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Study for the comparative evaluation of the performance of different agitation systems in anaerobic digesters

SUMMARY REPORT

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Venice, April 2021

Mixing systems

The mixing operation is one of the most important unit operations at the base of the chemical and process industry including anaerobic digestion for the production of biogas from organic matrices of different origins: food waste, sewage sludge, biomasses of agro-zootechnical origin. In terms of process, the mixing of the reaction environment is infact one of the main services needed for the proper functioning of a reactor, both chemical and biological. This aspect plays an even more marked role in the anaerobic digestion process, where most of the reactors belongs to the continuous type (CSTR - Continuous Stirred Tank Reactor). In this type of reactor engineering, one of the basic hypotheses made in order to consider the reactor as ideal, and therefore maximize the specific conversion yield referred to the useful volume, is precisely the fact of being able to guarantee a total uniformity of the internal parameters (pressure, temperature and, above all, concentration of reagents, products and bacteria). The presence of inadequately mixed areas actually leads to a reduction in the useful volume of the digester. Operating with less volume inevitably implies that the sludge remains inside for a shorter time, and therefore a shorter contact time with the bacteria that must degrade it. This therefore translates into both a lower daily biogas production and a lower degree of stabilization of the sludge.

For this reason, much has been done and is currently carried out to ensure high standards regarding this aspect, in order to substantially guarantee:

i. the homogenization of soluble compounds in the digester and therefore the contact between substrates to be degraded with the anaerobic bacteria and/or exoenzymes in solution in the liquid medium;
ii. the dispersion of the gases produced by fermentation;
iii. keeping in suspension the bacterial cells present in the digester;
iv. the uniformity of energy distribution in its various forms, the heat first and then the temperature in the anaerobic digester.

Infact mixing, in addition to reducing the degree of non-homogeneity of a system, is essential to maximize not only the exchange of matter, but also the exchange of heat. This is of considerable importance in systems involving chemical or biological reactions.

In anaerobic digesters, this objective is achieved by moving the matter from one point of the system to another using three main approaches:

i. using a suitably shaped rotating blade systems: mechanical agitators;
ii. recirculating the fluid in the reactor by means of external pumps;
iii. injection of biogas to move the liquid phase into the reactor, through extraction, compression, re-injection with lances or programmed injection systems from the bottom of the reactor.

Technical-performance comparison between mixing systems

A comparison between the different mixing technologies cannot ignore the evaluation criteria to determine the mixing efficiency. As already mentioned, the sizing of the various stirring systems considered here is based on indexing of specific parameters, and in particular:

- mechanical stirring: power density (W/m^3);

- external recirculation with pumps: digester volume turnover rate, i.e. digester volume/recirculation pump flow rate (1/h);
- gas-mixing: volume of recirculated gas per unit of digester volume in the unit of time (m^3/m^3 10^3 min)

In general, the following main evidences are observed:

a. Mechanical mixing can be carried out using continuous, discontinuous and intermittent mixing systems, using blades of different shapes, sizes, number and using a draft tube or not. From the analysis of the literature it is observed that the number of blades, their geometric arrangement and their dimensions can influence the biogas production.
b. The mixing systems by means of external pumps or injectors located inside the reactor determine their success in mixing in relation to the geometric distribution of the injectors and the amount of recirculated flow, therefore essentially the energy used.
c. In case of biogas recirculation mixing, the efficiency is substantially linked to parameters such as the available energy density (W/m^3) and the gas volume ~~of~~ per m^3 of reactor (m^3 biogas per m^3 reactor per hour).

A key point of immediate evidence is given by the fact that while the first two systems provide for direct contact with the liquid part being stirred, gas mixing involves contact between moving mechanical parts and the biogas only. Given the aggressiveness of the reaction environment, this is a key aspect regarding the reliability of the system over time.

These aspects are dramatically highlighted in several literature publications. One of the fundamental points that is often reported (Uslar et al., 2019 a, b) is linked to wear due to struvite deposit / hydroxyapatite on the moving and fixed parts in contact with the reaction environment. The photos below clearly shows the problem. In particular, it should be noted that these are submerged mixers, where replacement can probably only be done after emptying and reclamation of the reactor, which normally has dimensions of thousands of m^3. Surely, this is the most devastating aspect in use of those technologies that involve moving parts inside the reactor, and it is also the main deterrent to their use, although not the only one.

Examples of immersed mixers damaged by wear and crystalline deposit.

Although maintenance can be facilitated by the presence of special hatches that come down from the digester dome under the free surface of the liquid in order to avoid gas leaks, these equipment keeprequiring that a periodical and very careful maintenance is carried out at all times

The alternative of using to side-inlet mixers, where motor remains external to the reactor and only the mixer shaft enters the reactor, also involves significant problems. Wear and deposits remain a problem, often causing serious damages. The following pic shows the photographic document of a sliced shaft extracted from a digester.

Sliced shaft extracted from a digester

In a second study (Uslar et al., 2019b) dedicated again to the mixing of anaerobic digesters for the treatment of sewage sludge, developed for Alensys Engineering GmbH, the comparison is made among the external recirculation pumps approach and the gas lances (Uslar et al., 2019a). Specifically, the substantial differencial element compared to the previous case is linked to the fact that there are not moving parts inside the digester, but, as already mentioned, the fact remains that these organs remain in contact with the sewage with all the critical issues associated with it. So, If apparently from this point of view the problems related to maintenance are clearly less, since it does not have to operate inside the digester, the problems arising from the aggressiveness of the work environment in relation to the moving parts remains unchanged in terms of maintenance. The risk of clogging in the pump body or in the connection pipes due to deposit of heavy materials including the precipitation of phosphorus salts (struvite, hydroxyapatite, bruscite, vivianite etc. (see the following figure) represents a further maintenance problem

Another important factor related to the mechanical mixing to be considereis the rotating parts are subject to heavy wear when sand and suspensions are present.

as in the case of submerged mechanical mixers and perhaps worse, given the more confined environment in which they operate

Since the pumps, in a medium-sized digester, operate in flows that range between 10 and 200 m^3/h with thousands of m^3 to be moved in a short time, the total number of pumps required is also high and variable in relation to the size of the digester. Generally speaking, it is necessary to be able to guarantee flow rates up to 350 m^3/h to avoid the loss of turbulent conditions and therefore the risk of sedimentation.

Damage to circulation pumps caused by phosphorus-based crystal deposits (Uslar et al., 2019b).

So far, the comparison focuses on the aspects that characterize the reliability of the installation. However, considerations related to the installed power and the energy used for the service must be included in the picture. It should be remembered that for a good mixing it is possible to assume an operating data of at least 8 h per day and a handling capacity equal to the volume of the reactor (therefore for example for a 3000 m^3 reactor it is necessary to move at least 3000 m^3 per day). As you can see, this turn over time is certainly much less heavy than that reported by Metcalf & Eddy (8 hours against 20-30 min), and is therefore to be considered very precautionary against mechanical agitation.

Considering the situations currently existing on the market, Uslar et al. (2019 a, b) report a power index value applied for mechanical stirring between 10 and 30 W for each m^3 of useful digester. Therefore, for a digester of average volume, let's say 3000 m^3, the average power installation to be provided with a mechanical stirring system ranges from 30 to 90 kW. Certainly not negligible, both in terms of plant cost and operating costs. A quick calculation: assuming that the system works for only 8 hours a day, we will have 240 to 720 kWh/day of consumption. An agitator of this volume, in mesophilicity, fed with mixed sludge, considering a residence time of 30 days and a dry input content of 4%, can produce up to 1400 kWh/day (SGP equal to 0.2 m^3/kgTVS, standard CHP group). Considering that the thermal part is totally absorbed by self-heating, **it means that a variable percentage between 17 and 50% of the recovered energy is spent on the energy needs of the mechanical stirring**. And this considering only 8 hours a day of operation, a very conservative assumption. The consumption associated with mechanical stirring is therefore definetely considerable.

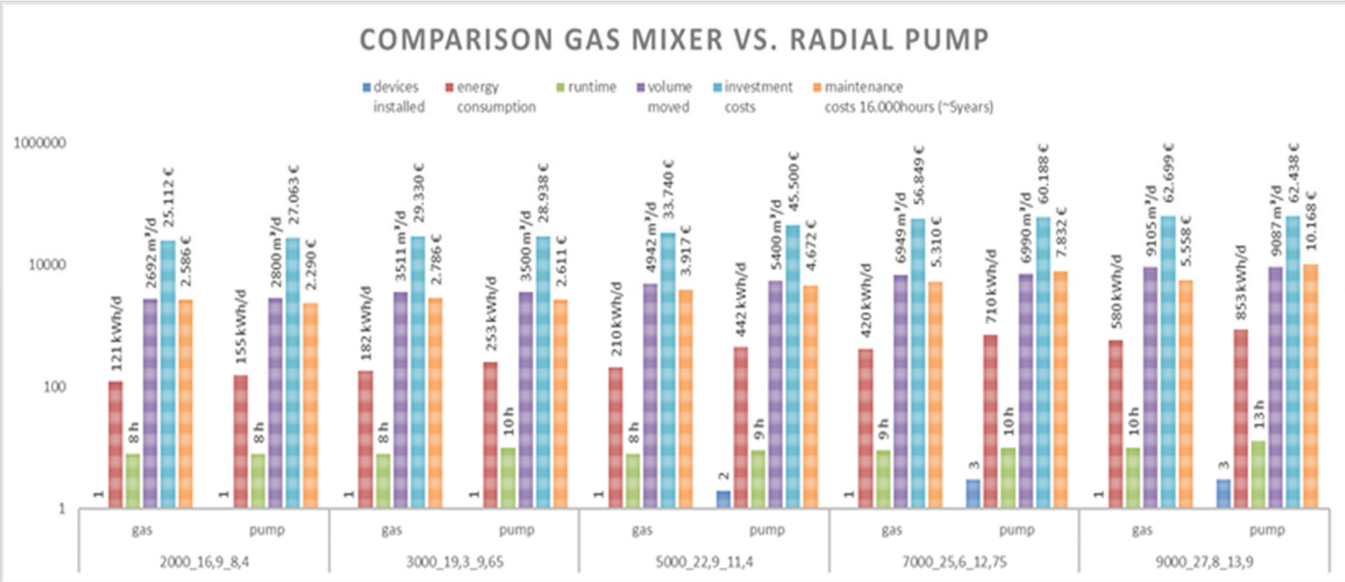
In reverse, a gas lances system sizing is based on a parameter equal to 1.5 m^3/h per m^2 of digester section (section intended as product of the base diameter by the useful filling height). In this case the parallelism with the literature index is not possible, as it is based on a different sizing index: in the first approach the index is given as flowrate on surface, in the second as flowrate over volume per unit of time.

Anyway if we want to make a parallel with a gas lances system, it is necessary to refer to the digester plan surface. Assuming a height / diameter ratio of 1.4 whichis the canonical ratio in the design of sludge digesters. For a rough 3000 m^3 digester ~~of~~ this would result in a diameter of 17 m and a useful height of 14 m, therefore a section of a total of 226 m^2. Considering a power index equal to 1,5 m^3/h per m^2, we would obtain a necessary flow rate of 340 m^3/h, with a delivery pressure, taking into account the pressure and hydraulic head losses, of 1,5 bar. A compressor with these features, such as sliding vane, requires an installation of only 17,4 kW. **Even if we consider a 24-hour operation, we would not go beyond 420 kWh per day, which is considerably below the maximum defined for mechanical agitation but with a triple daily operating time.** Considering 8 working hours per day, we can obtain an energy consumption value of only 139 kWh/d, sensibly lower than the minimum limit expected for mechanical mixing systems.

The validity of gas mixing compared to mechanical agitation is also evident from an energy point of view. The study Uslar et al. (2019b) comparatively evaluates the agitation system with external recirculation with respect to gas mixing, this time consider an even wider database. putting in relation several indices and comparing them as the volume of the digester varies. The parameters taken into consideration are:

a) Plant cost
b) Energy cost
c) Daily use time
d) Volume handled in one day
e) Maintenance costs

For the calculation of the system costs with reference to the recirculation pumps, the sizing was carried out considering a complete volume change per day concentrated in 8 hours. For the prevalence, the volume of the digester was taken into account, considering a canonical relationship between the base and the useful internal height of the sewage. For gas mixing, the assumptions were the same used in the previous case. The results obtained are shown in the following graph. The numbers at the bottom mean respectively volume / diameter / height of the subject digester. The numbers on the bottom left indicate the quantity of individual units set for each case.



Trend of the different parameters as the reactor volume varies (Uslar et al., 2019b)

Analyzing the results we can state that:

a) the investment costs of the two systems are comparable;
b) the maintenance costs of the two systems are comparable too, not considering extra maintenance costs due to malfunctions and / or incrustations (that are very common to expect on mechanical mixing systems and on recycling pumps, as already explained);
c) energy costs are always in favor of gas mixing, and ~~of~~ in asignificant amount (up to 50% lower, since the graph is logarithmic).

In addition to what has been extensively reported in terms of literature analysis and comparative research carried out by Uslar et al. (2019 a,b), it is worth recalling a fairly recent review published by Lindmark et al. (2014). The authors have produced an extensive study on the different mixing processes of anaerobic digesters in relation to mixing mode and its intensity. In this analysis the distinctions are made among:

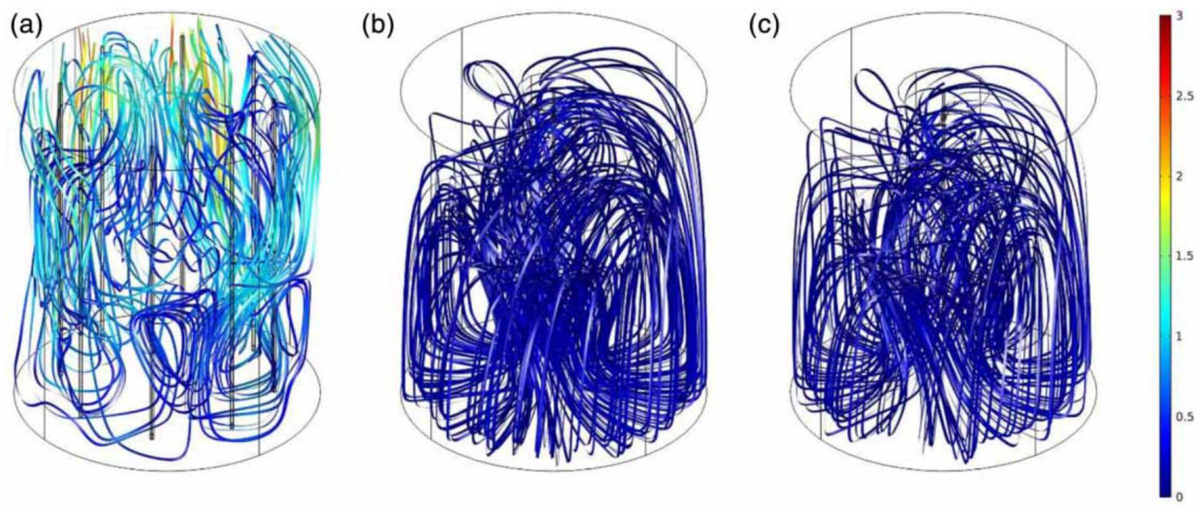
1. pneumatic mixing, thru biogas recirculation;
2. hydraulic mixing, by means of pumps located outside the digester;
3. mechanical mixing, by means of agitators inside the digester.

Overall, the work led to two conclusions of strong applicative interest:

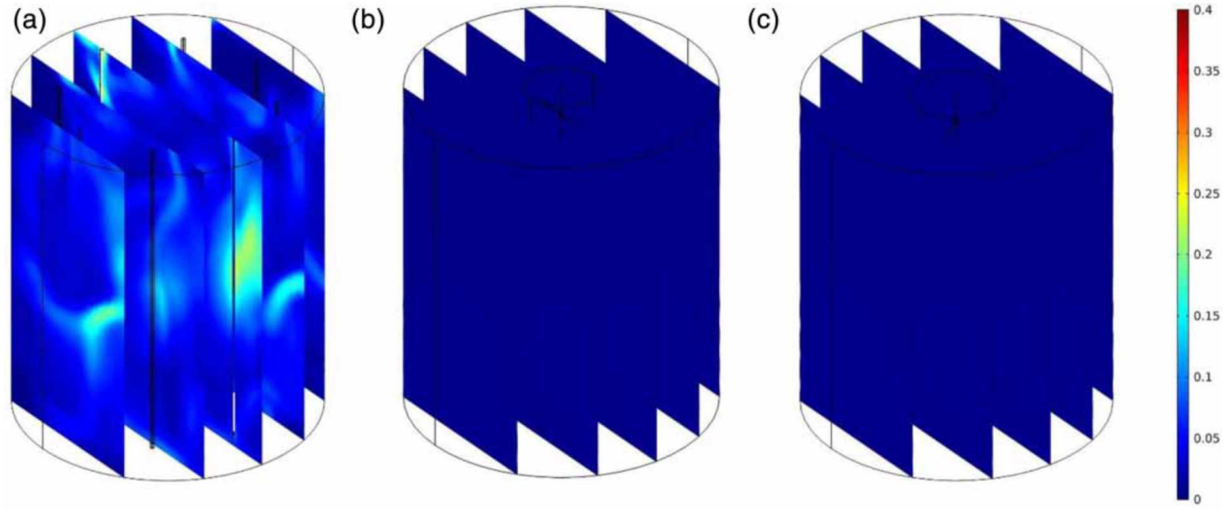
a) intermittent mixing gives results comparable to continuous mixing (24 hours / day). Obviously, the comparison is made with the same amount of energy spent (i.e. a lot of power in a short time versus a little power distributed in 24 hours);
b) mixing can also cause important disturbances on the methane biomass which suffers from excessive handling. While mild mixing ensures the formation of well-structured biomass flakes, strong turbulence associated with high blade revolutions destroys the clusters and cause the dispersion of fine biomass. However, the evidences found indicate that even in the absence of real flakes (dispersed biomass) the process is able to develop equally.

Studies carried out in even more recent years have further strengthened the vision that mixing using gas lances is particularly effective in the case of mixing digesters that treat sewage sludge. Bergamo et al (2020) reported the results related to the study of mixing a digester with a volume of 1400 m^3 dedicated to the treatment of sewage sludge. In particular, the researchers applied a three-dimensional CFD (Computational Fluid Dynamics) model in order to verify the mixing efficiency of a gas lances system in comparison with a mechanical mixing system (agitators). The study showed that the gas lances system gives better results than a mechanical mixing system both in terms of maximum sludge speed (3 m/s versus 1 m/s), kinetic energy (0.24 m^2/s^2 versus 0.001 m^2/s^2) and dead zones (5% versus 50%) with the same energy consumption, equal to 140 kWh for both systems. In particular, as can be easily seen from the following figures, the system mixed by means of gas recirculation, made it possible to reach linear speeds between 1 and 2 m/s while in the case of mixing with mixers, values > 0.5 m/s were not reached.

In terms of kinetic energy density, it is noted that in the case of mixing with gas lances, turbulent kinetic energies between 0.05 and 0.2 m^2/s^2 were observed while in the case of mixing with mechanical mixers, values <0.05 m^2/s^2 were observed (Bergamo et al., 2020).

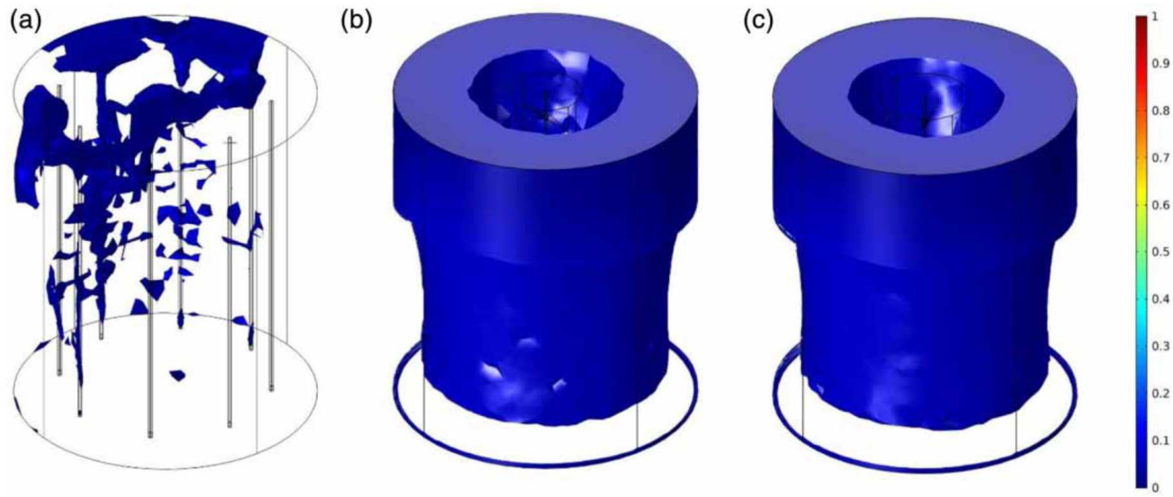


Linear speed (m / s) for systems (a) Gas mixing; (b, c) Mechanical mixing (Bergamo et al., 2020)



Kinetic energy of the turbulent regime (m2 / s2) for systems (a) Gas mixing; (b, c) Mechanical mixing (Bergamo et al., 2020)

Concerning the distribution of dead zones (see the following figure), the effectiveness of the mixing system with gas lances is observed with even greater evidence, clearly superior to that obtained with mechanical mixing systems.



Dead zones for systems (a) Gas mixing; (b, c) Mechanical mixing (Bergamo et al., 2020)

Full scale real case monitoring and analysis (Germany)

In order to verify the actual effectiveness of the gas mixing in relation with the literature presented and with the sizing indexes found, the survey was integrated considering a real full-scale application case.

A digester serving a wastewater treatment plant in Germany, for which extensive monitoring data, in terms of sizing and operation are available, was used as a model

The digester considered has the features shown in the following table.

Digester characteristics of the of a sewage treatment plant in Germany.

Parameter	Units	Value
Reactor type		CSTR
Kind of Installed mixing system		Gas mixing, 2 sliding vane compressors, 8 perimetral lances
Insulation		Classic composite concrete / rock wool / cardboard containment
Wirking volume	m^3	2500
Radius	m	7,5
height	m	17,8
Installed power for each compressor	kW	30/20,5
Biogas flowrate for mixing	m^3/h	415
Adsorbed energy for mixing	kWh/d	225
Primary sludge daily fed	m^3/d	40
Sewage sludge daily fed	m^3/d	40
Food industry residue (gelatine)	m^3/d	20
Primary TS	g/Kg	61
Sewage TS	g/Kg	79
Cosubstrate TS	g/Kg	80
Working temp.	°C	39-42
Biogas produced	m^3/d	1400 m^3/g (average year value)

The only assumptions made for this part of the data concerns the volatile contents of the three matrices, which are widely documented in the literature. All the remaining data comes directly from the plant manager. The digester in question operates in a mesophilic range of temperature, with an average hydraulic residence time (HRT) of 25 days and a relatively high organic load (OLR), i.e. 2.1 kgTVS/m^3 d. Digestor yield verification is carried out considering the incoming mass flows and the relative average production in biogas found, approximately 1400 m^3/d. In these conditions, ie with low residence time and high organic load, the exploitation of the matrix is partial and therefore lower yields would be expected (unlike what was actually found). By imposing a specific production for the sludge of 0.25 and 0.15 m^3/KgTVS respectively, more than acceptable for these matrices in these conditions, the calculations show a SGP for the third substrate of 0.45 m^3/KgTVS, perfectly in line with the type of material, a starchy residue composed of long-chain molecules and therefore not easily biodegradable.

Therefore, in terms of yields, the digester operates in an extremely satisfactory wa, even if only the biogas produced is considered as an index. Going further, it is significant to consider the installations used for agitation and the resulting energy balances. The digester, as shown in the previous table, is stirred by gas mixing, using a simple perimeter lances system. The gas compression is carried out thanks to two MAPRO RFL 50 G units, that are high efficiency units on sliding vane logic, 415 m^3/h capacity and 20.5 kW installed power for each unit. Considering the exchange surfaces, calculated on the basis of the project plans by assimilating the useful volume of the digester to a cylinder, associated with each the exchange coefficients and defined the corresponding heat flows, it is clear that the system is not only capable of self-sustaining itself, but can also be used to produce electricity. A delta of about 850,000 kcal/d is determined in favour of the energy produced, which more than enough to guarantee operation even in the coldest periods. Furthermore, the digester, equipped with a 150 kW CHP unit, can produce approximately 3600 kWh every day, for an annual production of over 1300 MWh/year.

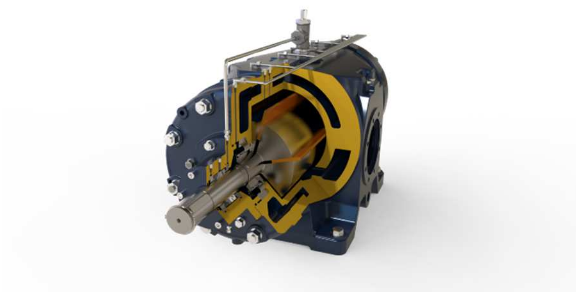
These data therefore support the assumption of the proper functioning of the process, certainly thanks to the appropriate stirring system adopted.

Now, in terms of installed and used power, as shown in the following table, The system is equipped with a compressor absorbing 20,5 kW (only one compressor while the second serve as stand by unit. The manager reports a daily consumption of only 225 kWh/day. If we would assume a unitary yield it means that the digester would be completely agitated making the unit work only 11 hours a day (in reality, the compressor, having an efficiency of about 85%, actually operates on a basis of about 9.5 hours). In the worst case scenario, that is having to recirculate gas 24 hours a day (which is purely theoretical, since experimental evidence shows that a shorter time is sufficient), we would obtain a daily consumption of 984 kWh, equal to less than 28% of the energy produced.

As we can see, the system, operating at full scale, unequivocally demonstrates the value of the gas mixing option. In fact, in terms of specific power, the system occupies about 8 W/m^3 of useful volume, against the range previously indicated by Uslar et al. (2019 a,b) between 10 and 30 W/m^3 for mechanical agitation (internal mixers or pumps).

Ultimately, therefore, the full-scale example reported, substantially demonstrates the thesis already developed through the literature survey, which as a conclusion leads to the fact that the agitation system through gas-mixing has significantly higher values than the other systems studied.

Whatever the biogas insufflation system inside the digester, lances or bottom injectors, it is clear that a key point is the reliability of the compressor. Having units based on sliding-vane technology, which allow you to separate the internal surfaces of the compressor from the contact with the gas by a film of mineral oil, implies a further and final guarantee of reliability.



MAPRO Sliding-vane compressor construction approach

The logic therefore leads to a double action:

- on one hand, continuous lubrication of all parts, protecting them from contact with pollutants and from excessive friction at the contact points;
- continuous cleaning of all surfaces, bringing all deposits and encrustations that may have formed during operation to the oily phase. In this action, even the condensate water, certainly corrosive, passes into the oily phase and is removed from the system. Under these conditions, it is possible to treat gas with moisture equal to saturation. Finally, it is clear that a system of lubrication so efficient, playing a role on internal frictions, helps to significantly reduce specific powers in relation to performance.

Conclusions

The survey conducted has started considering the three most common agitation systems for anaerobic digesters on the market:

- Mechanical agitators;
- Recirculation pumps;
- Injection of biogas.

These issues have initially been approached with a general description and then by going into the detail of the topic through the study of texts, scientific works and specialized websites that address the topic.

In particular:

- Reference texts for the engineering sector applied to anaerobic digestion and wastewater treatment processes;
- Scientific publications published in international sector journals;
- websites of companies in the sector, viewing technical-commercial material describing the various products available on the market today;
- a full-scale investigation of an anaerobic digester loaded with mixed sludge and co-substrate.

The set of effects that the unit mixing operation must perform has been defined, namely:

i. the homogenization of soluble compounds in the digester and therefore the contact between substrates to be degraded and anaerobic bacteria and / or exoenzymes in solution in the liquid medium;

ii. the dispersion of the gases produced by fermentation;

iii. the maintenance in suspension of the bacterial cells present in the digester;

iv. the uniformity of energy distribution in its various forms, first the heat, and then the temperature in the anaerobic digester.

The three reference systems have been described in detail, also with reference to the market offer. In particular, a complete dissertation has been conducted for the mechanical stirring with mixer, for the application logics (types of mixers and their installation) and or the typical indexes used in the fluid dynamics study of these units, also with photographic documentation. For external recirculation systems, the currently most used solutions have been considered, in particular those involving the use of high-speed tangential nozzles and grinder pumps, as they are more representative of the current situation. For this system, CFD simulation information was also recovered, which lead to a very precise knowledge of the fluid dynamics inside the reaction environment. Finally, concerining gas mixing, both the canonical lances systems and the sequential bottom insufflation system (Valorga patent, in particular) have been examined, discussing in particular about the peculiarities offered by the new compressors on sliding vane logic, which offers, in parallel with cleaning and consequent lower maintenance, installations with lower power. The results that emerged from the evaluation are quite clear, and are supported by the full-scale study carried out to support them.

In particular:

- Both mechanical stirring with mixer and with external recirculation have a heavy critical element in common, namely the contact of moving parts with the reaction environment. The mechanical agitation carried out using internal submerged mixers has an even more marked critical issues in the event that maintenance requireds that the tanks must be emptied alongwith the relevant-costs related with the reclamation of the reaction environment.
- The crystallization of phosphorus and ammonium salts in various forms is strongly associated with areas of high turbulence. Both mechanical systems involve this critical issue, with a further maintenance increase. Furthermore, the external recirculation system suffers from this problem also in the supply and delivery pipes, complicating the overall picture even more. This aspect is totally absent in gas-mixing systems.
- The investment costs are in favor of gas mixing, thanks to the simplicity of installation and the reduced components associated with it.
- In terms of installed power, the systems can also be considered similar at first glance. In reality, as widely demonstrated also by the full-scale study, as well as by the literature, gas mixing involves reduced powers when using latest generation compressors (sliding vane).
- Energy consumption clearly in favor of gas mixing, as a consequence of the previous point. An installation with a power index of only 15W / m3 is more than enough to ensure the perfect functioning of a digester with a high dry content (even over 5% TS, as demonstrated by the real case studied).
- Gas mixing, as demonstrated by the large number of European plants based on the Valorga technology (one of those, in Bassano del Grappa, Vicenza, operating for over a decade), is a very viable option also on those systems different from the digestion of simple sewage sludge, and can be extended to complex substrates such as agro-industrial or FORSU, as long as the sequential insufflation system from the bottom is used.

Therefore, for all the evidences found and the deductions associated with them, the investigation led to a complete and exhaustive verification, which indicates how the gas mixing type agitation system, associated with high efficiency compressors (sliding vane) is currently the best choice on the market for the agitation of CSTR type anaerobic digesters.

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