Sustainable Energy Research, Development & Demonstration Programme 2016

RD&D Project No 99

# ADbag project, Phase 3 – design for manufacturing and pilot demonstration

# Contents

## 1 Introduction

Over the last two decades about 17.000 Anaerobic Digesters have been built in Europe, but over the same period the contraction of the CAPEX has been negligible, especially for the small-scale plants.

At the beginning of 2015 Demetra started the ADbag Project to improve the economic and technical aspects of small-scale AD plants, believing that an extensive diffusion of small plants will have strong environmental impact helping a larger exploitation of the renewable energy.

The project has been designed in four phases which started since the middle of 2015.

Phase 3 is the part of the project for which we applied for founding at the SEAI RDD Programme. It has provided both the definition of the specifications of the whole parts of the plant and the deployment of a pilot plant to test the solutions and evaluate the fallouts.

## 2 The four phases

The previous and completed phases are:

*Phase 1: Analysis on potential improvements for small biogas plants (Ireland/EU).* The analysis went through the design and operational aspects of the existing AD systems. We combined this set of information with our experiences and our already innovative patents and solutions. We defined a set of steps and technologies that were most suitable to solve some of the problems identified. A first draft of the new system was defined. This phase was completed by the beginning of 2016.

*Phase 2: Development of a set of solutions. Digital models and Computational Analysis.* We started to solve the details of the new system and we identified some of our suppliers. The most important piece of analysis was a Computational Fluid Dynamic Analysis that was aiming to clarify the behaviour of the treated sludge in our innovative reaction tank. An Enterprise Ireland Innovation Voucher helped us to engage with the department of Engineer in DCU and we developed a computer model which provided information on the potential flow of the jet mixing system as well as on the shape of the jets.

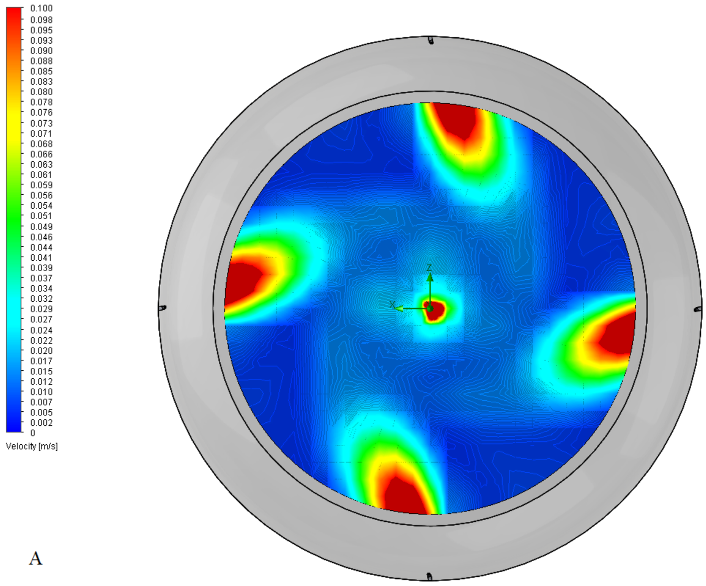


**Fig. 1** - *Computational Fluid Dynamic Analysis on the Bag Tank*

As said *Phase 3: Design for manufacturing and pilot demonstration* is the theme of this RDD and will be extensively described here further.

*Phase 4: Market deployment. Marketing strategy, Construction of the first plant.* The fourth phase will start with the conclusion of the tests on the pilot. We will disseminate the results and we organize visits to the installation. A marketing strategy for Ireland and UK and one for the rest of the World will be drafted.

## 3 The design for construction

The plant could be divided into two blocks: on one side the reaction tank and on the other side the technical container.

One of the innovative aspects of our product is that the reaction tank will be made in Polyvinylidene fluoride a weldable, chemicals resistant plastic sheet from which we will produce a sort of ellipsoid bag. All the pipes for the recirculation of the sludge, the pipe for the gas and the control devices are connected to the bag by specially designed flanges installed on the bag during construction.

The technical container houses the pumping station, the heat exchanger, the control panel and where required, the CHP.

The pumping station system is responsible for the recirculation, heating and mixing of the sludge. Through a central pump it can address the feedstock coming from the drainage point of the bag to the jets through the heat exchanger or to the sprinkler on top of the bag or to the discharging tank.

The control system operates the whole plant. Through a few pressurized air controlled valves, it will run the day by day operations following a defined program and a number of data retrieved from the plant itself.

After Phase 2 a quite defined general definition of the plant was agreed between the design team. The suppliers of the main parts of the systems were identified. The product was decided to be produced in three different sizes: 12, 15 and 18 meters diameters corresponding to 375, 588 and 850 m3 of volume of process in order to accommodate a much wider set of potential customers.

During the design for construction phase we engaged our suppliers in order to refine the technical aspects as much as we could.

The full set of details for piping and cabling of the technical container where developed with the help of Biogas Engineering srl and the final details for the construction of the bags where completed by PM Engineering srl which is in charge of the bag production and supply.

A full bill of quantities has been defined and a set of manuals has been drafted.

## 4 AD-bag features vs. other digesters

AD-bag design is aimed to achieve a cost-effective device to produce biogas in small installations, such as dairy farms or little food processing facilities. Simplifying the plant management and maintenance and decreasing the energy consumptions were taken in consideration as other key factors.

A short overview of the digester types may highlight most substantial features of the AD bag. Digesters can be classified in 3 main categories:

1) Concrete/ steel tanks, that can be built either in a cylindrical or parallelepiped shape
2) Egg-shape digesters
3) Green-Heart Digesters

**Concrete tanks (Fig.2)** are the most common digester that we find among the present AD installations. Steel is sometimes employed as a construction material taking in account some economical issues. The parallelepiped shape suits the plug-flow fluid-dynamics profile and the high density feedstock, such as dense sludge or OFMSW, when a dry process is run. This kind of digesters strongly affects the capital cost of an AD plant, as due to the materials cost and the significant construction commitments. Almost any kind of mixing systems can be installed.

**Fig. 2**

**Egg-shaped digesters (Fig.3)** are widely used for the Waste-Water Treatment Plants sludge digestion, when running a wet process. This kind of digester suits the installation of a jet-mixing system. The required space is strongly reduced, though the capital cost is quite high, due to the peculiar shape of the tank.

**Fig. 3**

The **Green-Heart digesters (Fig.4)** have been installed to provide an environmentally friendly solution for big installations within some protected areas as natural parks in Italy. GH is actually an anaerobic lagoon, provided with some advanced management and control systems. Capital cost is lowered comparing to the traditional concrete/steel digesters, as the walls are built with soil and covered by some layers of plastic sheets. As there’s no mixing system installed, GH digesters require huge process volumes and large areas for installation.

**Fig. 4**

**Mixing** is a design key factor for any AD installation. Anaerobic digesters usually employ **mechanical impellers (Fig.5)** to provide a proper agitation of the process volume.

Some **gas-lifter systems (Fig.6)** are also supplied for the digestion of WWTP sludge. Mixing is provided by biogas high-pressure recirculation inside the tank. **Jet- mixing (Fig.7)** is an alternative agitation system that shows some advantages compared to conventional mechanical mixers:

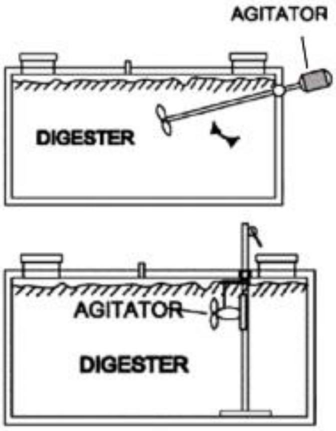


Fig. 5

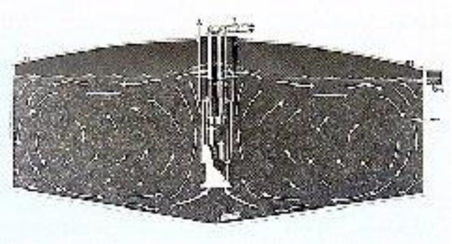


Fig. 6

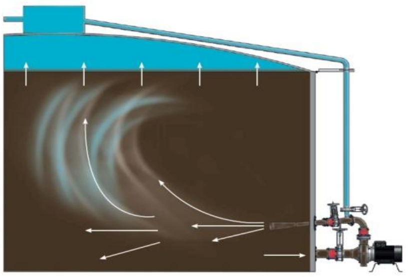


Fig. 7

- No moving parts are installed
- No support is required at the top or at the walls of the tank to hold the mixers
- Capital and maintenance cost are lower
- Energy consumption can be lower

In jet mixing, a pump sucks the liquid sludge from the tank (usually from the bottom) and re-circulates it at high velocities through some nozzles. Some transport phenomena occur as follows:

- the liquid is thrown at high velocity from the jet nozzle to the tank volume;
- while circulating inside the tank volume, the liquid induces a bulk transport of secondary liquids into the jet, so that the overall a significant increase of the mixing effect;
- by installing a proper number of nozzles inside the tank and regulating the jet velocities, mixing can be optimized.

The following table summarizes the advantages and disadvantages of the 3 AD conventional types and the AD bag, taking in account 4 point of views:

- "Light / low-cost materials" indicates the chance to reduce the overall capital costs of the plant, providing a simpler technical solution as well.
- "No foundations" concerns the construction commitments, especially connected to the reinforced concrete use and the yard management.
- "Reduced space" refers to the required area to build the plant, that sometimes is not available.
- "Jet-mixing" indicates the opportunity of employing an efficient mixing system, without using any mechanical devices, that could be a good advantage in terms of plant maintenance and energy consumptions.

| | Concrete / Steel Tanks | Egg-Shaped digesters | Green-Heart Solution | AD bag |
|---|---|---|---|---|
| Light / low-cost material | (−) | (−) | (+) | (+) |
| No foundation | (−) | (=) | (+) | (+) |
| Reduced space | (=) | (+) | (−) | (+) |
| Jet-mixing | (=) | (+) | (=) | (+) |

(+): advantaged / (=): neutral / (-): disadvantaged

AD bag shows the best performances regarding all the 4 points of view.

## 5 Design of the pilot plant

Based on the specs and drawings of the full plant we derived a set of information to build an in-scale pilot plant.

The pilot scale was set to be 1/100 in volume of the 18 Mt diameter unit. Not providing gas to a CHP or a gas boiler, the plant was decided to be heated by two electric residential instantaneous boilers. The gas produced will be stored in a gas holder and a pressure driven valve will release it when reaching certain values.

Great accuracy was given to design all the recirculating system in scale to retrieve a set of data that will be easily comparable with the full-scale plant.

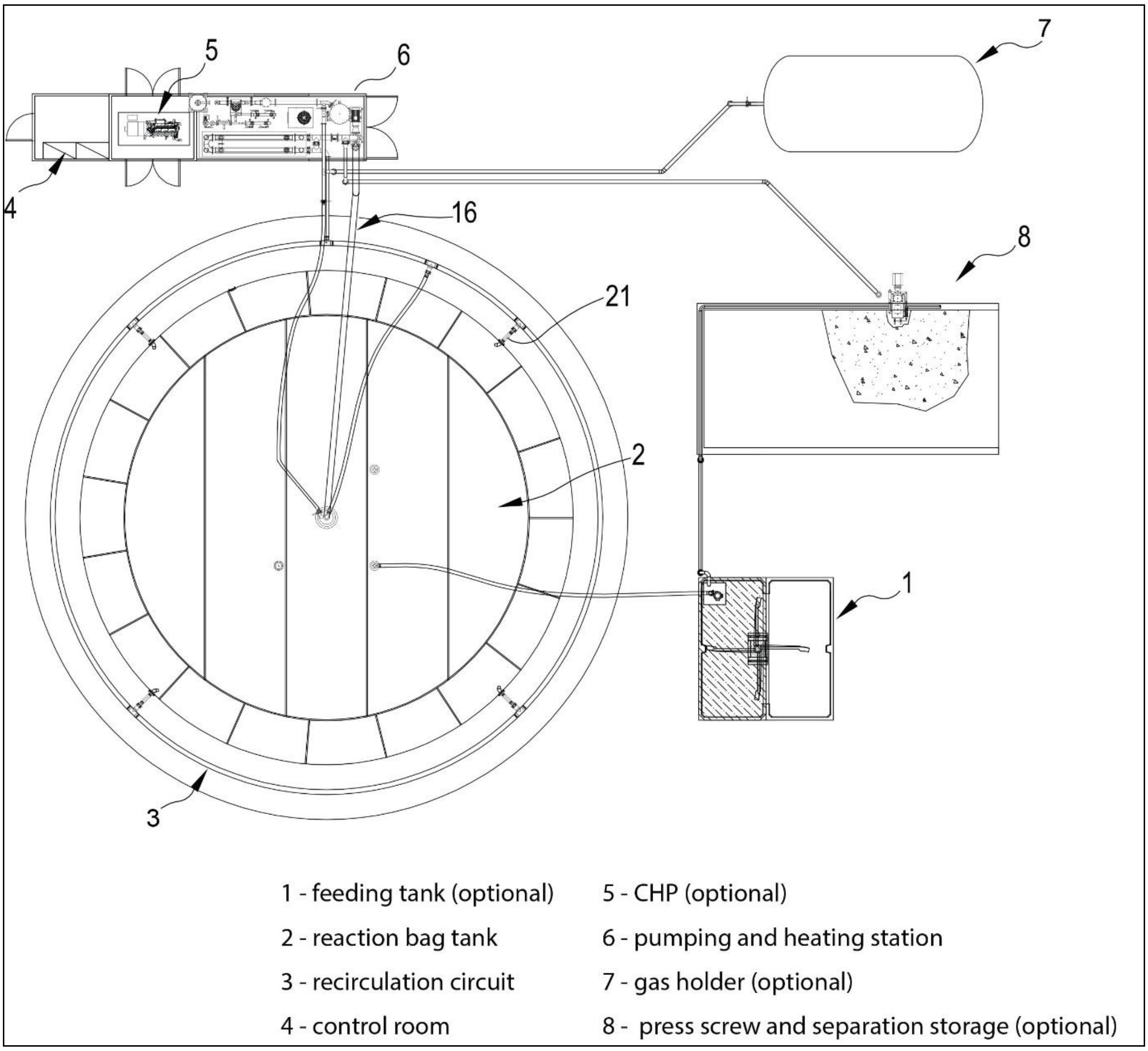


**Fig. 8** - *Scheme of the final standard installation of an ADbag 18mt*

The pilot plant supply provided:

- Nr.1 feeding tank inside the technical container and nr.1 further tank outside
- Nr.1 reaction bag tank downscaled 1/100 with the recirculation unit
- Nr.1 technical container with the main feeding tank, the pumping/heating station and the control room

| Feeding tank | Reaction bag tank |
|---|---|
| - Nr.1 1 IBC- CUBE of 1 m3 capacity positioned inside the container (a further cube was located outside to manage the slurry and whey loading to the system); the tank is stirred by a vertical mechanical mixer to provide an homogenous mixture to the digester<br>- Nr.1 2-blade vertical mixer 1,1kW;<br>- Nr.1 Centrifugal chopper pump 1,1kW controlled by the supervising system that sets loading times and flowrate;<br>- Nr.1 liquid collection pneumatic valve from feeding tank (EV-AL valve)<br>- Nr. 1 Flow-rate measurement device | - Nr.1 plastic fabric ellipsoidal-shape tank (capacity = 9,000 liters)<br>- Nr.1 loading/irrigation system provided with a sprinkler at the top of the digester; Nr.1 valve (EV-SP) is connected to a sprinkler at the top of the digester, and can operate automatically and manually;<br>- Nr.4 jet nozzles – diameter = ¾" positioned at the AD-bag "equator" level<br>- Nr.1 float ball for level measurement<br>- Nr.1 temperature measurement device<br>- Nr.1 digester mixing valve (EV-UG) connected to the 4 nozzles;<br>- Nr.1 drainage valve to load the exhausted material (EV-SC); |

The mixing system is equipped by a pneumatic valve (EV-UG) that feeds the nozzles. The system operates by setting the frequency (Hz) of the pump and the pause/working times.

The irrigation system depends on the performance of the sprinkler. Each irrigation operation is managed by an automatic cycle: the pump frequency varies through the cycle time, so that the spray path from the sprinkler will cover all the liquid surface.

The digester discharge is managed by the float ball measurement.

The heating system is equipped with a tube-in-tube stainless steel heat exchanger connected to a electrical boiler and a water circulator.

The following images (Fig. 9-10-11-12) and the table illustrate all the installed devices.

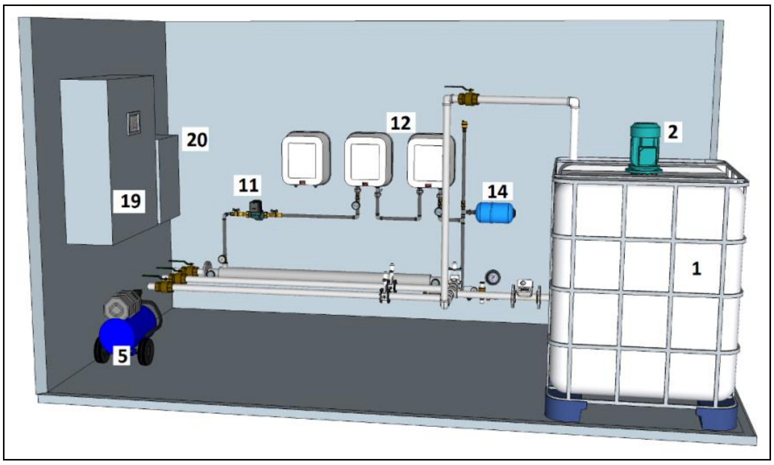


Fig. 9

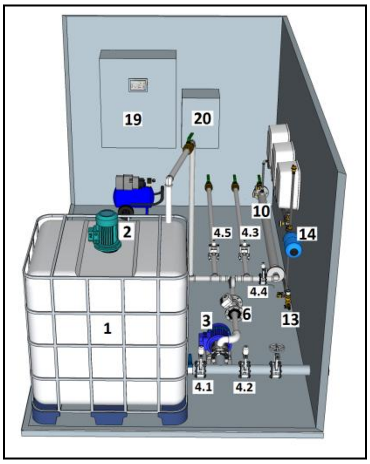


Fig. 10

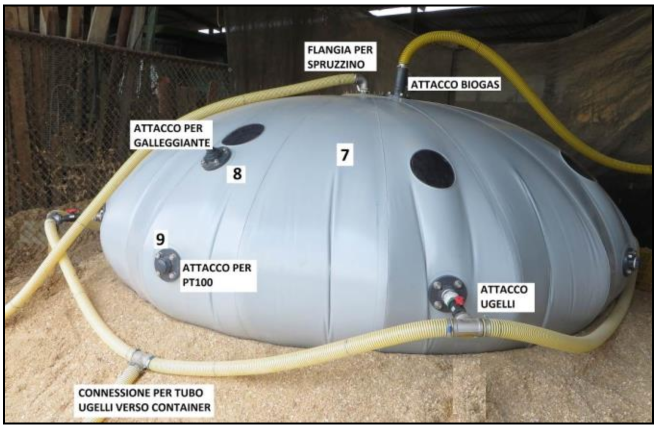


Fig. 11

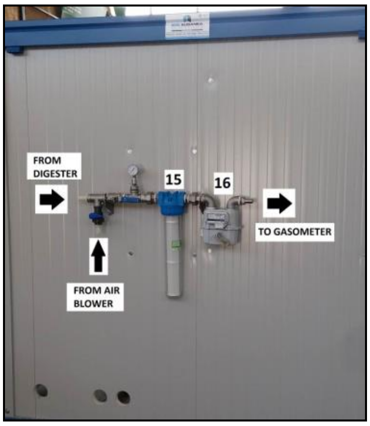


Fig. 12

| N° | Item | Nr. | Item |
|---|---|---|---|
| 1 | Feeding tank (IBC) | 9 | Temperature measurement device |
| 2 | Feeding tank mixer - 1.1kW | 10 | Tube-in-tube heat exchanger |
| 3 | Centrifugal chopper pump - 1,1kW | 11 | Hot water circulator - 0.1kW |
| 4.1 | Pneumatic valve (EV-AL) | 12 | Boiler - 3.2kW |
| 4.2 | Pneumatic valve (EV-DG) | 13 | Inlet for hot water circuit |
| 4.3 | Pneumatic valve (EV-SP) | 14 | Expansion tank |
| 4.4 | Pneumatic valve (EV-UG) | 15 | Biogas filter 20” |
| 4.5 | Pneumatic valve (EV-SC) | 16 | Biogas flowmeter |
| 5 | Compressor - 24 Litres | 17 | 1000 litre gasometer |
| 6 | Flowmeter | 18 | Overpressure safety valve 10mbar |
| 7 | Anaerobic Digester | 19 | Control panel and supervising system (QGP) |
| 8 | Float ball level measurement | 20 | Electronic valves control panel (QEV) |

## 6 On the field

The reaction bag produced by PM Engineering following our details has been delivered to our partners in Vicenza on the 12th of August. The bag has been subsequently tested in one of our Italian facility for leakages with water under pressure and a first assessment of the recirculating system was done.

The technical container has been delivered on the 30th of August after a series of test providing evidence of the correct installation of the full set of components and parts.

Heating system, pumping system and the control panel which collects data from all the digital checking points resulted perfectly working.

The container and the bag were shipped to Ireland and reached their destination at the Hayes Farm in Tipperrary on the 7th of September.

The day after the delivery of the container at Tipperary Cheese Company, we received 12 tons of fine sand that we shaped as the cradle of the bag-tank. We buried the drainage pipe in the sand after connecting the pipe to the bag and proceeded to lay the bag in the cradle. The four equatorial inlets and the recirculation ring were installed followed by the top inlet. In order to place correctly the equatorial inlets, the four jets were marked at the factory in order to provide a reference point for installers and operators to determine the angle of orientation.

All the pipes were then connected to the container. The gas holder was installed and secured on the roof of the container and the outlet valve was set on a pressure of 25 mm bar.

A blower pump was connected to a secondary valve of the gas circuit and we proceeded to inflate the bag.

The following day a layer of insulation was lain on the external part of the bag and between the sand and the bag in order to prevent major loss of heat. A waterproof membrane was lay on top of the insulation to cover the full set up.

The following day 4 cubic meters of seeding digestate was pumped into the feeding tank and subsequently injected into the bag. The recirculation circuit was set in motion and the boilers feeding the heat exchangers were activated.

The temperature probe was put in place and connected to the control panel. All the main circuits and valves were tested.

From the following morning the Digester was fed with fresh hot whey in order to reach the right amount of processing sludge and keep the temperature as high as possible.

Since then the plant has been operated and monitored remotely.

**Fig. 13** - *Final set up of the pilot plant at Hayes Farm, Two Mile Borris, Co, Tipperary.*

## 7 Tests run on the pilot plant

The purposes of a pilot plant, in our case, were to check the efficiency of the mixing system and its energy consumption on one side, and on the other to confirm that the behaviour of the biology of such a plant could be equate to the one of a standard AD plant.

### 7.1 Efficiency of the mixing system and its energy consumption

The fluid behaviour can be investigated by two points of view:

*Rheology.* A fluid can show a newtonian behavior, that means that the viscous stress arising from its flow is linearly proportional to the strain rate, so that flow patterns can be easily predicted. Compared to water, that can be taken as a typical newtonian fluid, some slurries and suspensions show non-newtonian behavior; feedstock that is usually fed to an AD system and that is mainly composed of animal slurries, organic liquids and fibrous biomass, can be classified as a non-newtonian fluid. By the anaerobic digestion process slurry behavior gets closer to a newtonian fluid, as a result of a decrease of both the solids content and viscosity of the material, and the raise of the temperature; nevertheless, as a precautionary approach, we'll consider a non-newtonian behavior inside the ADbag

*Flow patterns.* Flow inside the ADbag can be characterized as laminar (where viscous forces are prevalent), or turbulent (where inertial forces are dominant). In laminar flow, the fluid travels in regular paths, as occurs with low velocities and high viscosities liquids. In turbulent flow some vortices appear and interact with each other, as occurs with high velocities and low viscosities; thus, turbulent flow promotes good mixing inside a tank. Flow pattern can be estimated on the basis of the dimensionless Reynolds number, which is the ratio of inertial to viscous forces in a flow, expressed as $Re = \rho u\ d\ / \mu$ where $Re$ is Reynolds number, $\rho$ is the fluid density, $u$ is characteristic velocity, $d$ is characteristic length, and $\mu$ is dynamic viscosity.

It is commonly accepted for mixing, that Reynolds numbers less than 10 indicates laminar flow, while Reynolds numbers greater than $10^4$ indicates turbulent flow; among the in-between Reynolds numbers flow is transitional.

One of the most peculiar phenomenon observed in non-newtonian mixing systems is the "cavern formation". A cavern is basically a bounded region near the mixing devices that is highly agitated and turbulent surrounded by a region of stationary material. The ADbag shape, which is similar to a cavern, has been also determined in order to prevent the formation of a stationary volume and to optimize the mixing patterns.

In the pilot ADbag system the jet-mixing equipment has been supplied as follows:

- Nr. Jet nozzles = 4
- Nozzle diameters = ¾ " = 18.75mm

- Nozzle Section = 0,000276 $m^2$

As a result of the pilot ADbag test, we got some information about the flow patterns of the slurry. The first test has been made with water, which was pumped at 20 $m^3$/h, that corresponds to a 5,0 m/s velocity at each nozzle. Water viscosity is equal to 0.001 Pa s, so that the Reynolds number can be easily calculated:

Re = (5,0 x 0,01875 x 1.000) / 0,001 = 9.4 x $10^4$

The test with water showed:

- a massive turbulence inside the digester, as water shoved violently on the bag internal surface;
- a big vortex in the center of the digester, that leaded to air suction into the recirculating pump.

These results pointed out that a Reynolds number close to $10^5$, with that kind of arrangement (4 nozzles + 1 suction from the bottom of the bag) identifies a high turbulence flow pattern.

The same test has been done with cow slurries and whey: although the phenomenon was reduced, turbulent flow and a remarkable vortex have been noticed as well, so that 5 m/s can be taken as the upper limit velocity at the nozzles. Besides, as we assumed that a stable turbulence pattern occurs with *Re* > $10^4$ and the other parameters won't vary ($\rho$, $d$, $u$), we found out that the viscosity of the digestate may be estimated by one order of magnitude higher than water and equal to 0.01 Pa s. This is one of the first main outcome of the tests on ADbag.

As a matter of fact, viscosity is quite difficult to determine when dealing with slurries and sludge. Dense sludge can reach 0.5 Pa s values, that means 500 time higher than water. Viscosity depends on several parameters, but shows a sensible drop by increasing the process temperature and decreasing the solid content of the slurry; both phenomena occur in an AD reactor.

Jet mixing has been tested with 1, 2, 3 and 4 nozzles working; the results are indicated in the following table.

| Nr. Nozzles | Frequency (Hz) | Electrical Current (A) | Plant Power (W) | Pump Power (W) | Pump Flowrate (m3/h) | Specific Power (W / m3 /h) | Velocity | Re |
|---|---|---|---|---|---|---|---|---|
| **4** | 30 | 1.9 | 1,027 | 688 | 11.9 | 86.3 | 3.0 | 6.2E+03 |
| | 35 | 2.1 | 1,135 | 760 | 14.1 | 80.5 | 3.5 | 7.3E+03 |
| | **40** | **2.4** | **1,297** | **895** | **16.7** | **77.7** | **4.2** | **8.7E+03** |
| | 45 | 2.7 | 1,459 | 978 | 19.3 | 75.6 | 4.9 | 1.0E+04 |
| | 50 | 3.1 | 1,675 | 1,106 | 21.5 | 77.9 | 5.4 | 1.1E+04 |
| **3** | 30 | 1.9 | 1,027 | 688 | 11 | 93.3 | 3.7 | 7.6E+03 |
| | 35 | 2.2 | 1,189 | 797 | 13.2 | 90.1 | 4.4 | 9.1E+03 |
| | 40 | 2.4 | 1,297 | 895 | 15.3 | 84.8 | 5.1 | 1.1E+04 |
| | 45 | 2.7 | 1,459 | 978 | 17.8 | 82.0 | 6.0 | 1.2E+04 |
| | 50 | 3 | 1,621 | 1,070 | 19.9 | 81.5 | 6.7 | 1.4E+04 |
| **2** | 30 | 1.8 | 973 | 652 | 9.4 | 103.5 | 4.7 | 9.8E+03 |
| | 35 | 2 | 1,081 | 724 | 11.2 | 96.5 | 5.6 | 1.2E+04 |
| | 40 | 2.3 | 1,243 | 858 | 13.2 | 94.2 | 6.6 | 1.4E+04 |
| | 45 | 2.5 | 1,351 | 905 | 15 | 90.1 | 7.5 | 1.6E+04 |
| | 50 | 3 | 1,621 | 1,070 | 16.7 | 97.1 | 8.4 | 1.7E+04 |
| **1** | 30 | 1.8 | 973 | 652 | 5.9 | 164.9 | 3.0 | 6.1E+03 |
| | 35 | 2 | 1,081 | 724 | 7.1 | 152.2 | 3.6 | 7.4E+03 |
| | 40 | 2.2 | 1,189 | 820 | 8.3 | 143.2 | 4.2 | 8.6E+03 |
| | 45 | 2.4 | 1,297 | 869 | 9.5 | 136.5 | 4.8 | 9.9E+03 |
| | 50 | 2.7 | 1,459 | 963 | 10.6 | 137.6 | 5.3 | 1.1E+04 |

**Table 1** - *Relation between pump cycles and power consumption*

Pump flowrate was set by regulating the frequency from 30 Hz to 50 Hz.

Display shows the value of electric current, so we can determine the actual electric power of the pump, with the following formula (for instance we take the optimum working set: 4 nozzles + 40 Hz)
P = 1,73 x (400V) x (2.4 A) x 0.78 = 1,297 W

Pump power was a fraction (about 65-70% of the overall power) of P, and reaches the maximum value at 50 Hz**.**

**Fig. 14**

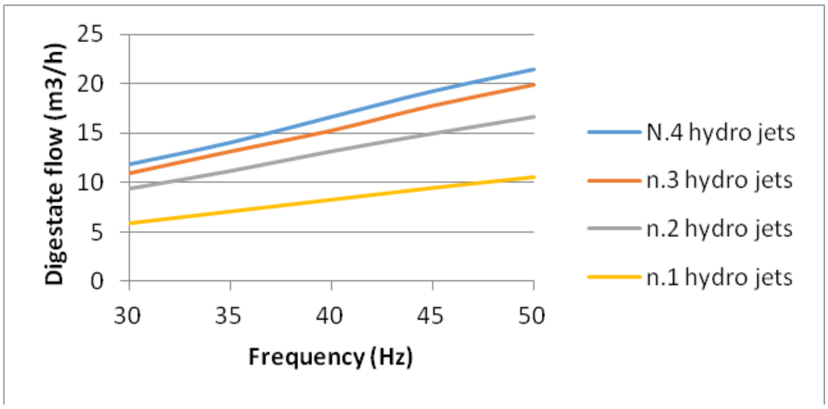


**Fig. 15**

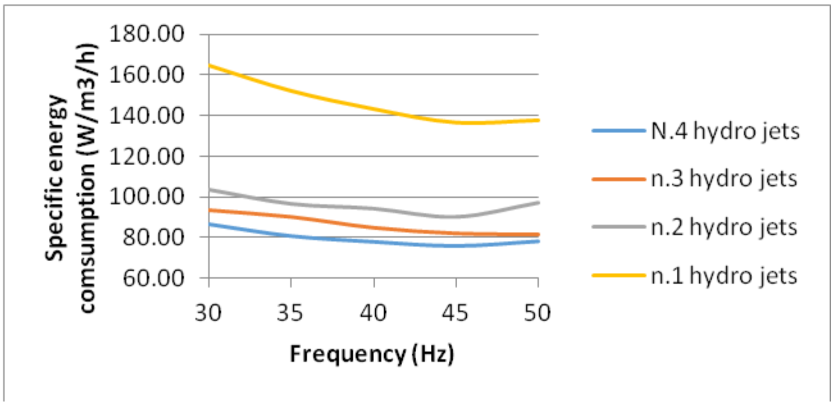


**Fig. 16**

4 operating tests have been made with in all cases, flowrate is proportional to the frequency. A 4 nozzle arrangement seems to be the optimal; the straight lines become nearer and nearer by adding further nozzles; more units seem to produce no increase in flowrate inside the ADbag.

Specific energy consumption shows a similar behavior.
Taking the same liquid flowrate, the 4-nozzle arrangement shows the optimal performance; further units wouldn't give any decrease.

The optimal working situation corresponds to a 40 Hz frequency that leads to 4,2 m/s nozzle velocity and Re = 8,7 x $10^3$

## 7.2 ADbag scaling-up

Scaling up ADbag test data is essential to predict the energy consumption for future installations in farms and industries.

We will compare a Small Scale tank (S), which corresponds to the pilot plant we tested, to a Large Scale tank (L), which corresponds to the actual digester that has to be installed.

| | **S** | **L** |
|---|---|---|
| Diameter | 3.8 m | 18.0 m |
| Height | 1.2 m | 5.0 m |
| Total Volume | 9 $m^3$ | 848 $m^3$ |
| Process Volume | 8 $m^3$ | 760 $m^3$ |

A scaling approach can be taken form “Preliminary Scaling Estimate for Select Small Scale Mixing Demonstration Tests” (B.E.Wells et altri -PNNL -22737 U.S, Department of Energy – September 2013). The aim is to determine the velocity that guarantees the same slurry concentration in both scales, that is given by the following formula:

$$\mathbf{u_L / u_S = (D_L/D_S)^{\alpha}}$$

Where:
$u_L$, $u_S$ = *jet velocities in large (L) and small (S) tank*
$D_L$, $D_S$ = *diameter in large (L) and small (S) tank*
$\alpha$ = *scale exponent*
Final recommendations highlight that for homogeneous components scale exponent should be taken equal to 0,33.

As the optimal velocity for S-tank has been determined equal to 4.2 m/s

$u_L = (4.2\ m/s) \times (18.0m / 3.8m)^{0.33} = 7.0\ m/s$

S-tank flowrate ($F_S$) has been determined equal to 16.7 $m^3/h$ with a nozzle diameter equal to 3/4”. When scaling-up the ADbag, one important issue to consider is the possible enlargement of the nozzle diameter. For the L-tank, we’ll go for a 1” ¼ nozzle (nozzle section = 0.000767 $m^2$), in order to prevent clogging.

$F_L = (7.0\ m/s) \times (3.600\ s/h) \times (4\ nozzles) \times (7.67 \times 10^{-4}\ m^2) = 77.3\ m^3/h = 0.0215\ m^3/s$

In order to calculate the pump consumption we have to use the following formula:

$P = \rho\, g\, F\, H / \eta$
*Where:*
*P = power required (W)*
*R = slurry density = 1.100* $kg/m^3$
*g = gravity acceleration = 9.81* $m/s^2$
*F = slurry flowrate* $(m^3/s)$
*H = total Head (m)*
$\eta$ = *pump efficiency (%)*

We run the pilot plant test with a 1.1 kW pump; by modulating the pump frequency, the electric power at the optimal conditions was equal to about 900 W, that corresponds approximately to 11m head (“H”), as we can see in the diagram (**Fig.17**).
The “H” parameter quantifies the overall pressure loss for the pump to win. “H” is basically the sum of the following terms:

- *Hg = gravity loss, due to the tank difference in height*
- *Hp = piping loss, due to friction*
- *Hc = concentrated loss, due to bends, elbows, tees, pipe entrance/exit, sudden expansion/contractions*

Hc can be measured in terms of “kinetic head” (“Hk”, equal to $u^2/2g$) and is proportional to the square value of the nozzle velocity. In the pilot-plant case:

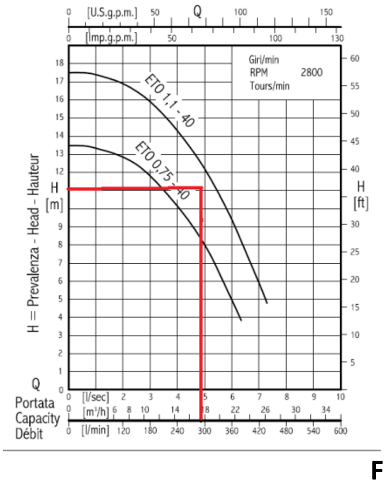


**Fig. 17**

$Hk = (4.2\ m/s)^2 / (9.81\ m/s^2) = 0.9m$

We determined that one kinetic height is approximately equal to 1 meter; in the pilot ADbag arrangements we have 4 nozzles, the pump entrance/exit and several bends, tees and elbows; each one of those may correspond approximately 1 Hk. We estimate that:

*Hg = 1,0m – Hp = 1,0m – Hc = 9,0m*

Scaling up to the Large-Scale AD-bag, Hc will rise with the square value of the velocity:

$Hc (L) = (9 m) x (7.0 / 4.2)^2 = 25 m$

We assume the same value for Hg and a double value for Hp, so that we can determine

$H_L = 28 m$

and then the pump power required (80% pump efficiency is assumed):

$P_L = (1{,}100 kg/m^3) x (9.81 m/s^2) x (0.0215 m^3/s) x (28m) / 0.8 = 8{,}120 W$

We determined that the L-scale AD-bag requires a 8 kW pump power

### 7.3 Behavior of the biology of the sludge

The pilot plant has been fed with a mixture of whey and cattle slurry following the amounts in the below table and has been kept at such a temperature to allow a mesophilic digestion process (temperature between 37°C and 47°C).

The final average mixture composition is the following **Table 2**

| Feedstock | Flowrate (Lt/day) | Feedstock composition (%) | Biogas specific production (Scm/tonTS) | Total Solid content (%) | Expected biogas production in steady condition (lt/h) |
|---|---|---|---|---|---|
| Cattle slurry | 168 | 70% | 350 | 6.0% | 147 |
| Milk whey | 72 | 30% | 500 | 4.0% | 60 |
| TOTAL | 240 | | | 5.4% | 207 |

We may notice that the "steady condition" can be achieved in about 2 months' time, when bacteria colonies have established and all the biochemical reactions have reached a steady equilibrium inside the bag reactor.

First the pilot plant has been inoculated with an amount of digestate from an external AD reactor, and then has been fed with an increasing volume of slurry-whey mixture. Daily volumes and feedstock composition have varied though the test period in order to control process parameters. Data shown in the previous table indicate the final/steady situation.

Biogas production showed a fluctuating trend, that certainly depends on the feedstock daily volume, but also on the frequency of the feeding. We mainly investigated 2 different situations:

1. a 180 lt/day (75% design flowrate) feeding mixture, that was fed every 5 hours
2. a 240 lt/day (100% design flowrate) feeding mixture, that was fed every 2 hours.

Referring to **Fig.18**, Situation 1 shows a massive instantaneous biogas production close to the feeding instant, but the average production is quite low. The dotted straight line figures the simulated situation of a 240 lt/day feedstock that is fed every 5 h.

In Situation 2 the biogas production peaks are lower but a higher average rate is shown. A further reduction of the feeding time would increase the average rate production, tending to the 200 lt/h value that is shown in **Fig.18** (as the AD process didn't reach the final steady condition, the diagram lines should slightly raise).

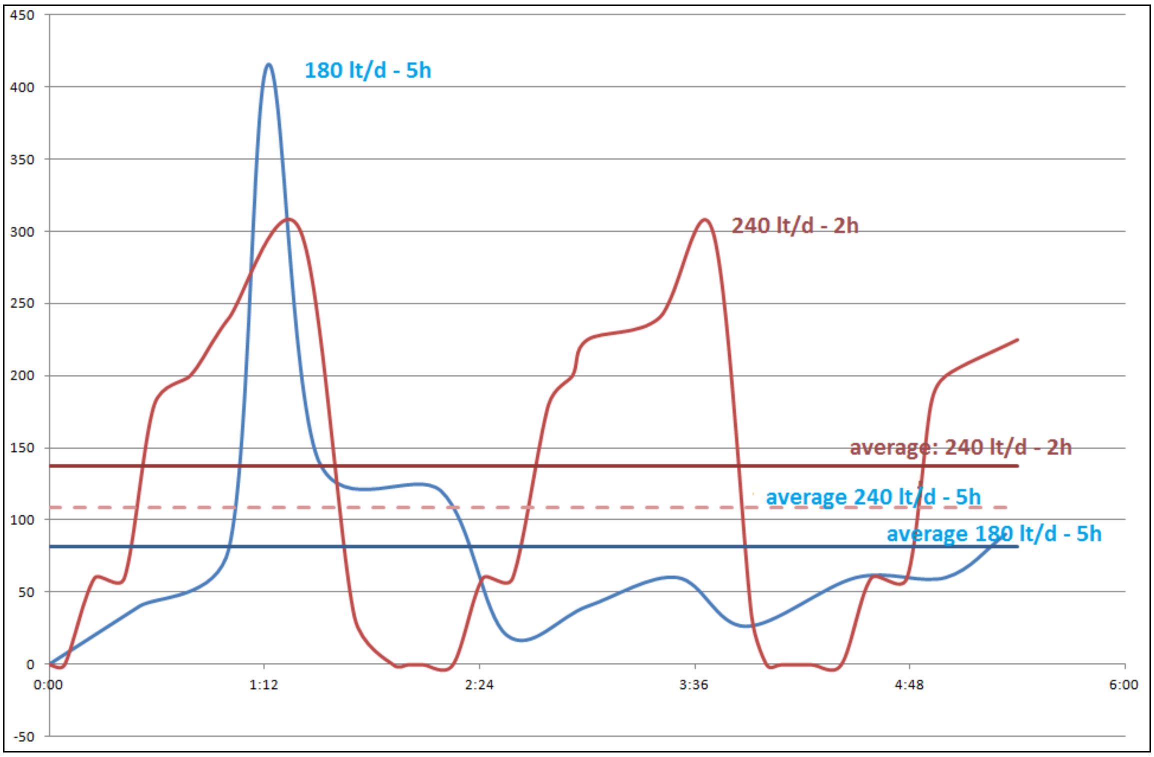


**Fig. 18 -** *productions of gas with different feeding cycles*

In this case slurry Total Solid content is strongly influenced by the rain water dilution and is equal to 6.0%, so that the final mixture with whey reaches 5.4% TS.

Let's consider a rough mass balance of the AD process, that calculates the digestate and biogas production:

*Biogas Output = (207 x 24) lt/d x 1.25 x 10*$^{3}$ *kg/lt = 6.2 kg/d*

*Digestate Output = 233.8 kg/d*

*TS digestate = (240 x 5.4% - 6.5) / 233.8 = 2.9 %*

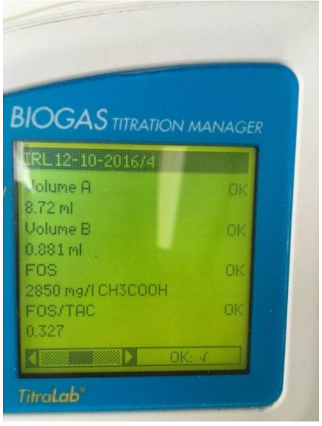
## 7.4 Results of the tests

The following are the values of the TS and VS of the sludge sample taken on the 12th of September:

| | | | |
|---|---|---|---|
| **TS** | 2,9 | % | Total solids |
| **VS** | 62,6 | %TS | Volatile solids |

**Fig. 19** *Reading of pH VALUE*

**Fig. 20** *Reading of REDOX VALUE*



BIOGAS TITRATION MANAGER

IRL 12-10-2016/4
Volume A OK
8.72 ml
Volume B OK
0.881 ml
FOS OK
2850 mg/l CH3COOH
FOS/TAC OK
0.327
OK: ✓

**Fig. 21** *FOS/TAC VALUE*

**Fig. 22** *BIOGAS ANALYSIS*

The results of the FOS/TAC reading on the sample.

| | Measure 1 | Measure 2 | Measure 3 | Measure 4 | Average |
|---|---|---|---|---|---|
| pH | 8,07 | 7,01 | 8,18 | 8,08 | **7,84** |
| FOS | 2999 | 2853 | 3052 | 2850 | **2939** |
| TAC | 12027 | 6510 | 8454 | 8725 | **8929** |
| FOS/TAC | 0,249 | 0,438 | 0,361 | 0,327 | **0,344** |

As you can see the reading number 2 is considerably off the average of the other three hence has been strike out and the set of results are as follow:

| | Measure 1 | Measure 2 | Measure 3 | Measure 4 | Average |
|---|---|---|---|---|---|
| pH | 8,07 | | 8,18 | 8,08 | **8,11** |
| FOS | 2999 | | 3052 | 2850 | **2967** |
| TAC | 12027 | | 8454 | 8725 | **9735** |
| FOS/TAC | 0,249 | | 0,361 | 0,327 | **0,312** |

The following table shows the parameters of the biology of the sludge

| | |
|---|---:|
| pH | 7.1 |
| % $CH_4$ | 71% |
| Digester Temperature °C | 39,5 |
| % TS digestate | 3% |
| % VS | 63% |
| FOS/TAC | 0,312 |
| redox (mV) | -372 |
| Avarage gas production produzione media gas (l/h)<br>from 12/10/2016 11:57<br>tu 18/10/2016 15:19 | 125.8 |

**Fig. 23** *FOS/TAC analysis*

From bibliography and experience the value of pH in our case should be within the range pH 6.5 – 7.5 and our data show an almost perfect 7.1.

The optimal value of the FOS/TAC reading should be in the range 0.2 – 0.3 and our plant is slightly above with a 0.312.

The production of biogas is as expected considering that the plant has been seeded only two weeks before the readings. On the other side the percentage of $CH_4$ is extremely good with a 71%.

## 8 Conclusions

The ADbag pilot plant installed at Tipperary Cheese Farm proved the new technology to be extremely efficient.

On one side the jet mixing system provided evidence that the previous studies were correct and helped to define the parameters for the construction of the full-scale reactor.

On the other side the measures and analysis run on specimens underlined that the biological reactions within the Adbag are similar to the standard ones found in any traditional AD system.