BEST PRACTICE DESIGN FOR CHALLENGING DIGESTER MIXING APPLICATIONS

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Abstract

The UK water industry is currently going through an optimisation phase of anaerobic digestion assets, upgrading sites to 'super centres' with Advanced Digestion technologies increasing digester loading and dry solids feed whilst at the same time reducing retention times. As technological advances push digesters ever harder, effective mixing becomes more and more critical to successful operation.

This paper looks at the mixing fundamentals and the use of sludge rheology to design effective systems for thick sludge digestion along with the effects of thermal hydrolysis pre-treatment. This paper reports on the performance of the sequential gas mixing at Aberdeen after 7 years of operation. It also presents the recent digester mixing installations in the UK latest Advanced Digestion sites, namely Riverside STW and Davyhulme WwTW where pump and sequential gas mixing systems have been respectively installed.

Finally the paper reviews what lessons from digester mixing in the water industry can be exported to the burgeoning Biowaste industry and asks if future trends such as co-digestion will have an effect on mixing technology selection.

Key words

Digester Mixing, Jet, Sequential Gas, Advanced Digestion, Co-Digestion

Introduction

The UK water industry has embraced an optimisation cycle of its digestion assets by upgrading sites to 'super centres' with Advanced Digestion technologies. These processes enable the digester loading and dry solids feed to be increased while at the same time reducing the digester retention times. As operational experiences and technological advances push digesters ever harder, effective mixing becomes more and more critical to successful operation.

Digester mixing has always been recognised as a key process unit and whilst a variety of mixing technologies have been recently implemented on AD sites, the primary objectives of a digester mixing system remain the same and are namely:

1. Provide contact between the feed sludge and the active biomass to maximise gas production.

2. Provide physical, chemical and biological uniformity within a digester in order to maintain a satisfactory environment for both acid and methane forming bacteria

3. Distribute organics and dilute inhibitory substances

4. Prevent stratification and temperature gradients

5. Utilise the digester volume effectively to maintain the required biomass residence time, i.e. minimise short-circuiting

6. Minimise the deposition of solids, as this reduces effective digester volume.

7. Minimise foaming and the formation of a surface scum layer.

The first three mixing objectives are related to blending the feed with the digesting sludge. The rate of blending is characterised by a time (the blend time) taken to reach a specified degree of uniformity. The biomass residence time is influenced by the flow pattern and residence time distribution (RTD) in the digester. Significant stagnant or dead regions reduce the effective or 'active' volume and hence reduce residence time. The active volume in the digester is characterised as a percentage of the total sludge volume.

This paper revisits one of the first digester mixing system specifically designed for thick sludge digestion and gives an operational performance update. It also presents the recent digester mixing installations on the UK latest Advanced Digestion sites, namely Riverside STW and Davyhulme WwTW where pump and sequential gas mixing systems have been respectively installed.

Finally the paper reviews what lessons from digester mixing in the water industry can be exported to the burgeoning Biowaste industry and asks if future trends such as co-digestion will have an effect on mixing technology selection.

Mixing Fundamentals

Mixing system refurbishment has figured very highly in the UK Water Industry since AMP3 with understanding that good mixing is necessary for effective performance of modern anaerobic digestion facilities.

Despite huge interest in mixing technology there is still no recognized standard applied in the UK. Each water utility has selected mixing technology in relation to their personal experience and preferences. Some water utilities have clearly defined criteria and have not deviated from their asset standard whilst others have allowed their contractor to select the mixing equipment as long as it meets their performance criteria.

Unconfined gas mixing and jet mixing systems are probably the two most widely accepted mixing technology for digesters in the UK. While both technologies benefit from the absence of moving parts inside the digester, there is a significant difference between these two technologies in relation to their respectively energy demand. This is inherent to their intrinsic principle of operation with pump mixing being more energy intensive.

Unconfined gas mixing

Unconfined gas mixing systems are based on the principle of biogas recirculation, compression and injection into the sludge either on a continuous or sequential basis. The biogas is externally compressed and delivered through a series of mixing point strategically positioned on the digester floor. The intensity of gas flow through each mixing point generates a stable mixing pattern in the tank which rotates the tank contents.

Unconfined gas mixing systems have been reported with net power inputs of 1.5-3.5 W/m3 (Harrison) and are determined using the isothermal expansion of rising gas plume:

$$P = \dot{m}RT\ln\left(\frac{p_1}{p_2}\right)$$

Where
p_1 = pressure at nozzle
p_2 = pressure at surface

Pump Mixing

Pump mixing systems are based on the principle of sludge recirculation. The sludge is externally pumped and delivered through a series of jet nozzles strategically positioned on the digester floor or wall. Methods to carry out design and calculation of mixing power used the following model:

$$\frac{P}{V} = \frac{0.5 \times Q\_jet \times \rho\_Jet \times \wedge\_Jet^2}{V}$$

Where,

ρ_Jet = Density of Liquid at jet outlet (kg/m^3)
Q_jet = Flow rate of jet (l/s)
$\wedge\_Jet$ = Velocity of jet (m/s)
And,

$$\varepsilon\_mix = Number\_Jets \times \frac{P}{V}$$

It has to be noted that some water utilities still have prescriptive system design criteria for pump mixing system. It is not uncommon to see reported mixing energy input in excess of 15W/m^3. Whilst this level of energy may be suitable for small sludge tank application, it is important to apply this rule of thumb appropriately as larger tank applications will be at risk of outsized installed power. Nozzles positioning and orientations should also form part of the principal design consideration

Thick sludge Rheology

The effect of digesting thick sludges was widely investigated and documented through a collaborative research work initiated between BHR Group Limited, Yorkshire Water Services and Monsal.

As part of this research project, a survey of sludge rheology from multiple digesters at twelve key Yorkshire Water sites was completed. The surveyed digested sludges ranged from 2.5 to 5%DS (w/w). To provide thicker sludge samples a 10%DS (w/w) sludge was formed by evaporation in an oven at 35°C. Three sludges (2.5%DS, 5%DS and 10%DS) were chosen as representative of the surveyed range of sludge rheologies and are shown in Figure 1.

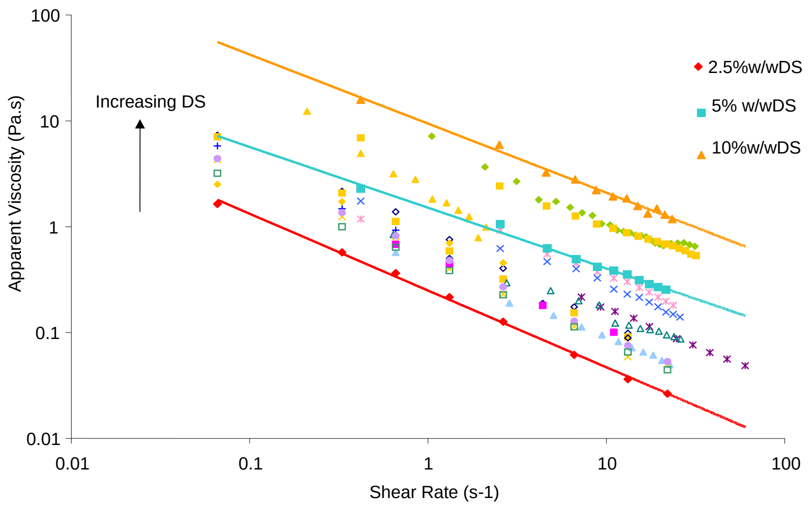

Figure 1: Range of apparent sludge viscosities found from site survey

As digested sludge DS was increased from 2.5 %DS to 5 %DS, apparent viscosity increased by nearly an order of magnitude over the shear-rate range tested. A further increase from 5 %DS to 10%DS resulted in another order of magnitude increase in apparent viscosity.

For a number of years the accepted UK industry standard prediction method was described in the Water Research Centre (WRc) TR185 report. Figure 2 shows an example of a comparison between the measured rheology of a digested sludge and that predicted from TR185.

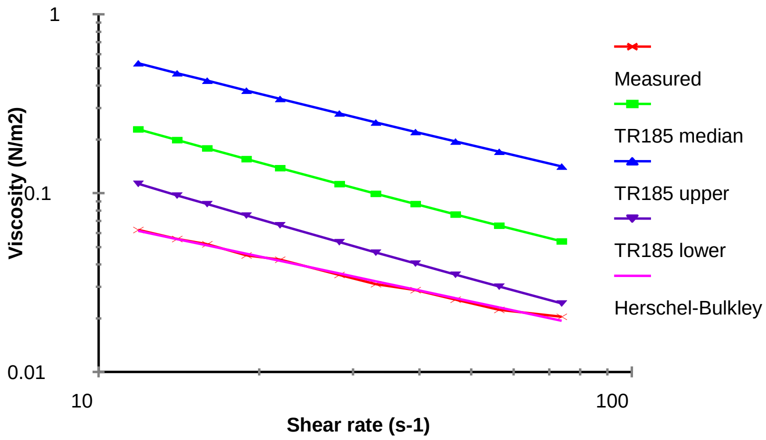

Figure 2: **Log-out plot showing comparison of apparent viscosity. TR185 predicted and measured for a 4%DS digested sludge**

In this case agreement between measured and predicted rheology is poor with the TR185 predictive method generally being not very accurate for thicker digested sludges.

Understanding the rheology of sludge to be mixed became essential to ensure effective mixing system design with special focus on the thicker sludge band (5-10%) because of the onerous mixing duty.

Hydrolysed sludge rheology

The rheology of hydrolysed sludge has been well documented over the years. Studies have demonstrated that hydrolysis changes the rheological properties of sewage sludge. As a result the hydrolysis process is making the sludge to behave as if it was thinner than its equivalent non-hydrolysed counterpart.

This is shown in Figure 3 where a 12%DS hydrolysed sludge is compared with two digested sludge samples at 7-8%DS. It can be seen that the rheological properties are similar. Figure 4 illustrates the rheological properties of the hydrolysed sludge (Aberdeen).

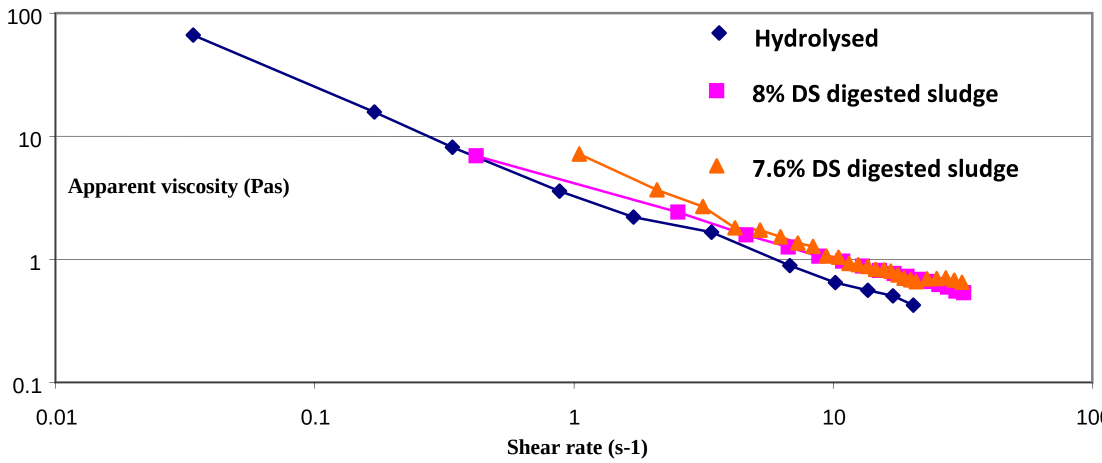

Figure 3: **Rheogram to compare hydrolysed sludge with digester sludges of 7% & 8% DS**

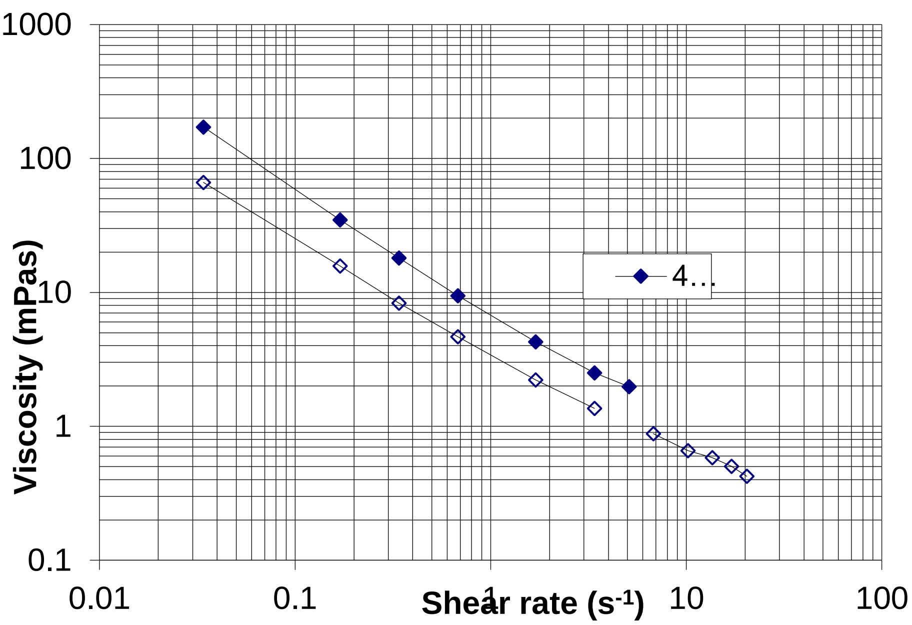

Figure 4: **Rheology figures for hydrolysed sludge (Earth Tech Data)**

More specifically to hydrolysed sludge, particular consideration should be paid to the dispersion of the thick feed sludge. As hydrolysed sludge enters the digester at 40°C, there is potential for an 'inactive zone' to develop as the hot feed stratifies on the surface. This problem has been observed to a lesser extend in conventional digesters and has been shown to result in a high acid concentration zone in the digester and serious foaming and other operability problems including untreated sludge short-circuiting to the digester outlet.

Case Study 1: Aberdeen Nigg – Scottish Water

The Aberdeen WwTW is an advanced digestion facility employing thermal hydrolysis followed by mesophilic anaerobic digestion. Commissioned back in 2001, this digestion facility is a regional centre processing imports from satellite works along with indigenous sludge produced at the works.

Aberdeen has a nominal treatment capacity of 16,000 tonnes of dry solids (tds) per annum and utilises 2No 4,000m^3 digesters with an organic loading of circa 4.1 kg VS / m^3. day.

The contractual mixing system performance criteria were:

1. Feed sludge: hydrolysed sludge at 37-39 °C with 10-12DS%.
2. Feed sludge dispersal within 120 minutes
3. Active volume > 90%
4. Less than 5% feed volume short circuiting

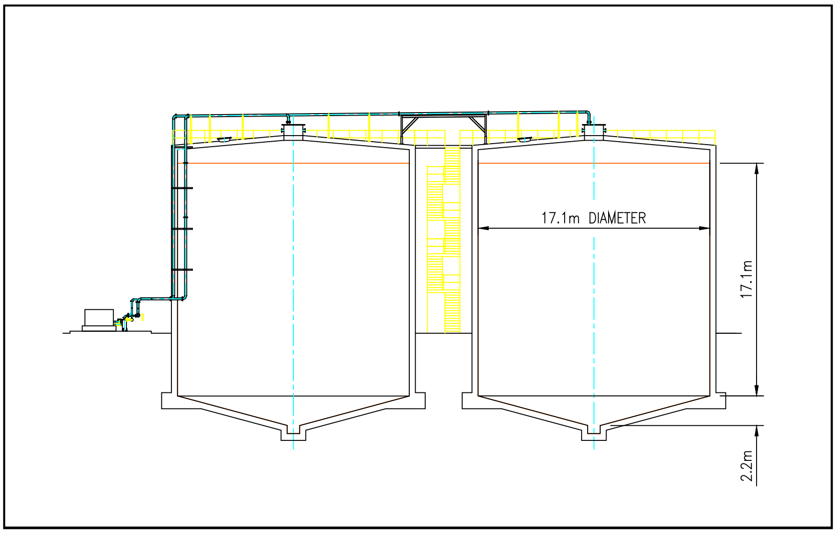

Figure 5: Section of the digesters at Aberdeen

The installed mixing system design criteria were:

1. Technology: Monsal sequential gas mixing system
2. Compressor installed power: 18.5 KW
3. Compressor absorbed power: 15.1 kW
4. Isothermal expansion power: 5.96 KW
5. System mixing energy : 1.49 W/m3

The mixing performance of this digester mixing installation was verified during November 2001 using lithium chloride tracer test.

Results are presented in Figure 6 (Digester lithium tracer test - 12 hours) and Figure 7 (Lithium tracer washout curve for the Nigg Digester over 36-day test).

It verified that based on the initial 12-hour mixing test period that the actively mixed volume of the digester was completely mixed within 75 minutes. The tracer signal remained relatively flat after the initial mixing and did not indicate any pockets of lithium solution that were subsequently reintroduced back into the active zone, while the mixing test was running.

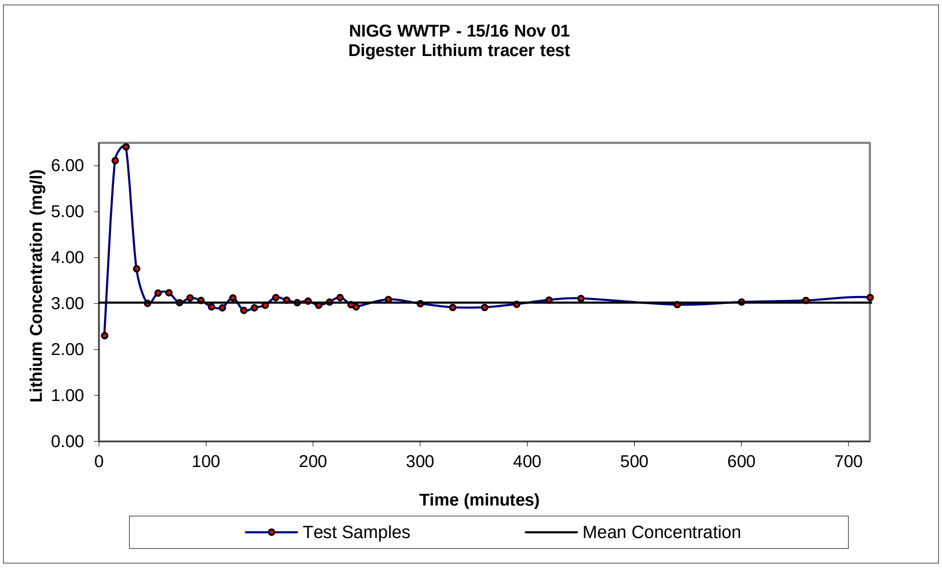

Figure 6: Nigg Digester: corrected data for the initial 12 hour period

Based on the data gained from the remaining 36 days washout curve, the actively mixed zone for the Nigg Digester consisted of approximately 93% of the total digester capacity. Hence, the percentage dead volume in the digester was approximately 7%. The calculated degree of short-circuiting was 5.8% of the average feed volume.

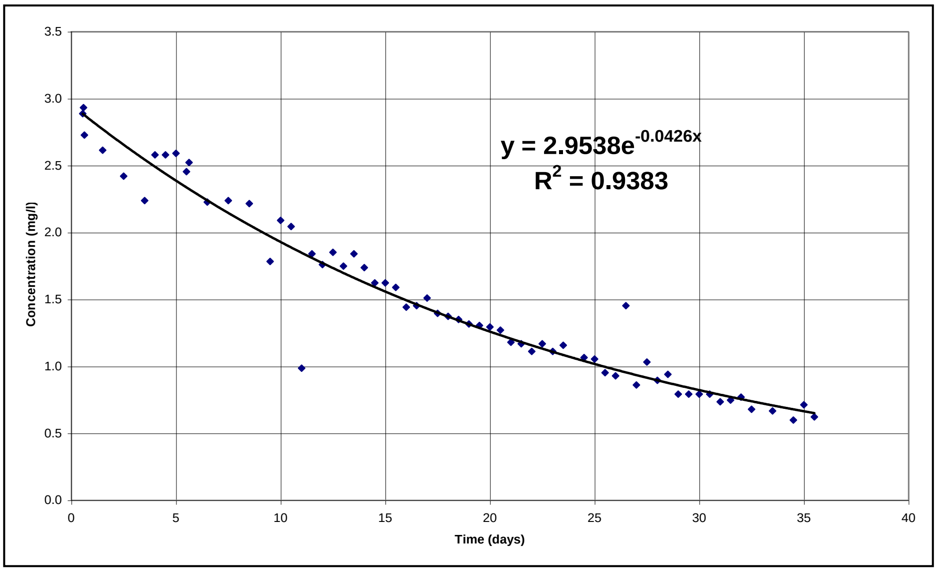

Figure 7: Lithium tracer washout curve for the Nigg Digester over 36-day test

The mixing performance of the digesters was retested on January 5th 2007 with a lithium tracer analysis (Figure 8) being carried out by Greenfinch Ltd on behalf of Grampian Waste Water Services Ltd.

Copy of the lithium tracer test interim report indicates:

1. The lithium was dispersed in 1.5 hours on Digester A and 1 hour on Digester B.
2. An effective volume for Digester A was assessed to be approximately 3200m^3 or 80% of the nominal volume, and an effective volume for Digester B being approximately 3300m^3 or 82.5% of the nominal volume.

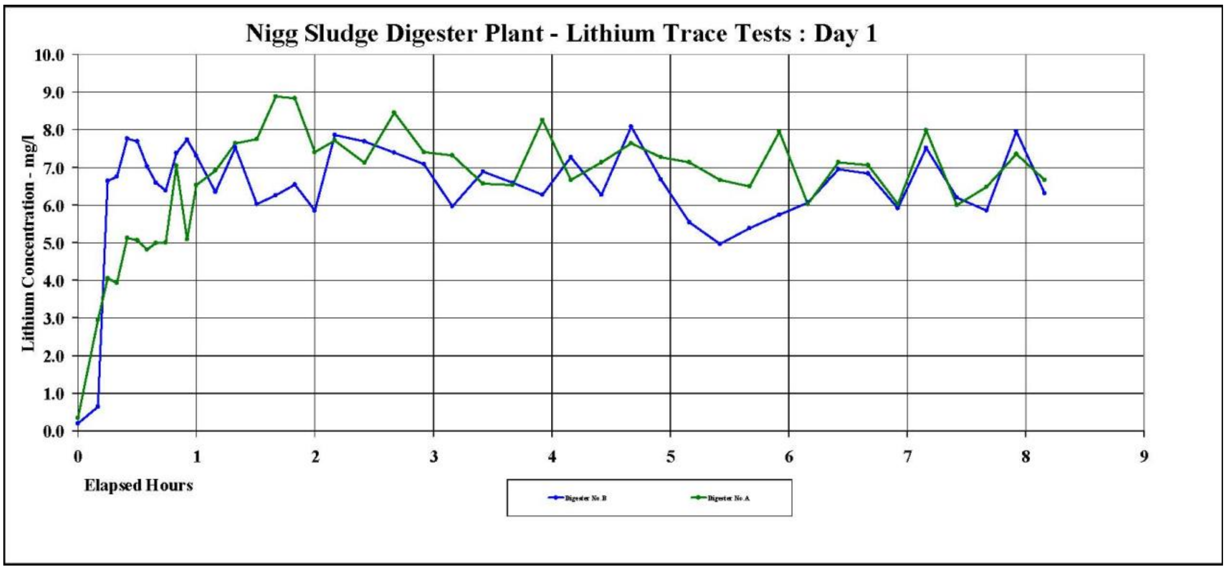

Figure 8: **Nigg Digester: corrected data for the initial 9 hour period – January 2007**

Conclusion

1. The full scale Monsal system as designed met the performance tests required under the contract back in 2001

2. Retesting of the sequential gas mixing system after 7 years in operation reported minimum loss of active volume and dispersion time still within the initial contractual mixing system performance criteria.

3. Monsal sequential gas mixing system is demonstrated as a proven, reliable, low energy mixing technology.

Case Study 2: Riverside STW – Thames Water

Riverside Thames Water's sewage treatment works is one of London's main sewage treatment facilities along with Beckton, Crossness, Long Reach and Mogden.

The sludge digestion plant at Riverside STW was built around 1963 and abandoned circa 1998, when Beckton STW commissioned its Sludge Powered Generator. From that time Riverside mixed sludges have been pumped to Beckton STW for treatment and disposal.

The plant is currently going through an extensive refurbishment programme during which a new Thermal Hydrolysis Plant is being constructed along with the refit of the four primary digesters. The site will provide enhanced digestion for both Riverside sludge and imported sludge from Beckton STW.

The digestion plant was constructed around four primary digesters of 5,150m^3 working volume each. The digesters are a traditional UK design of the time with integral floating roof and bells. The digesters have a reasonably good aspect ratio for mixing (20m diameter x 16 m sludge height).

Part of the refurbishment programme, new digester gas tight roofs were installed along a new mixing system designed for thermal hydrolysed sludge consisting of a high SAS proportion. Flow though the digester plant is by displacement with each digester being fed from the digester feed pumps in turn.

Riverside has a nominal treatment capacity of 40,000 tonnes of dry solids (tds) per annum and utilises 4No 5,150m^3 digesters with an organic loading of circa 3.98 kg VS / m^3. day.

The contractual mixing system design criteria were:

1. The digesters shall have an actively mixed volume of no less than 90%.
2. The difference between the theoretical Lithium concentration and the measured Lithium concentration once mixing has been achieved shall be no greater than10%
3. The digesters shall be fully mixed within 120 minutes of the commencement of the test

Mixing system design

The mixing system designed for these digesters is based around external pumps and internal jet mixing. Three 22kW pumps are provided per digester with mixing jets located inside each digester at a 120 degree angle apart in a plan view (Figure 9).

The system has been designed around a gross and net energy input of respectively 12W/m^3 and 1.63W/m^3 with the sludge being circulated from the base of the digester and distributed via strategically positioned jet nozzles on vertical risers inside the digester. The mixing system operates with chopper pumps to prevent clogging of the system.

Mixing system circulation pipework has been designed using ductile iron pipework for cost efficiency and ease of installation. Special considerations have been given to the nozzle internal surface finishes to prevent build up of foreign material at the outlet. Pump mixing design approaches are based on WRc's TR185 technical reports along with the latest system loss prediction calculation based on Monsal recent rheological work.

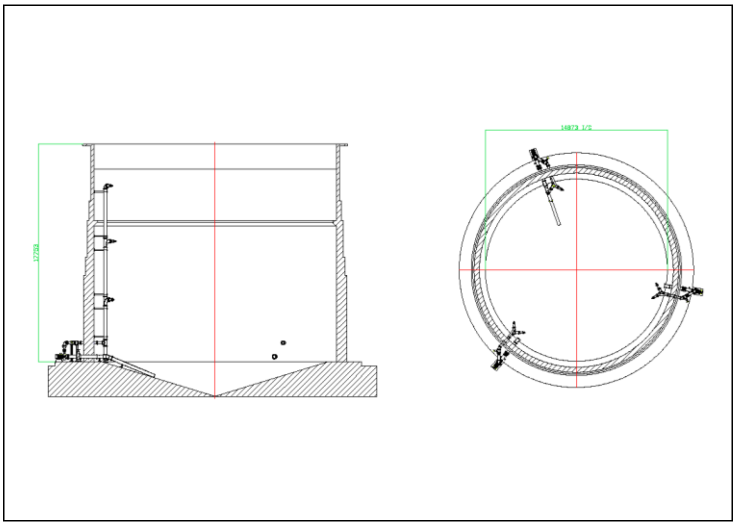

Figure 9: Section of the digesters at Riverside

Mixing system testing

Whilst Lithium tracer tests are to be carried out on 2 of the 4 digesters to demonstrate the effectiveness of the digester mixing system, the digestion plant is still in commissioning phase at the time of writing. Results will be presented in a follow up paper and compared against the CFD model commissioned.

The CFD analysis results from the simulation show that the tank is well mixed at the outer zones with high recycling sludge velocities at the nozzles. The velocity profile is decreasing from nozzle to the centre of the tank due to the high viscosity (Figure 10).

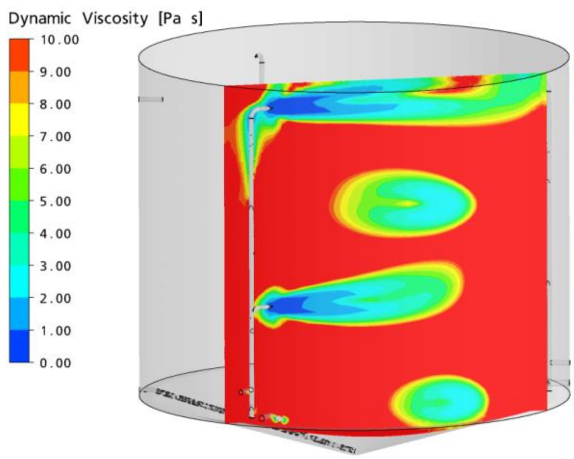

Figure 10: Evaluation of dynamic viscosity. Red: viscosity > 10 Pas.

Velocities at planes through the pump outtakes are shown in Figure 11 and Figure 12, with figure 13 illustrating the vertical ones.

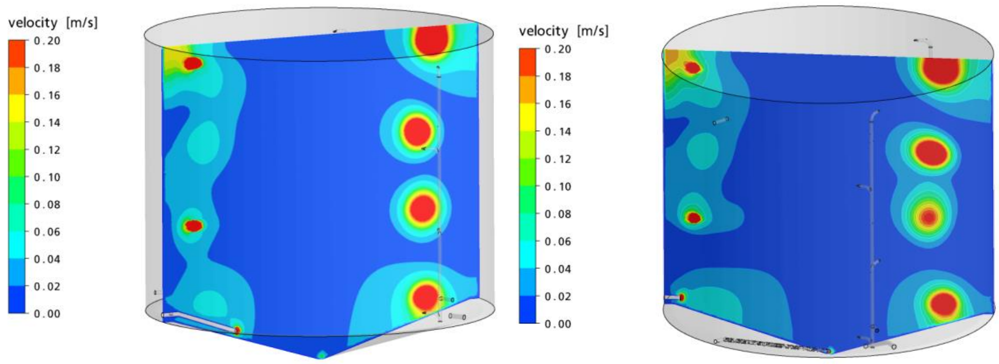

Figure 11: **Evaluation of flow velocities.**
Cross section through pump outtake 1 (left) and pump outtake 2 (right).
Red: v > 0.20 m/s.

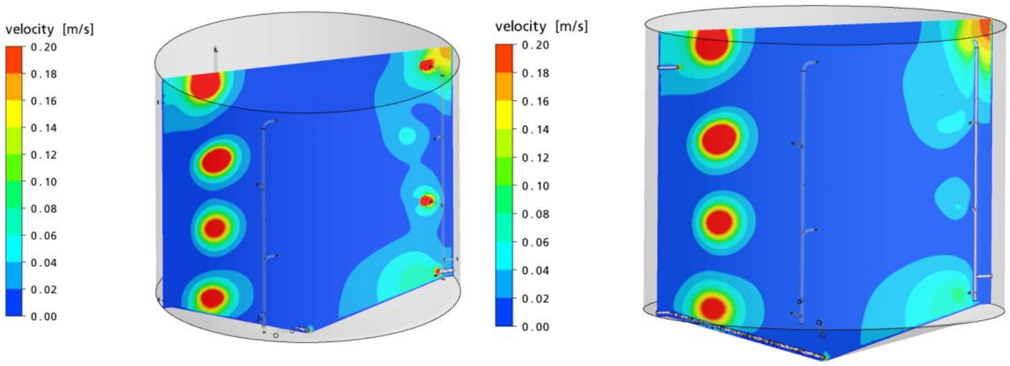

Figure 12: **Evaluation of flow velocities.**
Cross section through pump outtake 3 (left) and discharge + fresh sludge feed (right).
Red: v > 0.20 m/s.

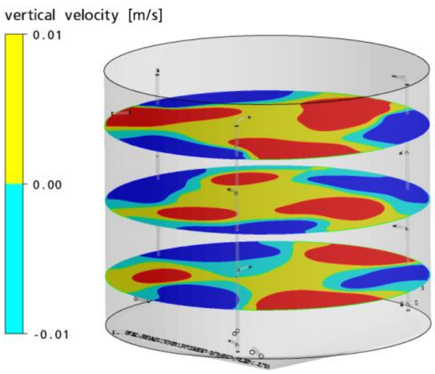

Figure 13: **Evaluation of vertical flow velocities (negative values: downwards flow, red: v > 0.01 m/s, dark blue: v < -0.01 m/s).**

Figure 14 shows the footpath of the sludge from the nozzle during a time of 2 hours. As illustrated the sludge is mixed within the tank in all direction but especially in horizontal flow and at the outer regions of the tank between the nozzles. Because of the high velocities, sludge is partly entrained from the region of one pump into that of another pump (jet pump effect).

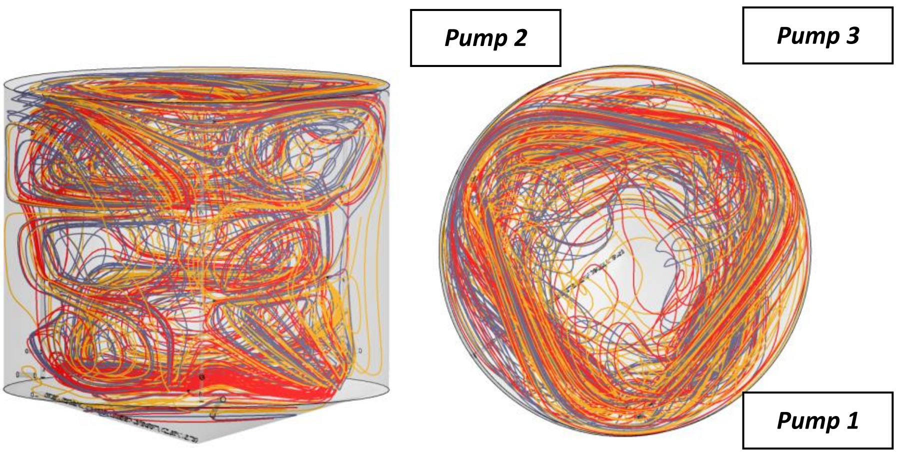

Figure 14 **Streamlines starting at the nozzles. Length of one streamline equals a time of 2 h.**
Red: pump 1, grey: pump 2, orange: pump 3.

Conclusion

It must be noted that for at similar contractual mixing system performance, Riverside digesters pump mixing system will require a greater energy input compared to the sequential gas system installed at Aberdeen. With a gross energy demand difference of nealy 3 to 1 and rising energy price, the system installed and absorded power must be factored in the final decision making process.

CFD analysis of the installed system shows a fast distribution of the fresh sludge feed into a wide area within the digester, with fresh sludge being transported from top to lower region of the tank. The simulation showed that the entire volume of the digester would be re-circulated in average 10.5 times every day.

Case Study 3: Davyhulme WWTW – United Utilities

Davyhulme Wastewater Treatment Works is one of the most significant treatment facilities in Europe. Having opened in 1894, it remains United Utilities largest wastewater treatment work serving a population equivalent of 1.2 millions in and around the city of Manchester.

The Works is currently in the final stage of a significant refurbishment project conceived to increase the capacity and improve the quality of treated sludge by providing a central sludge processing facility comprising a thermal hydrolysis process upstream of the existing eight mesophilic anaerobic digesters.

Davyhulme Digestion facility will have a nominal treatment capacity of 91,000 tonnes of dry solids (tds) per annum and utilises 8No 7,500m^3 digesters with an organic loading of circa 4.67 kg VS / m^3. day.

The contractual mixing system performance criteria are:

1. Feed sludge dispersal within 120 minutes.
2. Active volume > 90%.
3. Less than 5% feed volume short circuiting.

Mixing system design

Monsal sequential gas mixing technology has been retained as preferred technology for this site. Each gas mixing system has been designed around a duty 55kW biogas compressor and a gas flow of 480m^3/hr (nominal) which is distributed sequentially and uniformly across the digester floor.

With the digester walls not designed to be drilled, a bespoke stainless steel gas assembly has been designed to support the internal down coming gas pipes. Each digester was equipped with two gas assemblies fixed onto the digester base to minimise any dynamic loads applied onto the digester roof (Figure 15)

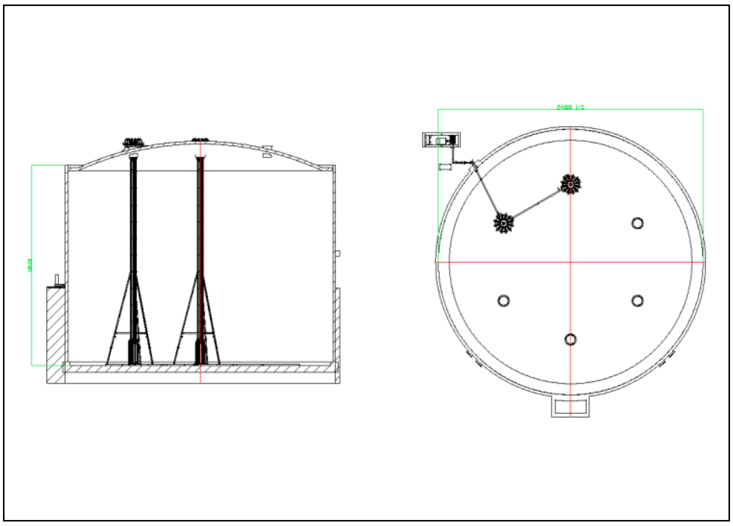

Figure 15: Section of the digesters at Davyhulme

Conclusion

1. A proven sequential gas mixing system has been installed at Davyhulme WwTW digestion facility which will equate to an energy input into the digester of 2.37W/m^3

exceeding Monsal experience at Aberdeen with a sequential gas mixing system developing 1.49 W/m^3.

2. The implementation of a sequential gas mixing system promotes better energy sustainability with an installed power of 55kW (45kW absorbed) against a 90kW equivalent with pump mixing.

Case Studies Summary and Conclusion

Case studies Summary	**Aberdeen Nigg**	**Riverside STW**	**Davyhulme**
Number of digesters	2	4	8
Digester volume (m^3)	4,000	5,150	7,500
Total digestion capacity (m^3)	8,000	20,600	60,000
Sludge type	Primary + SAS	SAS	Raw + Liquid
Digester temperature (°C)	35	35	35
Annual dry solids tonnge (tds)	16,000	40,000	91,000
TS raw sludge (% w/w DS feed)	10	10	10
VS raw sludge (%)	75	75	75
Digester design HRT (days)	18	19	16
Digester organic loading (kgVS/m3.day)	4.1	3.99	4.67
Monsal Mixing system technology	SGM	Pump mixing	SGM
Required blend time (minutes)	120	120	120
Active volume	>90%	>90%	>90%
Short circuiting	<5%	<5%	<5%
Installed power per digester (kW)	18.5	66 (3 X 22)	55
Gross energy input (W/m3)	4.6	12.8	7.3
Mixing energy input (W/m3)	1.49	1.60	2.37

Advances in the design of anaerobic digesters have seen a trend towards digestion of thicker sludges in the UK. This includes a number of new facilities using bolt on technologies to mesophilic anaerobic digestion such as Cambi Thermal Hydrolysis and Biological Hydrolysis.

Conception and implementation of efficient mixing systems are more than ever paramount to the modern digestion facilities. Whilst jet pump mixing and sequential gas mixing are both proven technologies for thick sludge application, a review of sequential gas mixing system demonstrates that low specific mixing energies and lower daily power consumption are achieved. The ongoing research & development in sludge rheology, such as the SRDB, will play an important role towards further optimisation of this proven mixing technology.

Sequential gas mixing also compares favourably with stated power of other mixing systems and considerations are recommended for exportation to the burgeoning Biowaste industry where thick slurries (10-12%) are being processed in dedicated anaerobic digestion facility.

With incoming gate fee and energy productions being the two main sources of income Biowaste facilities have to operate at a maximum efficiency to secure their operating margin. As energy cost continues to raise so does the search for proven lower power mixing technologies. Implementation of energy efficient mixing technology is unmistakable with Monsal already leading the way with SGM installations on Biowaste installations.

With regained interest by the Water Companies to develop co-digestion to capitalise on their strong anaerobic digestion experience and their existing assets, one may argue that this future trend will affect the long term mixing technology selection.

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