AD PRE-TREATMENT – PULSED ELECTRIC FIELDS IN COMPARISON TO OTHER PRE-TREATMENT METHODS

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Abstrac

Biogas production via Anaerobic Digestion (AD) is primarily limited by the rate-limiting stage of hydrolysis, in which high molecular weight substrates are cracked. Dewatering is also a common requirement in AD processes, both for feedstock and final solids. These processes are constrained by multicellular clusters (inc. organisms), agglomerations, cells and subcellular structures.

Various methods have been developed to accelerate these process steps which address differing feedstock issues in different ways. Matching method to feedstock, scale and process is essential as is ensuring a commercial return.

Pulsed Electric Fields (PEF) is the application of an electric field in pulses across biological cells. PEF can be used to create permanent pores in cells, but also to lead to their complete disintegration. By opening the cell structure microbial and enzymatic access is provided to organic compounds within the cells that would otherwise not be available, thus increasing digestion. It also disables pathogens and facilitates dewatering.

This paper outlines the background and history of PEF, its use in lysing cells and application to Anaerobic Digestion positioning it against other pre-treatment methods. PEF is illustrated as both an effective pre-treatment method, but also as complementary to other methods.

Energy consumption is a major factor. Conventional PEF consumes less energy than most other methods. A recent development is the use of precise high power square waveform pulses that both increase effectiveness and substantially reduce specific power consumption leading to substantial increase in the return on energy invested.

Keywords

Pre-treatment; Lysis; Pulsed Electric Fields; PEF; Electroporation; Sludge; Waste;

Introduction

Anaerobic Digestion (AD) comprises four main decomposition stages. The last three (acidogenesis, acetogenesis and methanogenesis) are not inherently rate limiting. However the first stage, hydrolysis, which converts feedstock into a form ready for the next stages is usually rate limiting. Complete degradation of the feedstock also minimise encapsulated water and eases dewatering.

Feedstock generally comprise biological structures (cells, fibres) which themselves are formed from mainly polymeric compounds. The first stage of AD both breaks down the structures and hydrolyses the compounds making them available for acidogenesis. Hydrolysis itself can be the primary method of achieving structure decomposition; mechanical, chemical and enzymatic methods are also used. The pre-eminent method for accelerating this step is Thermal Hydrolysis, however this is capital intensive
and thus mostly only economic in large scale plants. Other methods have been developed including enzymes, steam explosion, ultrasound and cavitation. With the exception of enzymatic treatment, most methods involve means of employing energy to disrupt the feedstock.

**Key Factors**

Ultimately any solution has to deliver a business benefit. The primary requirements are risk minimisation, maximising financial return and meeting regulatory requirements; these are followed by process stability, ease of operation, process flexibility etc. The financial case predominates, albeit balanced against risk.

**Conversion Efficiency**

AD systems are run to achieve 2 aims, waste reduction and energy production. Process efficiency can be approached from either perspective, but ideally leads to the maximum conversion of the feedstock into a suitable energy vector. Key considerations are therefore the proportion of the feedstock that is made available for energy conversion, the net efficiency of the process and the residual waste (both mass and ease of disposal).

The amount of energy consumed through the AD process is key. If the energy consumed is electricity, then the conversion efficiency from biogas to power has to be taken into account when making this comparison. Equally the energy embodied in consumables (e.g. enzymes) should be considered. A key measure is the amount of additional energy that is produced as a ratio of the energy input – sometimes referred to as Energy Return on Energy Invested – or EROEI.

Conventional PEF has tended consume a considerable proportion of the power realised from the additional biogas. ArcAromaPure set out to both improve PEF effectiveness and reduce net power consumption, albeit initially for non-AD applications. The approach has, however, resulted in a process able to achieve an EROEI >100 (gross) and >30 (net of power generation losses).

**Dewatering**

Dewatering is a necessary step in most liquid waste treatments, often at more than one point in the overall process. This both requires energy and leads to a concentration of the solid matter; reducing energy demand and facilitating the removal of water are therefore desirable. Dewatering is inhibited by material agglomeration and cell structures both of which have been shown to be reduced through the application of PEF (Kumar P et al 2011).

The use of pulsed electric fields has been explored extensively over many years as it is primary application is in perforating cells and organelles, ranging from temporary lesions to complete cell destruction.

**Treatment Methods**

The early stages of AD comprise the breakdown of the feedstock into forms accessible by microbes. In all approaches we are interested in two key factors:

- speed
- completeness

The first step is frequently mechanical breakdown - although some materials might be as well treated with heat.
Following mechanical treatment biological cells higher microorganisms and other more solid structures need to be tackled in AD. These structures present two challenges: their composition is inherently designed to resist microbes; equally they prevent access to their organic content that are readily processed by microbes.

The methods developed to increase microbial access to feedstock include Thermal Hydrolysis, Steam Explosion, Enzyme treatment, Cavitation and Ultrasound. Of these Thermal Hydrolysis is the most developed and extensively used.

**Pulsed Electric Fields**

PEF is the application of an electric field in pulses across biological cells. At lower voltages the pulses result in temporary pores in the cell wall that the cell is able to repair; at higher voltages the cell is irreparably damaged and lysed, essentially killed. Earlier references to PEF are from the 1980s as a method of creating pores in cell walls – or Electroporation. Applications included the transfer of DNA into cells, and this continues to be a key laboratory use today.

Cells have differing thresholds for each level of poration; for AD pre-treatment permanent lysing is required. Cells size also affects the voltage that needs to be applied; the primary criterion being the potential difference across the cell. Smaller cells need a higher potential gradient and thus, typically a higher voltage.

Many applications for PEF have been identified including cancer treatment and food treatment. In the latter case PEF provides better access to cell contents (e.g. for oil extraction) or destruction of bacteria – essentially low temperature pasteurisation. New applications are being explored continuously. PEF has been shown to have the following effects

- Electroporation (cell lysing)
- Pathogen destruction
- De-agglomeration
- Alteration of protein structures
- Increased solubility

**PEF - Pulse Form**

Permanent electroporation has been stated as occurring when the field strength exceeds a specific threshold for the cell for sufficient time to permit release of lipids in the cell wall (Joannes C et al 2015). Pulse strength is thus critical, however the period for which this is applied has also been stated as critical (Huang K, Wang J 2009). The implication is that a short high peak may exceed the critical voltage for a cell, however if applied for too short a period the cell wall will close and repair. So the critical issue is not how high the peak voltage is, but that the peak voltage exceeds the threshold for a sufficient period to create permanent cell lesion.

ArcAromaPure’s experience is different from this. Tests have shown that the frequency and amplitude of pulses is the main factor in damaging or destroying structures (cells, organelles, organisms). The conclusion is that the damage is caused by the impact of charged particles on membranes, both within structures such as cells and within the substrate as a whole.

The critical requirement is therefore to accelerate these charged particles in the most efficient way possible. This requires rapid changes in the field applied, i.e. a large delta V (or derivative). A conventional pulse (e.g. capacitive discharge or induced) does create this, however the precision of the
delta V can be poor (e.g. a ramp) and a significant amount of energy is consumed in the subsequent logarithmic decay.

By creating precise short square wave pulses a high delta-V can be delivered with a lower voltage and substantially reduced power demand. Power demand can be further reduced by using positive and negative pulses. Employing a conventional pulse from a capacitive or inductive discharge (e.g. a Marx generator or a conventional coil ignition system) generally results in high peak voltage and logarithmic decay. In order to ensure the peak threshold is exceeded for sufficient time a much higher peak voltage is required and a great deal of power is wasted. Error! Reference source not found. illustrates an idealised situation.

Figure 1: Conventional and Square Wave Pulses

The ideal pulse shape is a square wave form. Furthermore the voltage and duration to achieve permanent electroporation varies with cell type, so optimisation of the process requires the ability to adjust pulse duration and amplitude. The use of a square waveform has been demonstrated on Switchgrass and Wood Chip (Kumar P et al 2011), albeit at laboratory scale. The linkage between pulse duration and cell disintegration of soft plant tissue has also been illustrated (DeVito F et al 2008).

For commercial application it is also essential that sufficient power can be generated into the pulses in order to sustain PEF treatment at realistic feedstock flow rates.

Closed Environment PEF

The approach employed uses a bank of signal generators each able to deliver precise and adjustable 1kW square wave form pulses. To deliver sufficient power into a substrate to support viable flows the output of several 1kW square wave form generators is required. In order to synchronise the pulses the pulse generator are optically linked to coordinate pulse triggering (Figure 2).

The current configuration combines 8 generators allowing up to 8kW to be delivered into the reaction chamber. This combination allows each pulse to be up to 4.8MW whilst the pulse generators consume an average 5.2kW. Pulse amplitude, frequency and duration can be adjusted within the limits of these parameters; e.g. approximately 10 x 0.1mS pulses at 4.8MW can be delivered per second.

Figure 1 Optically Synchronized Square Wave Generators
Figure 2: Optically Synchronized Square Wave Generators

Reaction chamber and overall configuration

Closed Environment Pulsed Electric Fields system comprises two electrodes across a treatment chamber through which the material to be treated is pumped. Electric pulses are applied across the electrodes (Figure 3).

Figure 3: CEPT Configuration

Flow rate through the treatment chamber is up to $7\text{m}^3/\text{h}$. The treatment chamber can vary but typically has a minimum cross section of $20\text{mm} \times 55\text{mm}$ accommodating a maximum particles of up to $20\text{mm}$.

It has been very well established that PEF is highly effective in causing lesions in cells and cell organelles (Figure 4). Different types of material require different pulses to be applied – varying in frequency, duration and amplitude.
In sludge treatment applications PEF would normally be installed prior to preliminary dewatering, but could also be located immediately before or after the bioreactor (Figure 5). Location after the reactor has the potential to ease dewatering and also to kill remaining pathogens.

**Figure 4:** Effect of PEF on Cell Membranes

**Figure 5:** Application Locations for PEF

**Trials and Tests**

**Laboratory Tests**

In ideal laboratory conditions PEF has been demonstrated to have a significant impact on a number of key chemical disintegration indicators for animal manures (Guormundsson, M, SORPA). At low concentrations this, in turn, lead to a net increase in methane production (These solids concentrations and periods are outside the norm for commercial processes, but illustrate the potential for PEF.

Table 1 Error! Reference source not found.)
These solids concentrations and periods are outside the norm for commercial processes, but illustrate the potential for PEF.

Table 1: Laboratory Demonstrated Net Increase in Methane Production

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>% increase in methane</th>
<th>Period</th>
<th>solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig Manure</td>
<td>60%</td>
<td>80 days</td>
<td>1%</td>
</tr>
<tr>
<td>Pig Manure</td>
<td>125%</td>
<td>60 days</td>
<td>3%</td>
</tr>
<tr>
<td>Leachate</td>
<td>55%</td>
<td>25 days</td>
<td>1%</td>
</tr>
</tbody>
</table>

Methane Production - Klippan Trial

Installation

In 2015 the Swedish Energy Agency funded a trial of PEF (bioCEPT) on secondary sewage sludge at Klippan in Southern Sweden. Klippan is a town in Southern Sweden of about 10,000.

![bioCEPT Klippan Configuration](image-url)

This was a retrofit implementation with PEF treatment located after sludge dewatering and storage. In this installation dewatered sludge was diverted through one of two PEF treatment chamber before the bioreactor requiring interception and re-routing of pipes from the sludge storage tank (Figure 6). The trial also explored the potential of using a disc filter to increase the extraction of biosolids from the waste water prior to biological cleaning and discharge. Figure & Figure illustrate the installation.
Pulse parameters were 8 kV/cm, 500 Hz (between 1 and 2 pulses for the slurry) and 3 μs pulse length.

Results

As can be seen from Figure 7 PEF led to an immediate and sustained increase in methane production. Yield production can be viewed in two ways:

- Final production increase of 12.7%, or
- Achieving target methane yield in 35% of the time for untreated sludge

This demonstrates the potential to either increase gas production or throughput of the plant. This also illustrates the significant differences that can occur between laboratory conditions (Guormundsson, M, SORPA) and real-world operations.

Dewatering Tests

Electroporation also facilitates dewatering. This was observed on the Klippan Trial in which dewatering of final digestate improved, however specific measurements not reported.
Laboratory tests have been conducted on both sludge pre-dewatering and on biosolids post AD.

Typical dewatering pre-AD results in a reduction of approximately 20% of the total volume. PEF treatment achieved a 5% improvement (net 25%) – or removal of 25% more water.

These laboratory tests are consistent with experiences at Klippan and indicate potential for PEF to complement other processes by reducing the cost of dewatering and increasing process intensity in the following stages.

**Comparison with other Methods**

In all cases the cell walls are breached facilitating microbial action. Thermal Hydrolysis also directly decomposes (hydrolyses) cellulosic and hemi-cellulosic materials in the cell walls. Enzyme treatment facilitates cell wall decomposition.

**Thermal Hydrolysis (THP)**

Thermal hydrolysis is a widely used process intensification method. It reduces the viscosity of feedstock, increases biogas production, reduces digestate and can also reduce process scale by intensifying digestion. It is mainly applied to larger AD plants due the capital cost of the process. THP is energy intensive and it may not always yield a net energy contribution, however this does depend on application. For example where power is being generated there is waste heat from the accompanying Combined Heat and Power (CHP) plant; whereas if biogas is being upgraded for grid injection the heat demand of THP may outweigh the benefits.

The CAMBI (batch) and EXELYS (plug flow) forms of THP were compared on paper in 2012 (Mohammad Abu-Orf, M, Goss,T 2012) establishing them to be economically favourable compared to mesophilic digestion. The EXELYS approach had a lower capital cost and overall more favourable life cycle cost.

**Ultrasound**

Ultrasound has been demonstrated to achieve significant increases in biogas production in a similar way to PEF: by increasing the availability of feedstock for digestion. Laboratory tests showed for batch operation on sludge a 42% increase in biogas could be achieved and in continuous operation 37%. A key issue with the process is the net energy balance of the process, or Energy Return on Energy Invested (EROEI). At the laboratory scale EROEI was reported as negative; commercial operators report an EROEI of 3 - 10 (Pérez-Elvira S et al 2009).

**Enzyme Treatment**

The main classes of enzyme of use in AD are currently cellulase, hemicellulase and protease. Lipases are being explored. Enzymes need to be matched to feedstock composition. Enzymes act largely by breaking up long polymers into shorter structures, thus making their content more accessible to microbial action.

Dupont has undertaken at least trials of enzymatic treatment in Europe (DeMartini, J 2016):

1. Mixture of farm slurry (~10%) and energy crops (~90%) resulting a 12% reduction in feedstock; or the ability to increase gas production by ~ 12%.
2. Chicken manure, whey permeate, beet & corn sileage. Viscosity reduced by 2-3 x
3. Pig & cow manure, corn, sugar beet, oat & sheanut meal with glycerol added to maintain output. Result was an 8% increase in methane output while also reducing glycerol and a 10% decrease in operating costs (£/unit energy produced).

Enzymes were added daily, dosing levels were reported as being very feedstock dependent and ranged from 0.3 to 1.0 kg per dry metric tonne.

**Illustrative Effects of Methods**

When comparing the increase in gas volume it is important to keep in mind the total carbon content in the feedstock. If the existing process can utilise 85% of the carbon content then any increase is limited to that achievable from the remaining 15%.

Ideally comparison would be made using the same feedstock, or comparing ratios of residual to initial carbon.

However it should equally be noted that even if the feedstock carbon is low, pre-processing can accelerate AD resulting in faster production and thus greater throughput and lower specific CAPEX.

**Table 2: Preprocessing Methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>Cycle Type</th>
<th>Scale</th>
<th>Biomethane Increase</th>
<th>Feedstock</th>
<th>EROEI¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Hydrolysis</td>
<td>Batch</td>
<td>Operational</td>
<td>30 - 40%</td>
<td>Sludge</td>
<td>0</td>
</tr>
<tr>
<td>Pulsed Electric Fields</td>
<td>Cts</td>
<td>Operational</td>
<td>15 - 30%</td>
<td>Sludge</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Pulsed Electric Fields</td>
<td>Batch</td>
<td>Laboratory</td>
<td>50 – 125%</td>
<td>Animal waste</td>
<td>-</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Cts</td>
<td>Laboratory</td>
<td>37%</td>
<td>Secondary Sludge</td>
<td>3-10</td>
</tr>
<tr>
<td>Enzyme Treatment</td>
<td>Cts</td>
<td>Operational</td>
<td>8% - 13%</td>
<td>15% waste 85% energy crop</td>
<td>-</td>
</tr>
</tbody>
</table>

All processes are able to facilitate lysis, albeit over different periods, and thus accelerate hydrolysis. Reported biomethane increases range from 8% to over 40%; however in some cases these are laboratory results (Ultrasound). As illustrated for PEF there can be substantial differences between laboratory tests and operational performance.

Thermal Hydrolysis is an energy intensive process and EROEI can be shown to be negative. However the primary energy input is heat, typically derived from a CHP plant driven from the biogas. Heat is typically difficult to employ and thus often wasted (particularly in the UK). As a result, whilst the net EROEI may not be positive, the net power generation from biogas will increase, digestate reduce and use of the additional ‘waste’ heat employed for process intensification yielding a net benefit.

**Combining PEF with Other Treatments**

There is clearly potential to combine PEF with other treatments in order to gain an overall process and commercial benefit.

¹ Energy Returned on Energy Invested
PEF demonstrably facilitates dewatering of feedstock which can in turn, intensify subsequent process steps. This should provide a benefit to Thermal Hydrolysis applications (Figure 8) by one or more of the following:

- reducing the heat energy required for the THP itself
- increasing the throughput, or reducing the scale, of both the THP process and bioreactors

By disintegrating cells and providing access to cell contents PEF will also present greater potential for chemical and enzymatic action on the feedstock (Ganeva V et al 2014). There is therefore the potential to combine PEF and enzyme treatment to deliver a net benefit.

![Figure 8: Use of PEF in advance of THP](image)

**Conclusion**

Pulsed Electric Field Treatment has potential for enhancing the performance of Anaerobic Digestion:

1. Applied as a primary pre-treatment in the form of square wave pulses, it delivers a high energy return on energy invested for water sludge applications
2. It will also facilitate dewatering feedstock and may thus have potential to be applied in a number of stages in the AD process
3. It is complementary to other process steps, including Thermal Hydrolysis
4. It can be readily integrated and retrofitted to existing plants
5. PEF, as with other pre-treatment processes, needs to be matched against feedstock characteristics
6. Whilst laboratory results are indicative of potential results, operational scale tests are essential

Processes, feedstocks and applications vary considerably and the suitability of PEF, or any pre-treatment method, needs ultimately to be proven in live situations.

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Anders Bohman, ArcAromaPure

References


Barua, R et al (…) 17th European Biosolids and Organic Resources Conference


Tran, D (2016) Hydrodynamic cavitation applied to food waste anaerobic digestion. Linköping University, TEMA - Department of Thematic Studies