MUNICIPAL SLUDGE DIGESTER FOR CO-DIGESTION OF PRIMARY SLUDGE AND HIGH FAT INDUSTRIAL WASTE

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ABSTRACT

CPG (NZ) Ltd assist the Palmerston North City Council (PNCC) with the upgrade of its two municipal sludge digesters at the Totara Road WWTP. The upgrade is from municipal sludge digestion to co-digestion of municipal biosolids and selected agro-industrial co-substrate waste such as cheese whey, piggery manure and dairy wastewater treatment flotation foams. This creates added revenue from collected gate fees and sales of renewable electricity. A staged program for the digester system upgrade was proposed by CPG in 2008 that allowed the smooth upgrade in both digester tanks without interruption of the WWTP operation. Stage I of the upgrade added a low cost temporary improved biogas mixing system to the operating digester 1 giving PNCC the capacity to treat the full primary sludge load of Palmerston North in a single digester tank. Stage II added a new permanent hydraulic mixing system to digester 2 while digester 1 treated the full primary sludge load of Palmerston North at 15 days hydraulic residence time (Thiele 2009). In stage III of the upgrade, Digester 1 receives its own hydraulic mixing system while Digester 2 treats the full primary sludge load of Palmerston North. At this point the mixing system upgrade is expected to double the previous digester gas output to over 90 m^3 methane/hour. In stage IV of the upgrade, a recuperative sludge thickening module (booster technology) will be added to the codigestion system boosting the mixed liquor sludge solids levels in both digester tanks from 1.5 % to about 3 % total suspended solids (TSS). After completion of the upgrade the daily biogas production capacity is improved through improved mixing and the booster technology from 45 m^3 methane/hour (primary sludge only) to about 180 m^3 methane/hour. The additional biogas is produced through co-digestion of primary sludge with up to 100 t/day of additional co-substrate waste.

This paper is the follow-up/validation of the concept paper presented in the 2009 Water NZ conference on the digester upgrade and indicative costs (Thiele, 2009). We present the results from the digester operation with primary sludge before and after the mixing system upgrade. The new hydraulically mixed digester tank (stage II) produced better digester contact than the biogas recirculation mixed tank and achieved comparably low volatile fatty acid (VFA) levels (less than 30 mg VFA/liter), a higher pH and higher mixed liquor alkalinity. This indicated improved primary sludge stabilization with the new hydraulic mixing system. Selective addition of high fat content dairy wastewater flotation foams to stage II practically doubled the biogas production, while the volatile fatty acid levels remained low (less than 40 mg VFA/liter) consistent with improved sludge:biomass contact after the digester upgrade with the hydraulic mixing system.

A mass balanced sludge digester process computer model is then used to determine the additional gas production that can be achieved with addition of recuperative sludge thickening ("digester booster technology") to the upgraded digesters. Depending on the nature of the industrial waste mixture, a biogas production improvement from the current base of about 1,700 m^3 biogas/day (no co-digestion) to 5,400 - 7,900 m^3/d was estimated by the process model under a wide range of different booster operating conditions. The computer model results and a range of suitable co-substrate mixtures for the booster technology are presented. The results are now used for the implementation of digester booster technology at the PNCC municipal sludge digesters.

Keywords

Sludge digesters, trade waste, co-digestion, renewable fuel, cogeneration, regional digester facility

1 INTRODUCTION

The combined digestion (co-digestion) of selected trade waste materials, septage, grease trap waste, animal manures, cheese whey, industrial flotation foams, primary sludge (PS) and waste activated sludge (WAS) is a well proven and commercially beneficial method. The Danish government started a respective national initiative in 1988 and this leading example has been widely followed throughout Europe and North America with combined digestion of industrial waste, manure and municipal biosolids in a large number of large regional municipal, agricultural and industrial digester facilities (Al Seadi, 2000).

CPG New Zealand Ltd (CPG) has successfully designed, constructed and commissioned in the past 2 decades a number of well mixed (10-20 $W/m^3_{digester}$ mixing energy) waste co-digestion facilities with high volatile solids (VS) loading rates (4 - 5 kg VS $m^{-3}_{digester}.day^{-1}$), high biogas productivities (2 - 3 $m^3_{biogas}.\ m^{-3}_{digester}.day^{-1}$) and short hydraulic residence times (10-15 days). These systems use improved gas recirculation mixing, mechanical mixing (EarthPower Digester Facility, Sydney) or hydraulic venturi mixing (Chapel Street Digesters, Tauranga) and have the capability to process approximately 3 times the organic load of comparable municipal sludge digesters. However, the construction of new co-digestion facilities is quite capital intensive and the economic operation relies thus on collection of high gate fees for the waste materials (Thiele, 2000; Hearn and Thiele, 2004).

CPG were engaged in 2008 to assist the Palmerston North City Council (PNCC) with the upgrade of its two existing municipal sludge digesters at the Totara Road WWTP. The upgrade changes the digester system from municipal sludge digestion to capability for co-digestion of municipal biosolids and selected agro-industrial co-substrate waste such as cheese whey, piggery manure and dairy wastewater treatment flotation foams without construction of new digester tanks. A staged program for the digester system upgrade was proposed that allowed the smooth upgrade in both digester tanks without interruption of the WWTP operation. Stage I of the upgrade added a low cost temporary improved biogas mixing system to the operating digester 1 giving PNCC the capacity to treat the full primary sludge load of Palmerston North in a single digester tank. Stage II added a new permanent hydraulic mixing system to digester 2 while digester 1 treated the full primary sludge load of Palmerston North at 15 days hydraulic residence time (Thiele 2009). In stage III of the upgrade, Digester 1 receives currently its own hydraulic mixing system while Digester 2 treats the full primary sludge load of Palmerston North. At this point the mixing system upgrade is expected to double the previous digester gas output to over 90 m^3 methane/hour. In stage IV of the upgrade, a recuperative sludge thickening module (booster technology) will be added to the codigestion system by end of 2010 boosting the mixed liquor sludge solids levels in both digester tanks from 1.5 % to about 3 % total suspended solids (TSS). After completion of the upgrade the daily biogas production capacity is improved through improved mixing and the booster technology from 45 m^3 methane/hour (primary sludge only) to about 180 m^3 methane/hour. The additional biogas is produced through co-digestion of primary sludge with up to 100 t/day of additional co-substrate waste.

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2 RESULTS AND DISCUSSION

2.1 VALIDATION OF THE MIXING SYSTEM IMPROVEMENT

Good mixing is essential in municipal sludge digesters mainly for three key tasks

(1) distribution of heat to keep the digester at uniform and appropriate temperature

(2) effective contact between the fresh sludge material and the resident active anaerobic sludge/alkalinity buffer to promote biogas production and to prevent formation of acidic mixed liquor zones/pockets

(3) prevention of sludge settling

There are a large number of mixing systems options available that all can meet these three requirements. These encompass a wide range of mechanical, hydraulic and biogas recirculation mixers.

When CPG was engaged by PNCC for the digester upgrade design, a digester mixing efficiency test and mixing systems options review was conducted. The test and review established that that the previously installed biogas recirculation mixing was inefficient (Thiele 2009) and that about 50 % of the digester volume was poorly mixed. The options review further established that the upgrade costs for 100 % effective digester mixing by biogas recirculation or the installation of a new additional hydraulic mixing systems were comparable.

The digester upgrade with hydraulic mixing provided three additional advantages over an upgrade with improved biogas recirculation mixing

(4) reduction of digester foam formation risk because the total biogas loading through the mixed liquor surface layer with hydraulic mixing was about $1/10^{th}$ of the biogas loading with biogas recirculation mixing significantly reducing the foam formation risk

(5) elimination of the biogas blower noise allowing hydraulic digester mixing during the night time

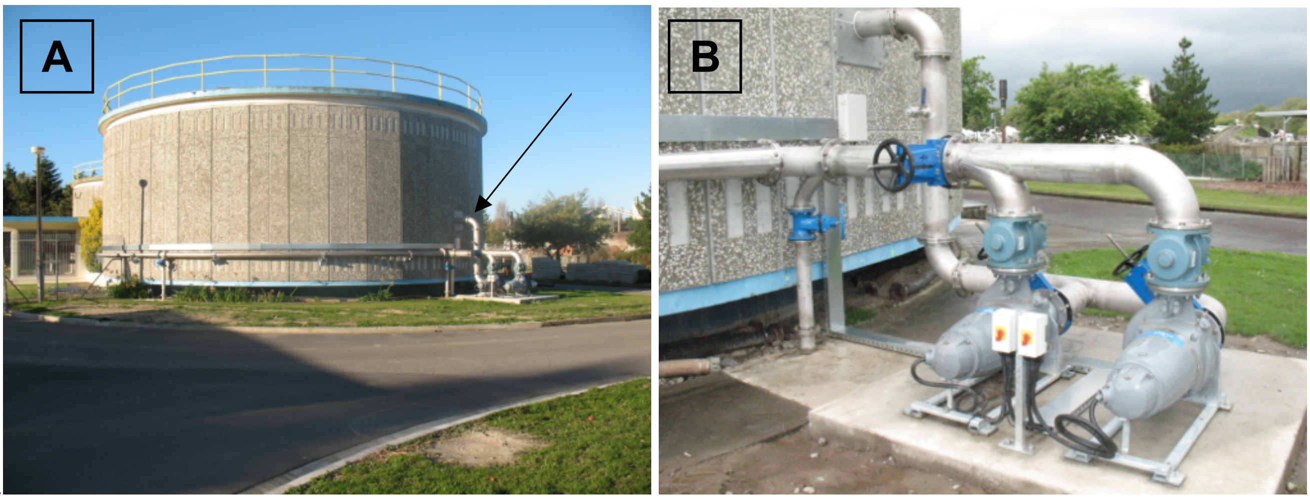
(6) successful demonstration of the hydraulic mixing system efficacy in the previous Tauranga Chapel Street digester upgrade by CPG New Zealand.

Figure 1 shows the installed hydraulic mixing system in PNCC digester 2 during stage II of the digester upgrade. A 316 SS ring main with five radial mixed liquor re-injection nozzles pointing downwards at 45^{o} angle and about 6 m vertical height difference between the re-injection point and the digester liquor surface (Figure 1 A) and powerful new mixed liquor recirculation pumps (Figure 1 B) generate a slow horizontal rotation of the digester liquor. A liquor intake point to the recirculation pumps about 0.7 m below the mixed liquor surface (Figure 1 A, arrow) generates an additional vertical turnover of the mixed liquor with an average total digester turnover time of 4.5 hours. A dedicated mixed liquor flow meter monitors the recirculation flow of the mixing system.

Figure 1: Installed hydraulic mixing system upgrade to PNCC digester No 2 (D2) for co-digestion of primary sludge, grease trap waste, whey waste, Dairy DAF sludge and piggery manure.

A: New mixed liquor recirculation ring main with mixed liquor off take (arrow) and re-injection to create a horizontal and vertical rotating digester liquor movement.

B: Details of the mixed liquor recirculation pump system (about 300 m^3/h for each pump)



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The PNCC digesters (D1, D2) have each a nominal working volume of 1350 m^3. About 110 m^3/day of pre-thickened PS at 4 % total solids with about 70 % VS in TS is digested at a nominal hydraulic residence time of 22- 28 days. The achieved volatile solids reduction of 50-55 % and the biogas yield (1.1 m^3/kg VS destroyed) are within expectation for primary sludge digestion. Table 1 gives an account of key digester performance during digestion of PNCC primary sludge (PS) before and during different stages of the digester mixing system upgrade.

Table 1: Summary of key digester performance indicators when operated on primary sludge during various stage of the mixing system upgrade. Note the improved daily biogas production, digester mixed liquor pH and digester mixed liquor alkalinity when the digesters were operated with the new hydraulic mixing system. The digester operating temperature was identical in all cases and close to 36^{o}C.

N/A: data not available due to uncertainty with the biogas flow measurements.

Operation Condition	**Nominal HRT (days)**	**pH**	**Volatile fatty acids (mg/L)**	**Alkalinity (mg $CaCO_3$/L)**	**Mixed liquor solids (%)**	**Biogas production (m^3/day) (For full primary sludge load equivalent)**
Before upgrade: Apr-Jul 08 – old biogas mixing system (D1 +D2)	25+/- 3	6.8 +/- 0.06	10-30	1500 +/- 200	1.44 +/- 0.25	1710+/- 280
Stage I: Apr-Jul 2009 – improved biogas mixing system (D1)	15+/- 4	6.8 +/- 0.08	10-20	1500 +/- 200	1.27+/- 0.25	1670+/- 200
Stage II: Jan - Mar 2010 – improved biogas mixing system (D1)	25+/- 3	6.7 +/- 0.05	20-30	1530 +/- 110	1.40 +/- 0.19	N/A
Stage II: Jan - Feb 2010 – new hydraulic mixing system (D2)	25+/- 3	7.0 +/- 0.07	23+/- 15	2150+/- 180	1.52 +/- 0.11	N/A
Stage II: Feb - Mar 2010 – new hydraulic mixing system in D2 with added 10 % Dairy DAF sludge (see figure 2 for details)	23 +/- 3	7.0 +/- 0.07	35+/- 20	2225+/- 170	1.52 +/- 0.15	3300-3400 m^3/d digester gas expected when both digesters are loaded with primary sludge PLUS dairy DAF sludge (prelim. data, additional 20 % of the daily primary sludge flow as dairy processing DAF sludge).

In the period prior to the digester upgrade the digester mixed liquor solids content was 1.44 +/- 0.25 % solids with an alkalinity of about 1500 mg/L ($CaCO_3$ equivalents) and volatile fatty acid (VFA) levels of 10-20 mg/L. The nominal HRT was 25+/- 3 days and the mixed liquor pH was about 6.7-6.8. It should be noted that the digester mixing efficiency test (Thiele 2009) had established that only about 50 % of the nominal digester volume was effectively participating in the sludge digestion putting the actual HRT closer to 13 days prior to the upgrade.

In stage I of the upgrade, digester D1 (fitted with an improved biogas recirculation mixing system) treated the full primary sludge (PS) flow of 110 m^3/day and produced virtually the same key digester performance indicators as before but at an HRT of 15+/- 4 days. This demonstrated that the temporary mixing system upgrade with the improved biogas recirculation system (Thiele 2009) was effective and allowed to practically double the well mixed and well contacted effective working volume in digester D1 (Table 1).

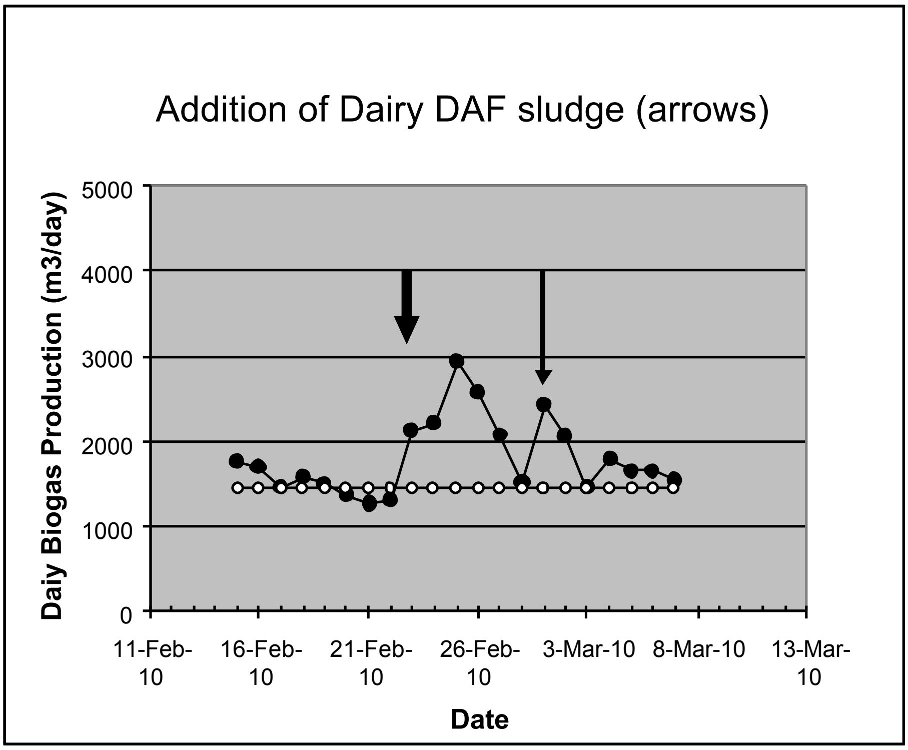
In the period January to March 2010 (stage II), digester D1 was compared side by side with digester D2 with the new hydraulic mixing system for more than 3 HRT, each receiving 50 % of the total PNCC PS load (about 55 m^3/day per digester tank). The digester D1 at 25+/- 3 days HRT (Table 1, stage II) produced practically the same key performance indicator values as during stage I in April to July 2009 when operated at 15+/- 4 days HRT (Table 1, stage I). This result demonstrated that the digestion of primary sludge in a well mixed digester was already complete at 15+/- 4 days. Increasing the digester D1 HRT to 25+/- 3 days did not further reduce the mixed liquor solids content or increase the daily biogas production, pH or alkalinity. However, slightly better key performance indicator results were obtained for the hydraulically mixed digester D2 between January to March 2010 when operated with primary sludge at 24 +/- 3 days.(Table 1, stage II). The residual solids content in the mixed liquor was indistinguishable from D1 but the pH as well as the mixed liquor alkalinity figures were significantly higher in the hydraulically mixed digester tank. Higher pH and alkalinity in the hydraulically mixed digester tank are both conducive to more stable co-digestion of primary sludge and added agro-industrial co-substrate waste.

The reason for the difference in pH and mixed liquor alkalinity between biogas recirculation mixing and hydraulic mixing is not fully understood. One hypothesis is that the observed difference could be partially due to the higher carbon dioxide pressure in the mixed liquor when injecting pressurized biogas for mixing.

In order to further validate the efficiency of the digester D2 upgrade with the hydraulic mixing system, dairy processing wastewater DAF sludge was selectively added to digester 2 for one month while receiving also ½ of the total PNCC PS load (Figure 2). A total of 164 m^3 of dairy processing DAF sludge were loaded to digester 2 representing about 10 % of the total volumetric load with primary sludge in this period. The strength of the incoming DAF sludge was not continuously monitored. From experience, the solids content would be between 10 - 15 % total solids and the fat content about 6-10 % (wet basis) of the loaded DAF sludge.

Figure 2: Rapid response time of PNCC digester system biogas production when small amounts of Dairy Processing sludge from Dissolved Air flotation (DAF) wastewater treatment were added to the hydraulically mixed digester D2. Both PNCC digester tanks (D1 and D2) were equally loaded during this period with PNCC primary sludge (55 +/- 10 m^3/day per tank, 4 % TS). Where indicated by the arrows, small amounts of additional Dairy DAF sludge were added to the primary sludge load to digester D2 only for a period of about 4 days each. The line with the open symbols represents the 4 year (2006-2009) daily biogas production average from primary sludge digestion (D1 + D2) at the PNCC WWTP in the months February and March.

$\Downarrow$: approx. 20 % of inflow to D2 as Dairy DAF sludge; $\downarrow$: approx. 10 % of total inflow to D2 as DAF sludge



Despite the significantly increased organic loading rate to digester D2 with the added DAF sludge, the hydraulically mixed digester system responded very well to the DAF sludge addition (Figure 2). Foam or fat layers did not build up in the tank , the VFA levels remained below 40 mg/L (Table 1, stage II) and the key performance indicators in the mixed digester liquor were virtually indistinguishable from the digester D2 operation with primary sludge alone (Table 1, stage II).

The added biogas yield in the period 23 February – 28 March 2010 resulting from dairy DAF sludge addition to digester D2 was determined by subtracting the four year average combined PNCC Totara road digester daily biogas production in the months February/March from the combined PNCC Totara road digester daily average biogas production in February/March 2010. More than 400 m^3/day additional biogas were formed for one month on average in the hydraulically mixed digester tank (D2) when receiving 10 % additional DAF sludge.

This preliminary result was used to estimate the total achievable daily biogas production increase from adding dairy DAF sludge to both digesters once the upgrade is complete (i.e., D1 and D2 both fitted with the new hydraulic mixing system). Based on an assumed sustainable added DAF sludge load of 20 % of the daily primary sludge flow (Figure 2 fat, arrow) the preliminary results available to date suggest the potential for additional biogas production of approx. 1600 m^3/day from DAFD sludge digestion practically doubling the daily digester gas production at the PNCC Totara Road WWTP (Table 1, last row: 2 digester tanks, added dairy processing DAF sludge 20 % of primary sludge flow to both digester tanks). This result therefore confirmed and validated the previously stated expected daily digester gas production improvement potential from co-digestion of primary sludge and added selected agro-industrial co-substrate waste (Thiele, 2009).

2.2 KEY CONSIDERATIONS FOR INCREASING THE DIGESTER GAS OUTPUT

The results of the digester mixing system upgrade efficiency validation at the PNCC Totara Road digesters presented in section 2.1 above are fully consistent with the international experience on co-digestion of primary sludge and selected co-substrate waste materials. However, the achieved daily biogas production through traditional co-digestion approaches (Figure 2) corresponds to an average hourly methane production of about 90 – 100 m^3 methane/hour and thus falls short of the PNCC digester gas production target of more than 180 m^3 methane/hour.

CPG proposed thus to add recuperative sludge thickening (booster technology) to the well mixed and contacted PNCC digesters (Thiele 2009). This step allows to thicken the anaerobic sludge in the digester effluent and by returning the thickened sludge into the digesters thickens the mixed liquor in the digester tanks from 1,5 % total solids content (Table 1) to more than 3 %. As a byproduct, this doubles the active anaerobic bacteria sludge concentration and active anaerobic sludge mass in the PNCC digesters allowing to double the organic loading rate and digester gas production. As additional benefit, the sludge age of the anaerobic sludge in the digesters is also doubled.

Booster technology addition also allows double the hydraulic loading rate to the existing well mixed digesters from 110-120 m^3/day (currently with primary sludge) to about 220-240 m^3/day (primary sludge PLUS selected suitable agro-industrial co-substrate waste materials, see tables 2 and 3 below) because of the improved anaerobic sludge retention through the thickening step. This technique was first applied at the digesters of the CPG designed Sydney biomass facility in 2002 (2 x 5,500 m^3 digester tanks; Thiele 2000, Hearn and Thiele 2004).

The "booster step" at the PNCC Totara Road digesters is currently under design and the booster implementation through addition and integration of a 25 m^3/hour throughput drum thickener is expected to be completed by the end of 2010. The system will be fully automated. The added power consumption for additional pumps and the thickener is in the order of 400-500 kwh/day and is expected to be less than 5 % of the added power production from the additional digester gas output generated through the booster step. The added cost for polymer flocculants are expected to be in the vicinity of 10-20 % of the value of the additional power production from the booster step.

The co-digestion of agro-industrial and municipal co-substrate waste with high fat contents (grease trap waste, DAF sludge) is highly desirable because the methane production from the fat content in co-substrate materials (m^3 methane produced/kg VS loaded) is about 3 times the methane production from carbohydrate content such as starch, sugar or cheese whey.

The biological digester process design limits and issues for the anaerobic digestion of fat, oil and grease have been described elsewhere (Broughton et al., 1998) and will not be further discussed here. However, a doubling of the active anaerobic bacteria sludge concentration and active anaerobic sludge amount in the PNCC digesters through use of the booster technology allows to double the daily fat loading rate without added process risks.

2.3 CO-DIGESTION WITH BOOSTER TECHNOLOGY INSTALLED

Figure 3 below gives a general outline of the co-digestion process model developed by CPG to design anaerobic co-digestion processes with and without booster step. These processes are suitable for co-digestion of municipal biosolids and selected agro-industrial waste materials in well mixed digester tanks. The mass balance process model of CPG is very flexible and can be applied to any co-substrate waste mixture and any municipal and industrial sludge digester facility.

Figure 3: Outline of the process steps included in the mass balanced co-digestion model. Input materials are specified as daily load (t/day wet), total solids content (%TS), volatile solids content (% VS in TS), nitrogen content (TKN; mg/L) and fat, oil and grease content (FOG, mg/L). Outputs are the expected daily biogas production from each digester and the flow and composition of treated effluent and surplus thickened sludge.

Recuperative sludge thickening flows $\boxed{3}$ and $\boxed{5}$ are variable and user programmable as well as $\boxed{4}$, the transfer of thickened digester sludge from digester 1 to digester 2.

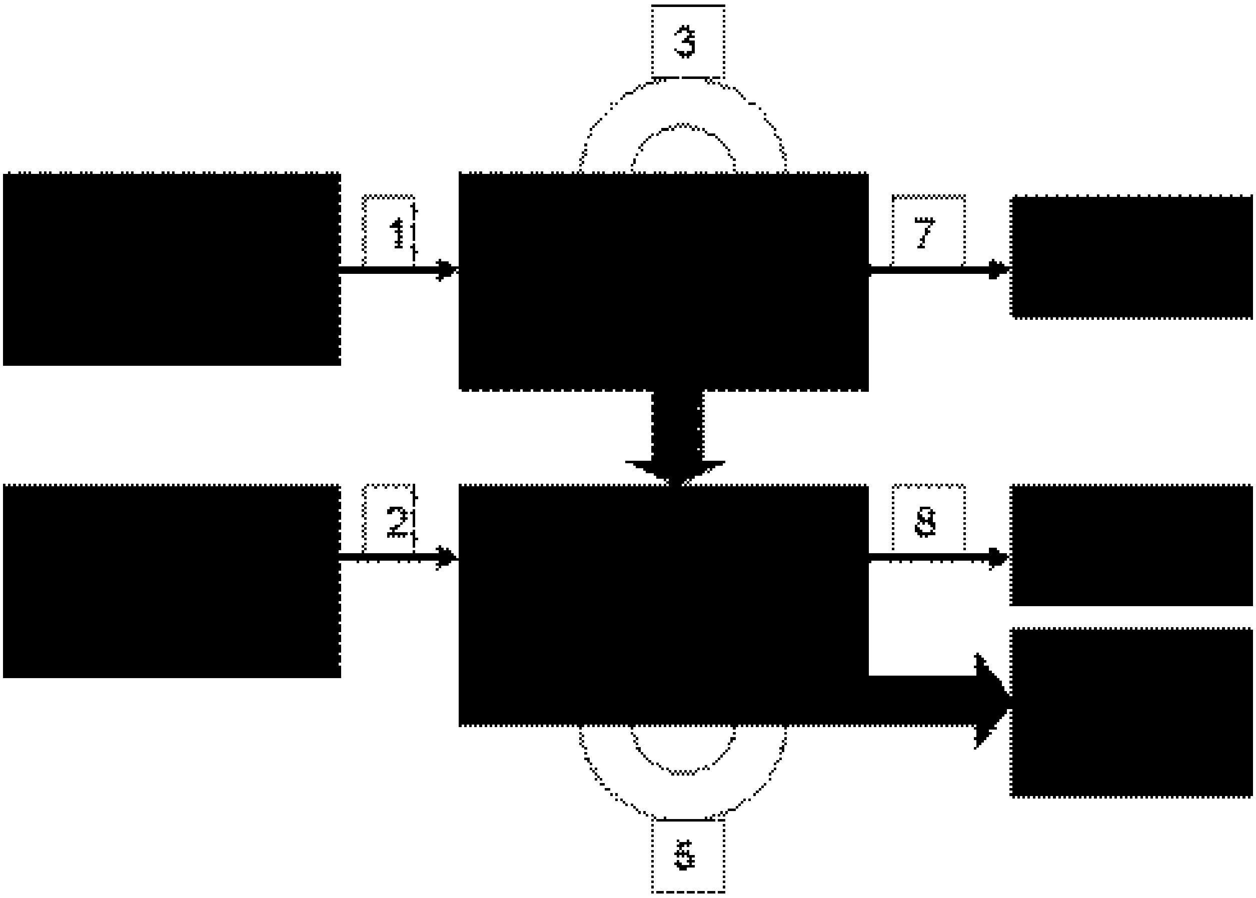


Table 2 and 3 below give examples of two mass balance calculation results for different co-substrate waste mixtures for the PNCC co-digestion facility. As expected, the waste mixture with a higher content of fat oil and grease (FOG) produces a higher methane content in the biogas of around 70 % methane (Table 2).

Both co-substrate waste mixture scenarios presented are within the limits of the available resource potential in the greater Palmerston North area. Both scenarios produce an expected hourly digester gas production of more than 180 m^3/hour methane with booster technology in 2700 m^3 digester volume and meet therefore the future digester gas production requirements of PNCC from its existing Totara Road sludge digesters. The expected digester gas production after completion of the digester upgrade with hydraulic mixing and booster step is more than 400 % of the digester gas production achievable from primary sludge alone prior to the upgrade (45 m^3 methane/hour).

Table 2: Typical mass balance summary information provided by the co-digestion model for a feedstock mixture with comparatively high content of fat, oil and grease (FOG: > 19-20 % FOG in total solids). The total digester volume was 2,700 m^3 including recuperative sludge thickening (booster technology). The expected total daily biogas production was 7570 m^3/day at 70 % methane (+/- 15 % relative uncertainty). The model assumes that 15 % of the biogas mass is from water incorporation during the hydrolysis stage of the digestion of biomass.

The sludge solids capture efficiency in the sludge thickener was conservatively set at 70 % capture and the return sludge thickness at 8 % TS. The specific loading rate with FOG in the digesters was less than 0.05 kg FOG/kg VSS/day and the sludge residence time in both digesters on average more than 35 days.

		Units	Amounts
Flow	Total flow in	m^3/day	211.6
	Total flow out	m^3/day	211.6
Total Solids (TS)	Total TS in	t/day	13.0
	Total TS out	t/day	13.0
	biogas TS	t/day	8.92
	sludge	t/day	0.73
	filtrate	t/day	4.72
	1.097	biogas (kg/m3) dry	
	70.00%	methane in biogas	
Input materials	Primary sludge	t/day	110
	Pig slurry	t/day	28.6
	Dairy WW DAF float	t/day	20
	Grease trap waste	t/day	20
	incl. FOG	t/day	2.5

Table 3: Typical mass balance summary information provided by the co-digestion model for a feedstock mixture with normal content of fat, oil and grease (FOG: < 19-20 % FOG in total solids). The total digester volume was 2,700 m^3 including recuperative sludge thickening (booster technology). The expected total daily biogas production is 7850 m^3/day at 64 % methane (+/- 15 % relative uncertainty). The model assumes that 15 % of the biogas mass is from water incorporation during the hydrolysis stage of the digestion of biomass.

The sludge solids capture efficiency in the sludge thickener was set at 80 % capture and the return sludge thickness at 8 % TS. The specific loading rate with FOG in the digesters was less than 0.03 kg FOG/kg VSS/day and the sludge residence time in both digesters on average more than 35 days.

		Units	Amounts
Flow	Total flow in	m3/day	222.2
	Total flow out	m3/day	222.2
Total Solids (TS)	Total TS in	t/day	11.5
	Total TS out	t/day	11.5
	biogas TS	t/day	9.21
	sludge	t/day	0.88
	filtrate	t/day	2.81
	1.172 biogas (kg/m3) dry		
	64.00% methane in biogas		
Input materials	Primary sludge	t/day	110
	Cheese whey	t/day	25
	Pig slurry	t/day	28.6
	Dairy WW DAF float	t/day	15
	Grease trap waste	t/day	11.5
	incl. FOG	t/day	2.1

3 CONCLUSIONS

The digester upgrade program for the PNCC Totara Road WWTP for co-digestion of primary sludge and selected agro-industrial waste materials has been successfully validated. The actual operation data after the upgrade show that digester clean-out and upgrade with a hydraulic digester mixing system allows to double the daily digester gas production of the existing digester tanks from 45 m^3 methane/hour to about 90 m^3 methane/hour providing the basis for co-digestion of primary sludge and industrial wastewater sludge with high fat content. Extensive digester process design and modeling work has shown that a further doubling of this improved rat to digester gas production levels above 180 m^3 methane/hour is technically feasible through the use of recuperative sludge thickening and return of the anaerobic digester sludge (booster step technology). A booster step using drum thickener technology is currently under construction for the PNCC digesters and completion of the digester upgrade is expected by the end of 2010. First booster step operation results are expected in 2011. Subject to availability and successful sourcing of suitable selected agro-industrial waste materials this digester upgrade of two existing digester tanks has thus created the additional digester gas production capacity of two additional new digester tanks at a fraction of the equivalent capital costs.

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