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Energy Saving for Biogas Production and Upgrading - Thermal Integration

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Abstract

Thermal integration of anaerobic digestion (AD) biogas production with amine based biogas upgrading has been studied for improving the overall thermal efficiencies of the two systems. The thermal characteristics have been investigated for typical AD raw biogas generation and MEA absorption biogas upgrading. The investigation provides a basic understanding of energy saving for both industrial scale biogas production and upgrading processes. The thermal integration is carried out based on the thermal characteristics of the two systems by well-defined case studies, which take the following factors into account such as important thermal conditions of sub-systems, material and energy balances, the efficiencies of heat exchange and heat transfer, necessary integration optimization and ambient conditions. The results show that the thermal integration is achievable with very positive effects for overall energy efficiency and water usage.

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1. Introduction

Anaerobic digestion (AD) of organic wastes is an environmental friendly process for biofuel production, in which the biodegradation of organic matter occurs in the absence of dissolved oxygen. In the last two decades, the technology development has gained great attention on upgrading of raw biogas through various processes to achieve high quality biogas. The upgraded biogas contains over 98%

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methane, which can be used for vehicle fuel or injected to the natural gas grid. In most biogas plants, approximately 10 to 15% of produced energy is internally used for heating substrates [1]. On the other hand, some waste heat is available in some of the biogas upgrading processes [2]. For example, in the amine based chemical absorption, the regenerated solvent needs to be cooled down before being recirculated back to the absorber so as to achieve high absorption efficiency, and the separated CO₂ stream also needs to be cooled down before release. Furthermore, the substrate should be heated to certain temperatures in AD system especially in the digester and sanitation processes. This means there is some waste heat available in the biogas upgrading system, which can be used for the heat demand for the AD process. A thermal integration of the AD system with the amine based biogas upgrading system could improve the overall thermal efficiency of the two systems. Thermal integration of biogas and CHP were investigated to utilize heat from CHP for AD [3, 4]. However, there is lack of study of thermal integration of biogas process and upgrading systems. This paper studies the thermal integration between an amine based upgrading system operated at 115 °C (stripper) and an AD system with two substrate sanitation methods (keeping the temperature at 70°C for one hour or 55°C for ten hours).

2. Methodology

Basic features of industrial biogas production has been studied in terms of major bio-reactor systems, feed stocks, general procedure of industrial biogas production, and efficiency of energy conversion. Typical biogas production system has been defined for this study. Material and energy balance has been analysed for the selected biogas production plant.

Current biogas upgrading technologies have been reviewed with specific focus on industrial applications. Amine based biogas upgrading system has been considered in this study due to the potential of waste heat available for further utilisation. A typical industrial amine-based biogas upgrading system has been evaluated and used for the thermal integration with biogas production system.

Several industrial biogas production and upgrading plants have been visited and studied in order to get practical data and information in real industrial processes, and have insight into the industrial systems.

Finally an integrated system has been established between the biogas production and the biogas upgrading for modelling of thermal integration. Several cases have been defined based on the potential options of the thermal integration. General considerations for thermal integration have been taken into account in these case studies, which including important thermal conditions of sub-systems, material and energy balances, heat exchange and heat transfer efficiency, necessary integration optimization and ambient conditions.

3. Material and Heat Balance of Biogas Production System

The typical biogas process mainly consists of anaerobic digester, sanitation units, suspension tank and substrate mixer as shown in Fig. 1 (left). After pre-treatment, substrates are fed into the anaerobic digester where the material remains for a suitable retention time under controlled conditions. The substrate slurry in the digester is heated to the desired temperature and is mixed by mechanic stirrer or gas injection. The temperature is an important factor that determines the rate of digestion. Most of anaerobic digesters are operated in the mesophilic temperature range (25–45°C) [5], which is used in this study.

The material balance is based on that total feedstock equals to total digestate and biogas. In biogas process, it is critical to achieve a water balance, which involves the water contained in substrate, generated in chemical reaction and lost with digestate as well as recalculated make-up water, the water balance is described as,

\[ m_{\text{water, feedstock}}^\circ + m_{\text{water makeup}}^\circ + m_{\text{reaction water}}^\circ - (m_{\text{water, biogas}}^\circ + m_{\text{water, solid digestate}}^\circ + m_{\text{water, liquid digestate}}^\circ) = 0 \]  \( (1) \)
Where \( m_i \) is the mass flow for specific component or stream \( i \) (kg/hr)

![Schematic flow chart of original and integrated anaerobic digestion and upgrading system](image)

Fig. 1. Schematic flow chart of original and integrated anaerobic digestion and upgrading system

The digestion process requires heat for keeping constant temperature, for substrate sanitation and for compensation of heat losses from tanks and pipe system. The heat balance within defined system boundary as in Fig. 1 can be expressed as,

\[
Q_{\text{heating}} + \sum Q_{\text{stream,in}} + Q_{\text{bioreaction}} - \sum Q_{\text{stream,out}} - Q_{\text{loss}} = 0
\]  
(2)

Where \( Q_{\text{heating}} \) is the digestion required heat (MJ/day), \( Q_{\text{stream}} \) the heat from various streams (MJ/day), \( Q_{\text{bioreaction}} \) the digestion reaction heat (MJ/day), \( Q_{\text{loss}} \) the process heat loss.

The stream enthalpies related to the mass transfer is a function of mass, heat capacity and temperature difference between stream and reference temperature.

\[
\Delta H_i = m_i \cdot C_{pi} \left( T_i - T_{ref} \right) \]  
(3)

where \( \Delta H_i \) is the enthalpy of stream \( i \), \( C_{pi} \) the specific heat of stream \( i \), (J kg\(^{-1}\) K\(^{-1}\)), and \( T_i \) the temperature of stream \( i \) (K).

The enthalpy of reactions in anaerobic degradation of organic materials depends on the composition of the biomass. The anaerobic degradation of fatty acids and proteins is endothermic; while the degradation of carbohydrates is exothermic reactions that release heat energy to facilitate the digestion process. The degradation enthalpies of various biomass substances have been well investigated and calculated by Gallert et al [6], Lindorfer et al [7] and Oh et al [8].

Case studies for both winter and summer operations have been made for two biogas plants with raw gas production capacities of 15.4 GWh/year and 30 GWh/year respectively. The anaerobic digesters in these two plants are operated at 41°C and 37°C respectively. Based on the principle of heat and mass
balance, energy flows of each stream are calculated and shown in Table 1. The heat requirements of the
digestion processes are given in Table 2. As shown in Table 2, more heat is required for the substrate
sanitation operated at 70°C during winter in comparison with summer. In addition to the heat
requirement, process make-up water is also required to compensate the water lost with digestate to keep
the required constant substrate consistency.

Table 1. Energy flows and process streams of biogas plants using 55°C 10 hours sanitation method

<table>
<thead>
<tr>
<th>Stream</th>
<th>Description</th>
<th>Cp (kJkg⁻¹K⁻¹)</th>
<th>15.4 (GWh/y) biogas plant Winter (MJday⁻¹)</th>
<th>15.4 (GWh/y) biogas plant Summer (MJday⁻¹)</th>
<th>30 (GWh/y) biogas plant Winter (MJday⁻¹)</th>
<th>30 (GWh/y) biogas plant Summer (MJday⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feed stock</td>
<td>3.18</td>
<td>956</td>
<td>4396</td>
<td>2085</td>
<td>9591</td>
</tr>
<tr>
<td>2</td>
<td>Water make up 1</td>
<td>4.19</td>
<td>776</td>
<td>3572</td>
<td>2418</td>
<td>11125</td>
</tr>
<tr>
<td>3</td>
<td>Influent to suspension tank</td>
<td>3.92</td>
<td>19689</td>
<td>27245</td>
<td>42298</td>
<td>59498</td>
</tr>
<tr>
<td>4</td>
<td>Influent to heat exchanger (cold side)</td>
<td>3.92</td>
<td>19466</td>
<td>27119</td>
<td>42075</td>
<td>59372</td>
</tr>
<tr>
<td>5</td>
<td>Influent to sanitation</td>
<td>3.92</td>
<td>30712</td>
<td>38365</td>
<td>66611</td>
<td>83909</td>
</tr>
<tr>
<td>6</td>
<td>Influent to heat exchanger (hot side)</td>
<td>3.92</td>
<td>48550</td>
<td>48550</td>
<td>105928</td>
<td>105928</td>
</tr>
<tr>
<td>7</td>
<td>Influent to digester</td>
<td>3.92</td>
<td>36192</td>
<td>36192</td>
<td>78964</td>
<td>78964</td>
</tr>
<tr>
<td>8</td>
<td>Biogas</td>
<td>1.53</td>
<td>4734</td>
<td>4734</td>
<td>11157</td>
<td>11157</td>
</tr>
<tr>
<td>9</td>
<td>Water make up 2</td>
<td>4.19</td>
<td>6891</td>
<td>8447</td>
<td>15870</td>
<td>16285</td>
</tr>
<tr>
<td>10</td>
<td>Effluent from digester</td>
<td>4.02</td>
<td>43812</td>
<td>43812</td>
<td>94785</td>
<td>94785</td>
</tr>
<tr>
<td>11</td>
<td>Influent to the water tank</td>
<td>4.09</td>
<td>33885</td>
<td>34211</td>
<td>77097</td>
<td>77097</td>
</tr>
<tr>
<td>12</td>
<td>Solid digestate</td>
<td>3.28</td>
<td>5445</td>
<td>5497</td>
<td>11701</td>
<td>11701</td>
</tr>
<tr>
<td>13</td>
<td>Water make up circulation</td>
<td>4.19</td>
<td>24831</td>
<td>26658</td>
<td>53628</td>
<td>55030</td>
</tr>
<tr>
<td>14</td>
<td>Liquid digestate</td>
<td>4.09</td>
<td>6047</td>
<td>6492</td>
<td>20463</td>
<td>20998</td>
</tr>
<tr>
<td>15</td>
<td>Water make up circulation to the feed stock</td>
<td>4.19</td>
<td>17957</td>
<td>19278</td>
<td>37794</td>
<td>38782</td>
</tr>
</tbody>
</table>

4. Thermal Integration

An integrated system is proposed and shown in Fig. 1 (right). Waste heat recovered from upgrading
system is reused in an anaerobic digester and sanitation unit. As consequences, internal biogas
consumption for substrate heating is reduced; therefore the net biogas productivity could be increased.
Since make-up water is needed to dilute the substrate slurry and condensate is generated during the drying
of biogas in upgrading processes. The integration could achieve a better overall water balance, and the
cooling water from both amine cooler and gas condenser can be used as processing water for the AD
system, which simultaneously provides the heat required by the digester and preheating of substrates.
Overall water usage could further be reduced through using the condensed water from upgraded biogas
and separated CO₂ for make-up water. The cooling water is circulated through a circulation pump. For the
case of sanitation temperature at 70°C for one hour, a small amount of additional high temperature heat is
needed externally. This heat can be supplied through a burner or local district heating system. For the case
of sanitation temperature at 50°C for ten hours, no external heat is needed. In addition to the heat
recovery, cooling duty of the upgrading process is also reduced due to process water from biogas process
is used as cooling source for amine cooler and gas condenser. There is a significant difference about the
heat requirement between summer and winter as shown in Table 2 for the digestion process. It results in
variation of waste heat recovery and biogas productivity in summer and winter. Based on two biogas
plant case studies, 64% to 85% of waste heat from the amine based upgrading can be recovered in
summer and 100% waste heat can be recovered in winter. Because of reduction of internal raw biogas
consumption, the raw biogas productivity is increased from 5.3% to 10% in summer and 11.3% to 17.4%
in winter. The sanitation temperature at 55°C for ten hours gives higher raw biogas productivity.
However, the one at 70°C for one hour results in better waste heat recovery from the upgrading system.
Table 2. Heat recovery and raw biogas productivity by thermal integration in summer and winter

<table>
<thead>
<tr>
<th>Description</th>
<th>15.4 (GWh/y) biogas plant</th>
<th>30 (GWh/y) biogas plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Winter 70 °C for 1 hr</td>
<td>Winter 70 °C for 1 hr</td>
</tr>
<tr>
<td>Biogas production (Nm3/hr)</td>
<td>247</td>
<td>265</td>
</tr>
<tr>
<td>Biogas after integration (Nm3/hr)</td>
<td>275</td>
<td>279</td>
</tr>
<tr>
<td>Heat from upgrading (MJ/day)</td>
<td>18270</td>
<td>19654</td>
</tr>
<tr>
<td>Biogas process heat load (MJ/day)</td>
<td>26214</td>
<td>16642</td>
</tr>
<tr>
<td>Heat recovery (%)</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>Productivity increase (%)</td>
<td>11.3</td>
<td>5.3</td>
</tr>
</tbody>
</table>

5. Conclusions

The case studies show that the AD biogas production can be thermal effectively integrated with amine-based biogas upgrading. The performance of the thermal integration mainly depends on the operation conditions of the AD processes especially on the substrate sanitation process and ambient conditions. For typical AD biogas production and amine absorption biogas upgrading, the thermal integration could recovery 64% to near 100% of the waste heat from the biogas upgrading system, and could be reused in the AD system, which are corresponding to increasing of 5.3% to 17.4% of net raw biogas production. The waste heat recovery from the biogas upgrading system will also significantly reduce the cooling duty required for the biogas upgrading system. The external cooling may not be necessary for the upgrading system in winter, and may be reduced to around 35% even in summer. In addition to the effective thermal integration, the system could be further integrated for water recovery from the upgrading system and reusing in the AD system without significant additional efforts.

References


Biography

Xiaojing Zhang received the M.S. degree in environmental engineering from China in 1983 and Ph.D. degree in energy technology in 1997 at KTH, Stockholm. He joined ABB in 1998 and his career included 15 years of industrial experiences in process industry. Dr. Zhang is currently a principal scientist at ABB AB, Corporate Research, Sweden.