Process control for intensifying biogas production
in anaerobic fermentation

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Main degradation pathways of AD

- Hydrolysis
- Acidogenesis
- Acetogenesis and dehydrogenation
- Methanogenesis

Organic polymers → Soluble organic monomers → Fermentation intermediates

- Acetate
- H₂
- CO₂
- CH₄

CH₄, CO₂:

Modified from McCarty, 1982; Gujer and Zehnder, 1983.
Biogas production occurs spontaneously in nature

- Marshes
- Rubbish dumps
- Cow’s digestive tract
- Insect guts
Biogas production in engineered devices

Energy crops

Wastewater

Solid waste

Industrial AD bioreactor

Landfill

Biogas

Treated wastewater

Compost

1 m³ of Biogas (70% CH₄ + 30% CO₂)
= 0.66 liter diesel fuel
= 0.75 liter petrol
= 0.25 m³ propane
= 0.20 m³ butane
= 0.85 kg coal
### History of AD as a process for practical use

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920</td>
<td>Sanitation concerns</td>
</tr>
<tr>
<td>1973</td>
<td>Closed-tank reactor with heating and mixing</td>
</tr>
<tr>
<td>1985</td>
<td>Rapid and worldwide development of simple AD</td>
</tr>
<tr>
<td>1996</td>
<td>Energy + waste handling + pathogen reduction</td>
</tr>
</tbody>
</table>

#### Pioneer work by Buswell in microbiology
- Waste stabilization using AD
- Biogas was occasional used for heat
- China began using biogas for heat, light and cooking

#### Fueling street lamps in UK
- Biogas was used for street lighting in the UK

#### Energy crisis (1973, 1979)
- Made biogas as an energy source

#### Limited research in AD
- Millions of small digesters were constructed in China, India.

#### Non-energy benefits of AD were recognized - sludge and odor reduction,
- Small-scale energy and sanitation systems were promoted in Asia

#### Rapid and worldwide development of simple AD
- Fram-based & centralized digesters were developed in Europe

#### Being a part of integrated recovery system for sustainable development
- Pioneer work of ICA for high rate AD

#### ICA+D in AD
- AD + FC

**Timeline:**
- 1920
- 1973
- 1985
- 1996

**Key Points:**
- Decomposition of organic toxic and hazardous compound
- Municipal solid waste handling
- Pioneer work of ICA for high rate AD

**Notes:**
- Biogas was occasionally used for heat.
- Sanitation concerns.
- Fueling street lamps in the UK.
- Rapid and worldwide development of simple AD.
- Non-energy benefits of AD were recognized - sludge and odor reduction.
Characteristic of AD

**Advantages**

- Renewable energy
- Waste handling
- Nutrients recycle
- Sludge reduction
- Pathogen control
- Sustainable development

**Disadvantages**

- A multi-step process
- Low cellular yield
- Methane production
- Low energy yield from acetogenic step

- Long retention time
- Large reactor volume
- Unstable process
- Sensitive to environmental changes
- Risk of system overload
Problem-solving strategies

Suitable reactor configuration
- UASB, anaerobic filter (packed-bed reactor), suspended bed reactor, baffled reactor, rotating disk, etc. → Intensify the process by maintaining a high density of microorganisms.
- Two-stage or multi-stage design → To achieve a separate optimization in different stages
- Properly mixing feedstock from various sources that characterize in enrichment of different nutrients → optimization of C/N ratio

Disadvantages
- Long retention time
- Large reactor volume
- Unstable process
- Sensitive to environmental changes
- Risk of system overload

Microbiological study
- Close study of microbial consortia and anaerobic ecosystem → better understanding of complex degradation and gain process knowledge

Optimization of feedstock
- Enhanced process monitoring and control
- Often being neglected in full-scale plants

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Full scale operation

- Poor information flow from the process (often only flow rate, temp, etc)
- Process operation in “black box” mode, relies on operator's experience
- A large safety margin for a reliable operation
- Control variables are uncoupled from the dynamic state of process
Problem-solving strategies

Disadvantages

- Long retention time
- Large reactor volume
- Unstable process
- Sensitive to environmental changes
- Risk of system overload

Intensify the process by maintaining a high density of microorganisms

Operate bioreactors far below their max. capacity

Enhanced process monitoring and control - ICA

Smaller reactor volume
- Short retention time

Ensure reliable and stable operation
- Prevent the process from failure
- Allow the degradation and biogas production at a higher specific rate

Combine a suitable bioreactor design with enhanced process monitoring and control technologies

Operate bioreactors far below their max. capacity
A cascade control structure and a rule-based system with extremum-seeking feature.
Rule-based system with extremum-seeking feature

- To add a small increment in the feed rate over a short period of time, then to closely monitor and analyze the process response.
- To test the upper limit of the process treatment capacity and maximize the reactor performance.

Graph showing:
- Gas flow rate (L gas (l reactor)·day⁻¹)
- Time (hour)

Legend:
- GasFlow (setpoint)
- GasFlow (monitored)
AD reactor can be operated close to its maximum capacity

- Develop a fast reacting control system based on existing simple sensors
- Schedule control tasks according to different time scales
- Protect process from overload
- Reject disturbances

An anaerobic bioreactor can be operated close to the maximum capacity, still having enough safety margins for reliable operation.
Only 4 days were needed to increase the OLR from 0 to 27 g COD·l\textsubscript{reactor}⁻¹·d⁻¹.
Short term under- & overload
Long term underload
Long term overload & shock load
Temperature variation

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Process control – stability problem at high load

![Graph showing gas flow rate and organic degraded over time]

- Gas flow rate (Lgas·Lreactor⁻¹·day⁻¹)
- Organic degraded (g COD·Lreactor⁻¹·day⁻¹)
- Time (hour)
Selection of parameter for variable gain

\[ \Delta pH = pH_{\text{setpoint}} - pH_{\text{reactor}} \]
Rule-based model for variable gain control – estimate the process gain via observation of the ΔpH (pH_{setpoint} - pH_{reactor})
State machine representation of the rule-based model for variable gain control in the inner feedback loop. Each circle represents an individual state. The arrow with fine line indicates the direction of state shift.
Pathways of state shifting

<table>
<thead>
<tr>
<th>No.</th>
<th>State shifting</th>
<th>Shifting condition</th>
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</tr>
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<tbody>
<tr>
<td>1</td>
<td>S1→S4</td>
<td>ΔpH &gt; C</td>
<td>14</td>
<td>S5→S4</td>
<td>ΔpH &gt; C</td>
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<tr>
<td>2</td>
<td>S1→S5</td>
<td>ΔpH &lt; -B</td>
<td>15</td>
<td>S5→S8</td>
<td>being in S5 more than 3 h</td>
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<tr>
<td>3</td>
<td>S2→S3</td>
<td>-B ≤ ΔpH &lt; -A or A &lt; ΔpH ≤ C</td>
<td>16</td>
<td>S6→S4</td>
<td>ΔpH &gt; C</td>
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<tr>
<td>4</td>
<td>S2→S4</td>
<td>ΔpH &gt; C</td>
<td>17</td>
<td>S6→S5</td>
<td>ΔpH &lt; -B</td>
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<tr>
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<td>S2→S5</td>
<td>ΔpH &lt; -B</td>
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<td>S6→S7</td>
<td>-B ≤ ΔpH &lt; 0</td>
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<tr>
<td>6</td>
<td>S3→S2</td>
<td>-A ≤ ΔpH ≤ A</td>
<td>19</td>
<td>S7→S2</td>
<td>-A ≤ ΔpH ≤ A</td>
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<td>ΔpH &gt; C</td>
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<tr>
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<td>S4→S5</td>
<td>ΔpH &lt; -B</td>
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<td>ΔpH &lt; -B</td>
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<tr>
<td>10</td>
<td>S4→S6</td>
<td>0 ≤ ΔpH ≤ C</td>
<td>23</td>
<td>S8→S2</td>
<td>-A ≤ ΔpH ≤ A</td>
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<tr>
<td>11</td>
<td>S4→S7</td>
<td>-B ≤ ΔpH &lt; 0</td>
<td>24</td>
<td>S8→S3</td>
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<tr>
<td>12</td>
<td>S5→S2</td>
<td>-A ≤ ΔpH ≤ A</td>
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State dependent variable gain control
Conclusions

- Steer the process for a fast start-up according to the state dynamic
- Considerable improvement of the process stability at high-rate operation
- Improved performance is achieved by varying the proportional gain of inner feedback loop according to the process dynamic
- Controller and control structure are still quite simple allow to be easily implemented
- Further improvement of operational stability is possible by scheduling the pushing authority of extremum-seeking control.