal.

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http://dx.doi.org/10.1016/j.enconman.2015.03.023
0196-8904/

amount of heat and simultaneously produce significant amount of waste heat that is normally rejected into the cooling system [23]. This means there may be a potential to utilise the waste heat rejected from the biogas upgrading in the AD biogas production. The potential heat energy saving can generally be achieved through: internal energy optimisation in a process and thermal integration cross different process to enhance waste heat recovery [16]. The latter one can be the most cost-effective solution for existing industrial systems to improve the utilisation of waste heat and overall energy efficiency. However, the biogas production and biogas upgrading are normally separately operated, and there is little information and practice regarding the thermal integration.

Meanwhile, water as one of main components of raw biogas and the main substance in AD process, its effective-utilisation and balance in both biogas production and biogas upgrading are important for the whole production chain. However, very few attentions have been paid for this aspect in most commercial applications.

In this study, the thermal integration of AD biogas production with amine-based chemical scrubbing biogas upgrading was investigated with focus on the potentials to increase overall thermal energy efficiency and water recycle. Cost analysis was also performed for typical scenarios of the thermal integration in order to get a view of economic impacts of the thermal integration.

2. Materials and methods

2.1. Methodology

This study was performed by the investigating existing industrial-scale biogas production and upgrading plants in order to characterise the major thermal features of the two systems. A survey was carried out for two typical AD biogas plants. The main features of the biogas plants are shown in Table 1. The main purpose of the industrial investigation was to identify the basic characteristics of commercial biogas production system, in terms of feedstock, energy conversion, main material and energy balances, important subsystems, main stream parameters, and general operation conditions. The investigation results provide the input data for the calculations of the thermal integration between an AD biogas production system (as described in Section 2.2) and an amine-based chemical scrubbing biogas upgrading system (as described in Section 2.3).

As mentioned in the introduction section, the amine-based chemical absorption biogas upgrading may represent the current trend in industrial-scale biogas upgrading. In this study, a biogas upgrading system was defined based on commercial biogas upgrading plant using amine (MEA) as solvent for CO_2 removal from raw biogas. The amine-based chemical absorption biogas upgrading system was mainly defined by its thermal characteristics as described in the following Section 2.3.

Table 1
Main features of two investigated biogas production plants.

Parameters	Unit	Biogas production plant	
		A	B
Biogas production	GW h/y	15.4	30.0
Feedstock			
Household kitchen waste	ton/y	14,000	4000
Liquid sludge waste	ton/y	4000	5000
Waste water sludge	ton/y		430,000
Ley crop	ton/y	5000	
Digester			
Digester volume	m^3	4000	11,400
Dry matter after dilution	%	8	8
Solid digestate (25–30% DM)	kg/h	6500	3800
Liquid digestate (2–3% DM)	kg/h	16,500	5700

Thermal integration was taken into account for the thermal characteristics of the integrated system. Calculations of thermal integration were conducted for typical scenarios, which are defined by the normal operation conditions of both biogas production and upgrading processes. The principle of heat and mass balance was applied to the thermal integration calculations for the pre-defined scenarios.

As one of the thermal integration targets [19], general cost analysis was performed for the integrated system and compared with the original separated ones in order to evaluate if the thermal integration is a cost-effective option.

2.2. Biogas production system

The biogas production system was defined based on the industrial survey for two commercial AD biogas plants (as described in Section 2.1. Fig. 1 shows a simplified flow diagram of the biogas production system. The bio-wastes (1) are feed into the turbo mixer. The process water (2) is added into the mixer to make a suspension slurry which is pumped into a suspension buffer tank (3). Pathogenic micro-organisms are removed in the sanitation procedure by heating the suspension up to 70 °C for one hour or 55 °C for 10 h (5–6). After the sanitation step, the suspension is cooled down (6–7) to a temperature (e.g. 37–41 °C) that is required by the mesophilic process in the digester. The raw biogas generated in the digester (8) is sent into biogas storage tank for biogas upgrading or internal use. The main thermal energy consumption in the AD biogas production is heating of the suspension in the sanitation stage and the heat loss to surrounding. The internal thermal energy use may account for 10–15% of the energy yield of the biogas production if the raw biogas is used for the internal heat demand. It has to be noticed that relatively low temperature heat is required for the thermal demand. Therefore it is possible to use the waste heat from the biogas upgrading through thermal integration. The digestate is separated into solid digestate by dewatering unit, and the liquid fraction is sent to the water tank, which can be recirculated into the turbo mixer.

2.3. Biogas upgrading system

A typical amine-based chemical absorption system has been defined for biogas upgrading as shown in Fig. 2. After pre-gas cleaning to remove or control contaminants (e.g. H_2S), the raw biogas is sent to the absorption column, in which the CO_2 contained in the raw biogas is captured by the amine-based solvent (e.g. MEA) under relative low temperature (40–50 °C). The methane concentration in the biogas can be raised up to 98% (as dry basis) after the chemical absorption column. The CO_2 rich solvent is then sent to stripper, in which the CO_2 rich solvent is thermally regenerated under relatively high temperature (100–120 °C). As the CO_2 absorption by amine is exothermal, the CO_2 lean solvent has to be cooled before being sent back to the absorption column in order to achieve a high absorption efficiency. The CO_2 system released from the stripper also needs to be cooled down in order to reduce the solvent evaporation and to condense the moisture. The two cooling processes could provide the heat needed by the AD process.

2.4. Thermal integration

Although pinch point analysis [5] is the most widely used for internal thermal integration to improve the thermal efficiency of a process, the currently developed Total Site Analysis [21] with the target and design principle [19] enables to determine the