INVERTED PHASE FERMENTATION FOR DIGESTION INTENSIFICATION

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ABSTRACT

Inverted Phase Fermentation (IPF) is a sludge thickening process that operates on the basis of flotation with nascent carbon dioxide. The biogas given off during the initial stages of fermentation causes the sludge to concentrate in a top layer known as the solid phase. With up to 11% dry solids (DS) the solid phase enables the digestion process to be intensified by up to 300% compared to the un-thickened feed. Since no polymer is used, the solid phase is less viscous and is expected to be more easily blended in the digesters than belt thickened sludge. In addition to the sludge thickening effect, IPF also provides improved pathogen destruction and a carbon source at the same time.

The application of IPF should allow the operation of existing digestion assets to be intensified to operate with organic loading rates up to 4.9 kg of VS/m^{3}d without any significant modifications or increased risk of foaming. Benefits to the operators would include alleviation of any hydraulic overloads; increased digestion capacity; and greater availability of biogas for power generation or conversion to biomethane for transport. Other technology benefits include the elimination of process emissions from secondary digesters; and a free carbon source for biological nutrient removal applications.

This paper reports the findings of an initial study of the effect of sludge source, temperature, initial dry solid content and fermentation time on process performance.

KEY WORDS

Sludge thickening; Intensification; Fermentation; VFA production; *E. coli* reduction; Viscosity

INTRODUCTION

Sustainable waste management concepts are high on the agenda of EU and UK government policies. Research has shown that the agriculture recycling of many wastes will have the highest benefits for the environment [Lema and Omil, 2001]. Anaerobic digestion (AD) offers the advantages of both a net energy gain by producing methane as well as the production of a fertilizer from the residuals [Edelmann et al., 2000; Sonesson et al., 2000]. There are more than 36,000 anaerobic digesters today in operation in Europe, treating around 40 - 50% of sludge generated [Mata-Alvarez et al., 2000]. This suggests a shortage of digestion capacity which will be more serious, if as expected there will be a step increase in sludge volume as sink disposal units become more common place. One way of increasing the digestion capacity without a massive capital investment programme is process intensification.

Sludge arising from sewage treatment typically contains 2-5% dry matter (average 3.5%DS). Digestion typically results in an organic conversion rate of 45% (also known as VS reduction) and with just sufficient biogas for process heating. In the last decade, gravity belt thickeners (GBT) have been introduced to provide solid concentration or sludge volume reduction in order to reduce the cost of building new digesters. That also reduced the digester heating requirement but since there was no other use for the biogas, any biogas surplus was simply flared off. Recently there has been an increase in the use of biogas for electricity generation with CHP plants. However, as amount of useable heat from a CHP plant is typically less than 50% of the output from a boiler for the same amount of gas, GBT or other forms of sludge volume reduction become essential.

The gravity belt thickener [Kormanik *et al.*, 1986] involves the use of a water-permeable belt and the addition of a polymer to flocculate the sludge in order to effect water removal. The gravity belt thickener has been a successful invention and its application has been widespread. However, such equipment requires housing in expensive buildings, high level of operator intervention and maintenance. The use of a polymer also significantly modifies the sludge rheology making it very difficult to pump and mix.

INVERTED PHASE FERMENTATION

An ideal digestion intensification technique should have some if not all of the following characteristics:

1. Ability to cope with a wide range of sludge feed (2 – 5% DS)
2. Increase digester throughput by at least 200%
3. Reduce digester heating mixing pumping requirements
4. Use little or no chemicals
5. Deliver at least 99% reduction in *E. coli* content
6. Provide a carbon source from the sludge for BNR applications [Le *et al*, 2007]

The present paper covers the work under the Knowledge Transfer Partnership between United Utilities and Cranfield University. The two years programme aimed to develop Enzymic Hydrolysis technology as a pre-treatment for more efficient digestion.

It has been discovered that during the early stages of sludge fermentation the substrate undergoes hydrolysis and acidogenesis. These processes result in the evolution of a small quantity of biogas, which typically comprises over 80% carbon dioxide [Le *et al*, 2008]. Surprisingly, the nascent biogas bubbles have the ability to attach themselves to the raw sludge particles and cause the latter to float. Left undisturbed, the essentially raw sludge separates into a top layer of concentrated sludge and a bottom layer of sludge liquor. The splitting of a sludge stream into layers of similar materials is known as phase separation and the entire process is known as Inverted Phase Fermentation (IPF). Figure 1 shows an illustration of the IPF process. The top layer of concentrated sludge is to be referred as the solid phase and a bottom layer of sludge liquor is to be referred to as the liquid phase.

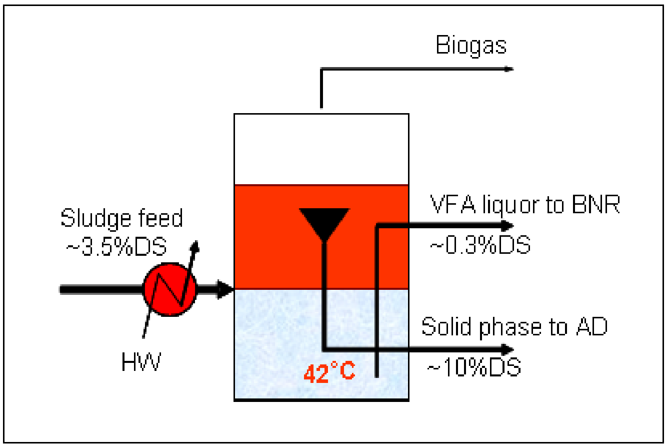

Figure 1: Inverted Phase Fermentation

The surface of raw sludge particles has a degree of hydrophobicity; therefore they have a tendency to attract gas bubbles, which are naturally hydrophobic. On the other hand, under the effect of digestion sludge particles gradually lose their hydrophobicity and the tendency to attract gas bubbles. Digested sludge particles, being denser than water would tend to settle to the bottom layer. There may be other variables that may affect the process which are currently unknown. In order to make good industrial use of phase separation, the process conditions and parameters that affect the process kinetics need to be further explored. The description in the following pages represents the work done to date.

MATERIALS AND METHODS

Sludge samples

The raw sludge samples used in this study were collected from a number of United Utilities wastewater treatment sites, including: St Helens, Ellesmere Port, Blackburn and Weaverham. All samples were freshly collected from the treatment sites and not stored for more than 3 days at 4℃. The use of septic sludge was avoided but both primary sludge (gravity or mechanically thickened) and combined sludge (primary and waste biological) were used in the tests.

Fermentation experiments

Fermentation experiments were carried out by using 1000 ml Kautex PP bottles. Grant SUB36 water bath and Binder R3 controller oven were used to maintain and control the process temperature.

The process comprises the steps:

1. Leaving the sludge to ferment undisturbed at a set temperature for up to 48 hours to achieve phase separation;
2. Removing the solid phase and liquid phase separately by decanting

Analytical methods

All the analyses were performed in triplicate. Ammonia, pH and DS of sludge sample were determined before and after treatment according to methods described in "standard methods for the examination of water and wastewater 20th edition" [Clesceri et al., 1998]. Other sludge samples (before and after treatment) were centrifuged (3500 rpm, 15 min) and filtered (with filter paper 1.2 µm pore). The filtrate obtained was used to determine VFA and Chemical Oxygen Demand (COD).

The viscosity data was measured by Brookfield Digital Viscometer Model DV-E with spindles s61 – s64.

The *E. coli* counts were determined at United Utilities' specialized laboratory using the Most Probable Number (MPN) method. All the samples were freshly prepared and tested within 24 hours in order to minimize errors.

RESULTS AND DISCUSSION

Raw sludge characteristics

Table 1 below shows a summary of the characteristic of the raw sludge samples used in this study.

Table 1: Characteristic of raw sludge samples used for the IPF investigation

Site	St Helens	Ellesmere Port	Blackburn	Weaverham
pH	5.1 - 6.3	5.4 - 5.8	5.3 - 7.1	5.2 - 6.1
DS (% w/w)	1.9 - 4.2	3.5 - 7.2	2.6 - 6.5	3.5 - 5.5
VS (% w/w)	65 - 72	59 - 77	64 - 73	62 - 73
Total COD (mg/L)	50000 - 55000	47000 - 51000	48000 - 52000	49000 -54000
Ammonia (mg/L)	180 - 220	200 - 210	190 - 200	200 - 230

VFA (mg/L)	800 - 1800	500 - 1200	650 - 1500	900 - 1900
E. coli (MPN/g solid)	1.2 - 6.9E+06	2.9 - 3.9E+06	2.2 - 4.5E+06	2.5 - 3.8E+06

Phase separation performance

1) Effect of fermentation time

Five replicate samples from St. Helens (initial DS = 2.3%) were fermented at 42℃ for different periods of time. The results (average values) are summarised in Table 2.

Table 2: Variations of IPF performance with different retention time

Retention time (hours)	Liquid phase volume (ml)	pH	VFA (mg/L)	COD (mg/L)	DS of Liquid phase (w/w)	DS of Solid phase (w/w)
0	0	5.45	1020	2122	/	/
12	350	5.41	1860	2456	0.37%	5.1%
18	500	5.38	2176	2621	0.28%	6.0%
24	550	5.28	2228	2692	0.24%	6.4%
42	600	5.27	2360	2862	0.20%	6.8%
48	600	5.28	2323	2873	0.20%	6.9%

The results clearly show that there was a significant increase in the level of soluble COD. The fermentation reduced the ratio of soluble COD to total VFA from 2.08 to 1.23 after two days suggesting that most of the soluble COD was converted to VFA. The conversion process was responsible for the production of the CO_2 that was necessary for the phase inversion. The increase in the VFA caused a slight reduction in the pH. Phase separation was essentially complete after 24 hours of fermentation with a 2.78 fold increase in the sludge solid concentration, but increasing the fermentation time up to 48 hours was beneficial in reducing the suspended solids level in the liquor.

2) Effect of fermentation temperature

Sludge samples (St. Helens with initial 2.2% DS) were fermented at different temperatures for 24 hours in order to investigate the phase separation performance. The phase separation performance can be conveniently described by a concentration factor, which can be calculated as follow:

$$\text{Concentration factor} = \frac{\text{Solid phase concentration}}{\text{Initial sludge concentration}}$$

Table 3: Variations of phase separation performance with temperature

Temperature	Liquid phase volume (ml)	DS of Liquid phase (w/w)	DS of Solid phase (w/w)	concentration factor
20℃	250	0.8%	3.6%	1.4
25℃	350	0.5%	4.4%	1.8
30℃	450	0.4%	5.7%	2.3
35℃	550	0.3%	6.9%	2.8

40℃	600	0.2%	7.6%	3.0
45℃	600	0.2%	7.8%	3.1
50℃	600	0.3%	7.5%	3.0

The results (Table 3) suggest any temperature in the range 30℃ to 45℃ would produce a good phase separation.

Further phase separation experiments were conducted with larger sludge samples for longer periods. Table 4 shows the phase separation results of the fermentation with Ellesmere Port co-settled sludge (20 L volume). Both samples were fermented in separate fermentation vessels at different temperature and without mixing for 96 hours.

Table 4: Variations of phase separation rates with time and temperature

Parameters	**Sample C1 at 15℃**	**Sample C2 at 42℃**
Fermentation period (hours)	**Liquid phase volume (L)**	**Liquid phase volume (L)**
0	0	0
16	7.37	11.43
24	7.89	12.86
40	11.05	13.81
48	12.11	14.00
64	12.20	14.00
72	12.63	14.29
88	13.00	14.29
96	13.68	14.29
Initial sludge DS, % w/v	2.9	2.9
Final Liquid phase DS, % w/v	0.3	0.3
Final Solid phase DS, % w/v	7.1	7.9

These results confirmed that phase separation was essentially a side effect of the fermentation process, which was significantly affected by the process temperature. Separation can be achieved within the temperature range of 15℃ to 50℃, but at either extreme of temperature the bacterial activity become too sluggish for the process to be useful. It should be noted that temperature affects the viscosity of the medium so that the rate of separation should also improve with increasing temperature.

3) Variations of phase separation performance due to sludge sources

Experiments were carried out in order to compare the performance of sludge samples from a number of different sewage works. Samples with similar initial DS were used and the results are shown in Table 5.

Table 5: Variations of phase separation performance due to sludge sources

Sludge sources	**Volume of raw sludge (ml)**	**DS of initial sludge (w/w)**	**Total COD of initial sludge (mg/L)**	**Volume of liquid phase (ml)**	**Volume of solid phase (ml)**
St. Helens	800	3.8%	55200	550	300
Weaverham	800	3.8%	52100	500	350
Blackburn	800	3.9%	49400	450	400
Ellesmere Port	800	4%	48600	450	400

It should be noted that the sum of the volumes the liquid phase and solid phase is greater than the original sludge volume because the solid phase contains a significant amount of trapped gas. The larger solid phase volume is an indication of a greater amount of biogas being produced which would result in a faster separation. Differences in performance of samples from different sources probably relate to the amount of readily fermentable organic available. This suggested that the sludge age and condition would have a strong impact on the separation rate.

4) Significance of initial dry solid content

Any differences in the quality of the separation were probably due to the initial sludge concentration, not the source of the sludge. Table 6 shows that the separation factor (ratio of solid concentration of solid phase to liquid phase) was about 32X in all cases where the initial sludge was over 3%DS. Better separation was observed at lower initial sludge solids.

Table 6: Quality of phase separation with different sludge sources

Sludge sources	DS of Initial sludge (w/w)	DS of liquid phase (w/w)	DS of solid phase (w/w)	separation factor (x)
St. Helens	2.40%	0.20%	8.60%	43
St. Helens	2.90%	0.20%	8.90%	44
Weaverham	3.30%	0.30%	9.10%	30
Ellesmere Port	3.80%	0.30%	9.80%	32
Blackburn	4.30%	0.30%	10.10%	33
Ellesmere Port	4.90%	0.30%	10.40%	34

The significance of the initial sludge solid concentration on the rate of separation and the quality of the separation was confirmed. Two sludge samples from the same site St Helens with different initial solid concentration were fermented in two separate fermentation vessels at 42℃ without mixing for 48 hours. The results of the phase separation were as shown by Table 7.

Table 7: A comparison of the separation rates for different initial DS

Parameters	Sample A1	Sample A2
Quiescent period (hours)	**Liquid phase volume (mL)**	**Liquid phase volume(mL)**
0	0	0
2	250	0
5	450	100
21	600	400
25	650	410
29	650	420
45	650	460
Initial DS, % w/v	2.4	4.1
Liquid phase DS, % w/v	0.2	0.3
Solid phase DS, % w/v	8.6	9.8
Separation factor (x)	43	32

The results confirmed that sludge with low initial solid concentration separated more rapidly then sludge with higher solid concentration. They also confirmed that a better separation factor was achieved at a lower initial sludge solid concentration. Generally, a higher initial solid concentration results in a more sluggish separation.

E. coli reduction performance

Raw sludge samples (St. Helens) were treated by the IPF process at 42℃. The *E. coli* counts were determined for different fermentation time. Each determination was done in duplicates (samples A1 and A2). The results (Figure 2) show that the process achieved over 99.9%

destruction of *E. coli* after 2 days of treatment. Most of the *E. coli* reduction takes place during the second half of the period. This *E. coli* reduction capability would obviate the need for pathogen attenuation in secondary digesters, thereby eliminating the biggest source of Green House Gas emissions from the sludge digestion process.

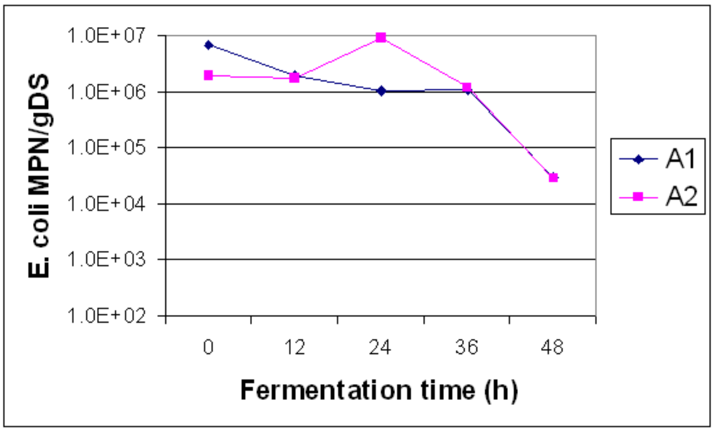

Figure 2: ***E. coli* reduction during IPF treatment**

Sludge Viscosity

The viscosity of the sludge feed affects the ease by which it may be pumped and mixed. The viscosity of a GBT sludge sample was compared with the viscosity of an IPF sludge sample. The GBT sludge sample was collected from Ellesmere Port and was found with solid content of 7.2%DS. The IPF sample was prepared by treating Ellesmere Port co-settled sludge for 24 hours at 42 ℃ to achieve a solid content of 7.9%DS. The rheograms of both sludge samples are shown in Figure 3.

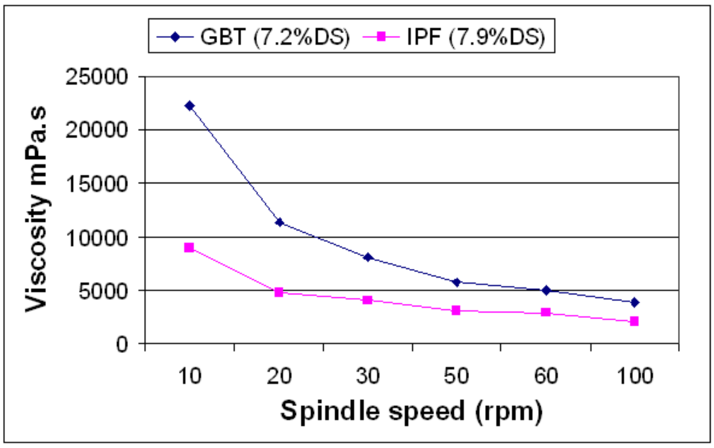

Figure 3: **A viscosity comparison of GBT and IPF sludge**

The results showed that IPF sludge generally exhibited a viscosity at least 50% lower than the GBT sludge with a similar solid content at all shear rates. Poly-electrolytes are used as flocculants in GBT and centrifugation processes. The ionic interactions between the sludge particles and the polymers produce an apparent increase in the viscosity of the media making the sludge difficult to pump and mix. In addition to a greater energy requirement for mixing and pumping, sludge that is difficult to disperse also poses a risk of digester foaming. The IPF process does not involve any added chemicals; therefore, it does not affect the rheology of the sludge. The use of IPF as a mean for sludge thickening is likely to improve sludge pumping and mixing. This should allows existing digestion assets to be intensified operating with sludge feeds in excess of 8-9%DS without resorting to very high temperature or chemical pre-treatment techniques. It would allow digesters to operate with organic loading rates up to 4.9 kg of VS/m^3 /day without any significant modification to the pumping and mixing equipment.

IPF PROCESS DESIGN CONSIDERATIONS

Sludge streams with initial solid concentration of 2% to 5% w/v are suitable for use with the Inverted Phase Fermentation process. The final solid concentrations in all the separated phases have been found to be within a very narrow range of values. The solid phase would typically have a solid content of 7% to 11% w/v; and the liquid phase would typically have a solid content of about 0.3% w/v. These results are summarised by Figure 4.

The phase separation process generally begins within 2 hours of the start of fermentation. Separation rate slows down significantly after 18 hours. Although the present data shows that the increased retention time can improve performance up to 48 hours, the optimum treatment time is probably about 24 hours.

The present work suggests that any temperature in the range 30℃ to 45℃ would produce a good phase separation. However, for most effective use of waste heat from CHP plants, the optimum process temperature is probably to be found at the lower end (30℃).

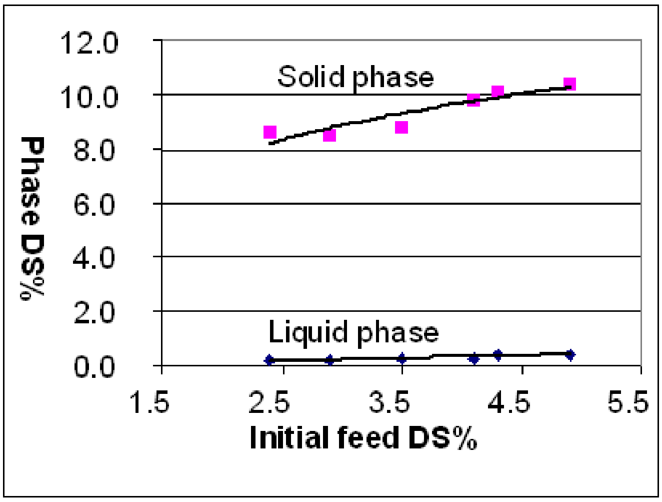

Figure 4: **Phase separation performance relative to initial sludge concentration**

In cases where IPF is considered as a mean for *E. coli* reduction as well as sludge thickening, a longer fermentation time (48 hours) and higher operating temperatures are recommended. IPF may be operated in a batch mode or continuous mode. Continuous operation has the advantage of a reduced reactor volume. The operation of the IPF process lends itself readily to integration into an existing digestion process. Figure 5 shows an example of how the process may be retrofitted to an existing EEH plant. This can be achieved by simply replacing reactors 2 and 3 with a single but larger reactor.

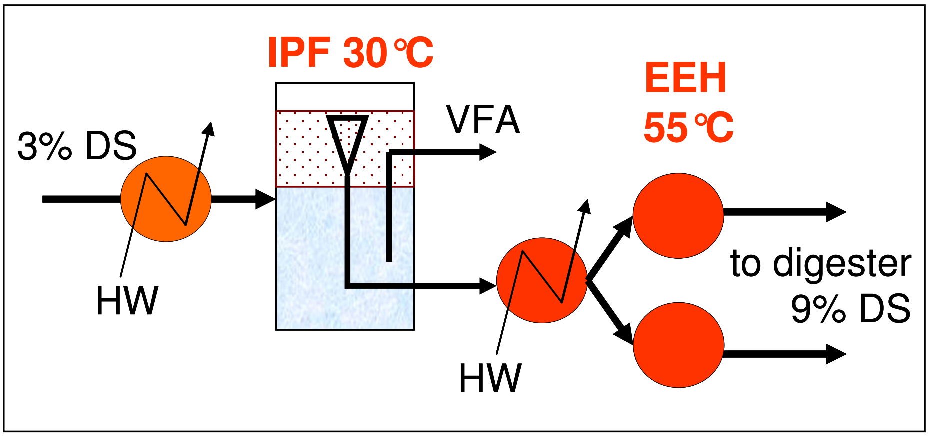

Figure 5: **Schematic diagram of an integrated IPF/EEH process**

CONCLUSIONS

IPF is a novel method for sludge thickening that offers improved pathogen destruction and a carbon source at the same time. The IPF thickened sludge has a favourable rheology which is likely to improve sludge pumping and mixing.

The application of IPF should allow the operation of existing digestion assets to be intensified to operate with organic loading rates up to 4.9 kg of VS/m^{3}d without any significant modifications or increased risk of foaming. Benefits to the operators would include alleviation of any hydraulic overloads; increased digestion capacity; and greater availability of biogas for power generation or conversion to biomethane for transport.

Other technology benefits include the elimination of process emissions from secondary digesters; and a free carbon source for biological nutrient removal applications.

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