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State of the Art of Bioreactor Technology and Mathematical Dimensioning Equations for Biogas Production

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Abstract The sizing of an anaerobic digester is generally a function of the main objectives pursued by anaerobic digestion, in relation to the available material, technological and economic resources, as well as the legislation in force. The main objective of the study of the sizing of an anaerobic digester is to optimize the treatment of organic waste and/or the production of methane. In this work we seek the theory of a technique for sizing a biodigester in order to store the biogas produced. To this end, we studied the design possibilities of different types of bioreactors that can be used for the production of biogas at the African Laboratory for Sustainable Development Research (AfricLab) and taken up at the laboratory of the Department of Physics and Chemistry, Ecole Normale Supérieure de N'djamena. Although the design technology is advanced, the aim of our work remains at the scale of a rudimentary study to be able to understand the simple ways and means of sizing and storing biogas, to do this an adapted table of the definitions and units of the parameters used in the equations for sizing was given. The laboratory work on the sizing of a biodigester and the storage time of the biogas produced required a small type of laboratory bioreactor of a few liters and fed with the real effluent considered. A ramp-up is carried out by following the yield of the biogas produced and measured according to the applied load. Based on this, we studied the different types of bioreactors in an industrial theoretical way and we presented them in the results and discussion section. This part has already been done on the work of BOUANIKA Nour el Imene & DJEDIA Arfa. Thus, a bibliographic synthesis is made for the production of this present scientific article.

Keywords: *sizing, anaerobic digester, storage, biogas, laboratory*

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1. Introduction

The objectives of anaerobic digestion technology for organic waste respond rather to demands for access to energy than to decontamination purposes. In this perspective, the choice of a type of anaerobic digester depends on 2 main categories of factors: 1) Internal factors such as the quantity of substrates to be treated and recovered, the nature of the substrates (in terms of texture, dry and organic matter content, in terms of rheology, etc.), the available construction materials and the complexity of the system; 2) External factors such as climatic conditions, investment capital, technical and operational skills available, etc. [1]. One of the first solutions to the flexibility of energy production is the storage of biogas produced by the digester. There are several storage technologies. Usually, biogas production facilities have a storage means to smooth out production gaps in both quantity and quality. Possible storages are non-pressurized, at low pressure (0.05 bar maximum), medium pressure (up to 20 bar) or high pressure. The latter remain very little used in agricultural biogas installations, due to the excessively high cost of compressing biogas. The most used are at low pressure and often consist of one or two membranes (single-layer or double layer), internal or external to the reactor. In general, storage capacities are around 4 to 8 hours of production,[2]. However, there are leakage problems on the most common storages, which can represent 1 to 5% of the volume produced by the digester [3]. In addition, depending on the country concerned, legislation limits biogas storage for safety reasons. This solution therefore has its limits, but biogas storage can provide an immediate reserve and it must be integrated into solutions for flexible production. Another storage solution is to purify the biogas to the quality of natural gas, and to inject it into the gas network when the demand for electricity is low: the excess biogas is therefore stored in the form of biomethane. To be injected

into the network, the biogas must be dried, purified of undesirable components such as H_2S and CO_2, compressed, and must have a minimum methane content, which also depends on each country. In addition to the biogas production facility, it is therefore necessary to equip the methanization units with a means of purifying the biogas produced to meet the specifications, with a view to injecting the gas into the network. The most common purification processes are physical absorption with water or chemical absorption with amines, adsorption, or purification by membranes [4]. The main objective of this work is to study a Techniques for sizing and installing a Biodigester and the physical storage of the biogas produced; A study on the kinetic sizing models will be made based on the research of [1]. Thus, models based on mass balance are among the simplest and most frequently used in the design and sizing of anaerobic digesters [5]. However, these models are generally applied to the anaerobic digestion of liquid effluents. The first-order model can predict the performance of infinitely mixed digesters for the anaerobic digestion of drainage water [6]; Furthermore, Ortolani et al. (1991) [7] and Florentino (2003) [8] proposed sizing models adapted to batch, Chinese and Indian digesters, with a size of less than 100 m3. These models were based on data relating to energy consumption (cooking, heat, lighting, electricity, etc.) and on initial parameters such as the internal height and diameter of the digester. From these data, the other parameters of the digester dimensioning (volume and dimensions of the gasometer, dimensions of the inlet and outlet of the digester, thickness of the walls, etc.) were calculated. Finally, the quantity of material required was also evaluated. Other mathematical tools, such as those of [8] for example, have also been proposed or studied to strengthen these first approaches. They are implemented from a nonlinear programming of simple resolution, the objective of which is to achieve a better performance of all the available resources. This involves minimizing the volume of the digester while it is subjected to restrictions ensuring its operating characteristics, efficiency for covering the demand for biogas, then selecting the optimal values of the initial parameters, while reducing iterations and errors. However, because of the rapid evolution of the multiple factors that influence the kinetics of anaerobic digestion and the difficulty of integrating them all into a single deterministic system, kinetic models generally require the support of empirical data, revision of calculations and calibration of field results. [1]

2. Materials and Method of Sizing the Installation of a Biodigester

A biomethanization installation generally consists of a digester, purification equipment, utilization equipment and connection accessories. The sizing techniques for a biodigester can be different from one digester to another, depending on the type of digester and also on the characteristics of the materials in place. We give an overview of the sizing of a simple-to-use digester.

To obtain a biodigester, the approach therefore consists of first sizing the gasometer, the useful volume of the digester and finally the total volume of the digester (tank volume) [9]

2.1. Gasometer Dimensioning Equations

After having evaluated the biogas requirements, the biogas production per m3 of the digester is therefore obtained from the following equation.

$$\mathrm{Pv} = \frac{Bo \times S}{TRH}\left[1 - \frac{k}{(TRH \times \mu m - 1 + K}\right] \quad (1)$$

With µm = 0.013(T)−0.129 Hashimoto model to determine the daily specific production Where **Pv** is the specific production, **B0** is the methane production potential for the substrate, **TRH** the hydraulic retention time, **S** the volumetric substrate load, **K** is the inhibition constant which is specific for a given substrate and for a bacterial consortium and finally µm the maximum growth rate of microorganisms. For a useful volume V of the digester, we then obtain a daily volume production de

$$\mathbf{G} = \mathbf{Pv} \times V = \frac{Bo \times S \times V}{TRH}\left[1 - \frac{k}{(TRH \times \mu m - 1 + K}\right] \quad (2)$$

2.1.1. Tank Sizing Equations

The volume of the tank (V_D) which is nothing other than the volume of the digester is the volume of the assembly formed by the gasometer and the volume of the effluent (useful volume V)

$$\mathbf{V_D} = \mathbf{V} + \mathbf{G} \quad (3)$$

With V= Q × TRH

By introducing the equations, we managed to express V_D as a function of Q by the following equation

$$\mathbf{V_D} = \mathbf{Q}[\mathbf{TRH} + \mathbf{B_O}(1 - \frac{k}{(TRH \times \mu m - 1 + K}][\quad (4)$$

The previous equation can be rewritten taking into account that: - the flow rate (Q) is not only a function of the mass (m) of the substrate to be digested, but also of the ratio of its mixture with water (1: x); the volume occupied by this mass of substrate is:

$$\mathbf{V} = \mathbf{m}/\boldsymbol{\rho s}\ \mathbf{v\ in}\left[\mathbf{m^3}\right]\mathbf{m\ in}\ [\mathbf{Kg}]\mathbf{and}\ \boldsymbol{\rho s}\ \mathbf{in}\frac{Kg}{m^3} \quad (5)$$

$$\mathbf{Q} = \mathbf{v}(\mathbf{1} + \mathbf{x}) = \frac{m(1+X)}{\rho s}\ \mathbf{x\ in}\left[\mathbf{m^3}\right]\ \mathbf{x}\epsilon\mathbb{Q}^+ \quad (6)$$

And

$$\mathrm{V} = \mathrm{TRH} \text{⁒} \mathrm{Q} = \frac{TRH \times m \times (1+x)}{\rho s} \quad (7)$$

The volumetric charge (S) is expressed as a function of the mass (m), the concentration (c) and the useful volume (V)

$$\mathrm{S} = \frac{m \times c}{V} \quad (8)$$

After substituting, we get

$$S = \frac{c \times \rho s}{TRH(1+x)} \quad (9)$$

To obtain the final sizing equation

$$\mathbf{V}_{=} \frac{m(1+x)}{\rho s}[\ \mathbf{TRH} + \frac{B.C.\rho S}{TRH(1+x)}(1 - \frac{k}{(TRH \times \mu m - 1 + K}))] \quad (10)$$

In addition to determining the size and components of the digester, it is also necessary to plan for the amount of heat that the digester will need.

• Heat consumption of the digester

The heat consumption of the digester in order to heat the substrate and maintain it at an average temperature of X°C constitutes a significant demand. It is necessary to estimate it because this heat will be provided by the recovery of the biogas. The digester is considered to be perfectly mixed. The drop in temperature therefore comes both from the substrate sent into the digester and continuously recovered at its outlet, and from the loss of heat by conduction on the walls. On the basis of a heat balance, we can then deduce the amount of heat to be provided. Note: The terms used similar to the previous equations are to be taken into account to better illustrate the equations.

Considering Ti the temperature inside the digester, Te the outside temperature, k the thermal conductivity of the walls, e the thickness and S the surface area of the walls, q the flow rate at the outlet and inlet in m3/d, p the density in kg/m3 which will here be equivalent to that of water and Cp the specific heat capacity at constant volume in J/(K.kg). We can determine the energy required for heating.

$$\mathbf{Q_{chauffage}} = \mathbf{q} \times \mathbf{p} \times Cp \times (\mathbf{T_e} - \mathbf{T_i}) + \frac{(Te - Ti)}{\frac{e}{k}} \times \mathbf{S} \quad (11)$$

Table 1. Definitions and units of parameters used in equations

Settings	Definition	Unit	How to obtain it
Pv	Volumetric production: biogas production per m3 of fermenter / day	$m^3g/m^3.j$	Calculation
S	Volumetric charge	Kg(MS, MO, DCO $/m^3$	Calculation
B0	Methane production potential	m3/KgMO	Laboratory
TRH	Average hydraulic retention time of the effluent in the reactor =V/Q	j	System dependent
K	inhibition constant which is specific for a given substrate and for a bacterial consortium	Dimensionless	Laboratory
µ m	kinetic coefficient (daily growth rate of microorganisms)	j^{-1}	Calculation
T	Temperature	°C	Measure
V	Useful volume of the fermenter	m^3	Calculation
G	Biogas produced per day	m^3/j	Calculation
Q	Influent volume flow	m^3/j	Calculation
VD	Total volume of the digester	m^3	Calculation
m	Mass of the substrate (raw material)	Kg	Measure
c	Concentration of organic matter in the substrate	% (en valeur relative)	Laboratory

Adapted from [10]

3. Result and Discussion

3.1. Energy Production

Electricity production facilities from biogas are generally digesters with integrated biogas storage, and one or more CHP. The calculation of the energy that can be produced by biogas in one year is calculated from the PCI of methane. It is 9.94 kWh/m3 under normal temperature and pressure conditions [11]. according to the equation

$$\mathbf{E_{tot}} = \mathbf{PCI}_{CH4} \times V_{CH4} \quad (12)$$

expressed in KWh

From this equation it is possible to calculate the recoverable energy produced in one year, assuming losses of 5% of energy in order to be sure that the engine is rather overfed than underfed (solagro 2001). The recoverable energy by the engine is therefore as follows:

$$\mathbf{E}_{valo} = \mathbf{0,95} \times \mathbf{E}_{tot} \quad (13)$$

expressed in KWh

An engine is designed to operate between 50% and 100% of its nominal load, with an optimal efficiency around 75% [12], the calculation of the energy provided by the biogas in one hour of time is given by the equation:

$$\mathbf{E}_{t=1h} = \frac{E\ valo}{365 \times 24} \quad (14)$$

expressed in KW

We can therefore calculate the annual production of electricity and heat.

$$E_{el} = E_{valo} \times \text{ rendement électrique de X \%} \quad (15)$$

expressed in KWh_{EL}

$$E_{th} = E_{valo} \times \text{ rendement thermique de Y\%} \quad (16)$$

expressed in KWh_{th} [13]

3.2. Result of Bibliographic Study of the Different Types of Bioreactor

In the dissertation work of BOUANIKA Nour el Imene & DJEDIA Arfa on the Valorization of sludge from the Ibn Ziad Constantine treatment plant by dimensioning an anaerobic digester [14] we can see the distinction between different types of anaerobic digestion reactors.

3.2.1. Discontinuous or Batch Mode

In batch mode, the hermetically sealed reactor is initially filled with organic matter to be treated and seeded with inoculum. The reaction takes place without any exchange of material with the outside and continues until the substrate to be degraded is exhausted. This mode is generally used to determine the methanogenic potential of waste [15].

3.2.2. Continuous Mode

Continuous mode operation is the most common on an

industrial scale. Continuous reactors are continuously fed at a so-called "nominal" rate, which generally corresponds to a constant material flow rate. At the same time, an equal quantity of digestate is removed from the reactor, which will thus retain its reaction volume. This technology is ideal for large installations. This operating mode is simple and generally suitable for the treatment of effluents heavily loaded with organic matter (agricultural waste, urban sludge [15]

3.2.3. Semi-continuous Mode

This operating mode, also called Fed-batch or sequential discontinuous mode (SBR, Sequencing Batch Reactor), is a hybrid mode between continuous and discontinuous. It consists of applying, in a digester, cycles alternating filling, reaction and emptying [15]. The advantage is to retain all or part of the microorganisms in the reactor for the next cycle. This mode is well suited to small methanization installations

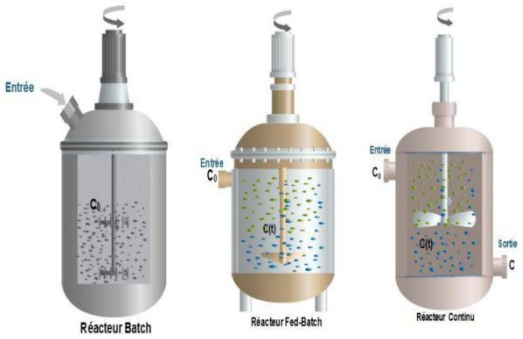


Figure 1. Different types of Bioreacteur according to [14]

3.2.4. Perfectly Mixed Reactors

Perfectly mixed reactors are also called CSTR (Continuous Stirred Tank Reactor) (Figure 2). Their contents are kept homogeneous by regular mechanical stirring or by recirculation of the biogas or liquid, which promotes contact between the biomass and the substrate to be treated. It should be noted that these reactors are currently the most used in the industrial sector [15].

Figure 2. Examples of the perfectly mixed digester: a) mechanically by blades, b) by compression and recirculation of the biogas, c) by recirculation of the medium. [14]

3.2.5. Plug Flow Reactors

In a horizontal plug flow reactor, the agitation systems mainly used are the recirculation of the digestate by an external pump, the recirculation of the biogas under pressure and the blades with a longitudinal or transverse axis (Figure 3). In a vertical plug flow reactor, a recirculation from the bottom to the top allows a mixing effect and an inoculation of the waste to be treated [16]

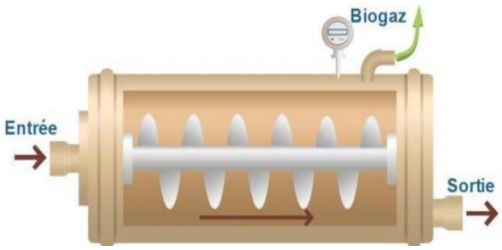


Figure 3. Paddle digester with a longitudinal axis

3.2.6. Fixed-bed Reactors

The support used in these reactors is a packing, which can have an ordered structure or can be placed in bulk (Figure 4). These reactors are used for the methanization of liquid wastes containing mainly soluble organic matter. However, a risk of clogging may be encountered due to the particulate matter present [17].

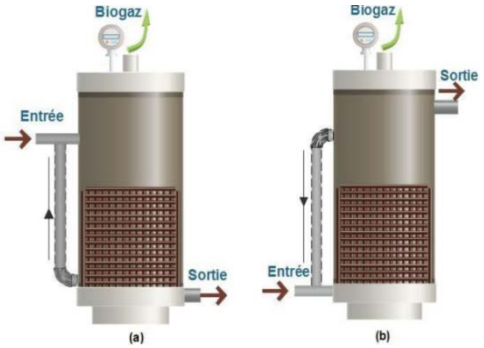
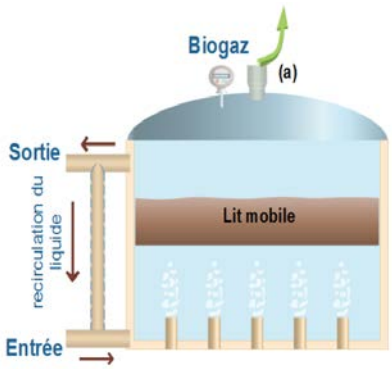


Figure 4. Fixed bed digester: a) downflow, b) upflow

3.2.7. Moving Bed Reactors

These reactors were developed to combine the advantages of fixed biomass reactors (high biomass retention rates allowing high feed rates) and free cell reactors (less sensitivity to clogging and good homogeneity of the medium) [15]. The support is a granular material or a set of specific moving elements, set in motion either by a liquid flow or by the biogas. The models generally used are upflow or downflow fluidized bed reactors, and turbulated beds (Figure 5). However, as in the case of fixed bed reactors, the biomass can become trapped between the supports [18]



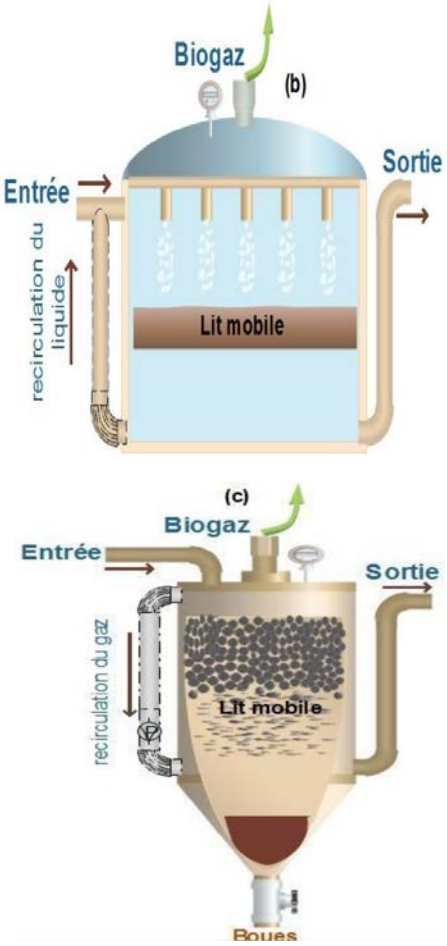


Figure 5. Fluidized bed digester (a) upflow, (b) downflow, (c) reverse turbulent bed

Another simpler design is defined by

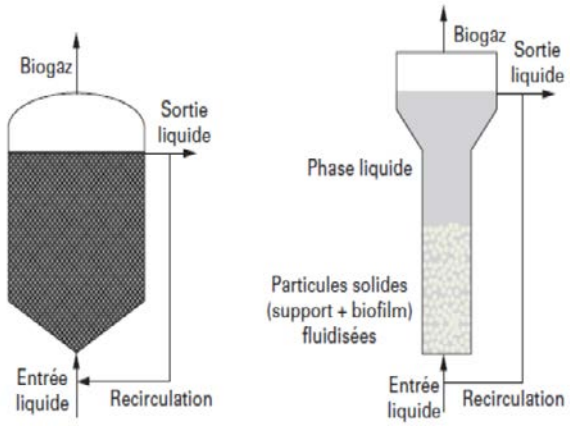


Figure 6. Supported reactors

This type of system (figure 6) has the advantage of being very robust with respect to feed disturbances and can treat high organic loads [19]

3.2.8. Upflow Anaerobic Sludge Blanket (UASB) Reactor

The UASB digester consists of passing the effluent to be treated through a bed of sludge, above which a separation between the sludge and the liquid forms.

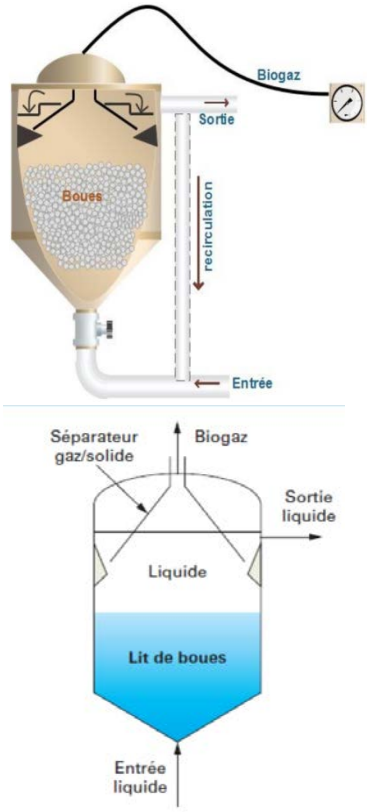


Figure 7. Up-flow Anaerobic Sludge Blanket (UASB) digester.

Microorganisms form flocs and settling takes place in the digester. This technology is suitable for effluents that are rapidly biodegradable and contain little particulate matter. Expanded Granular Sludge Bed (EGSB) reactors are UASB digesters in which the upward flow is significantly higher, which increases the height of the sludge bed. In this case, the tank is higher and the diameter is smaller[17,19].

3.2.9. Review of the Differences in the Type of Reactors

There are four generations of processes that have appeared successively according to Moletta and Torrijos (1999) [20]. In the order of appearance and complexity we can list them as follows:

- first generation: free sludge or "contact" reactors;
- second generation: UASB or granular sludge reactors;
- third generation: immobilized or "fixed" sludge reactors;
- fourth generation: fluidized bed reactors.

However, derived or combined techniques have appeared over time, such as aerobic lagoons (free sludge in extensive reactors without final clarification), EGSB (expanded granular sludge bed) reactors, IC (internal circulation reactor) reactors, hybrid reactors (combination of immobilized sludge and free sludge in the same reactor).The so-called second-generation UASB technology (including IC and EGSB reactors)

3.2.9.1. Free Sludge or "Contact" Reactors

It consists of implementing free biomass in an infinitely mixed reactor similar to aerobic activated sludge technology.

In the CSTR process, mixing is carried out mechanically. An external decanter is placed at the liquid outlet. The solids retained in the decanter are recycled into the reactor, which allows the biomass to be concentrated in the reaction medium. The hydraulic residence time is of the order of a week. It is particularly suitable for treating discharges containing solid particles that are difficult to degrade, which are recycled into the reactor at the same time as the biomass**.**

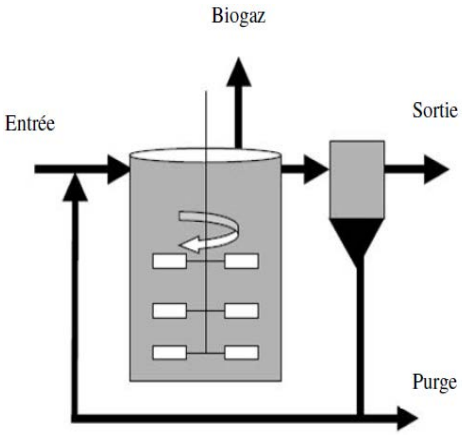


Figure 8. Free sludge reactors equipped with a biomass retention system (Michaud, 2001) [21]

3.2.9.2. UASB or Granular Sludge Reactors

Considered as the second generation technology, Rajeshwari et al. in 2000 [22] defined it as a reactor composed of a granular bed, and that the growth of this bed is essentially due to the suspended solid particles entering the reactor and the growth of bacteria. The bed is set in motion by natural turbulence, caused by the inlet flow of effluents and by the production of biogas, thus allowing good contact between the wastewater and the biomass within the reactor. The applications of these reactors are multiple. It can be used for the treatment of wastewater from municipalities, steel mills and foundries, the chemical industry, food industry facilities, the automotive industry and pulp and paper.

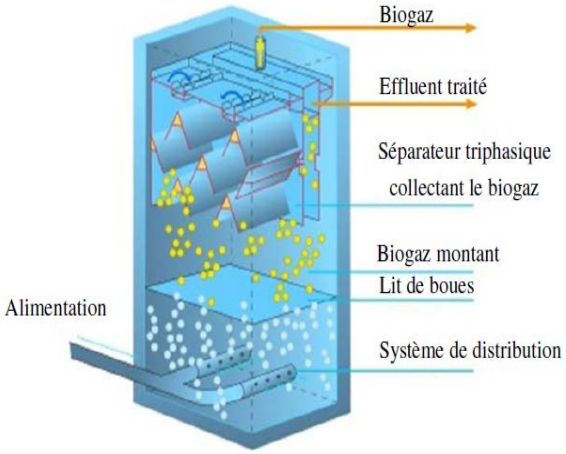


Figure 9. Schematic view of a UASB reactor (Paques B.V.)

3.2.9.3. EGSB Reactors

Based on the shortcomings of the previous technology, Seghezzo et al., (1998) [23] demonstrated that mixing was not optimal in the UASB due to the presence of dead volumes leading to a loss of efficiency. To improve this, it is necessary to better distribute the effluent. The use of recirculation with larger reactors led to the EGSB reactor in which the superficial velocity is higher. Chen, H et al., (2002) [24] for their part, explain that the EGSB was developed with dense transport particles such as sand, activated carbon or polymers.

This is called an anaerobic biofilm reactor rather than a granular sludge reactor..

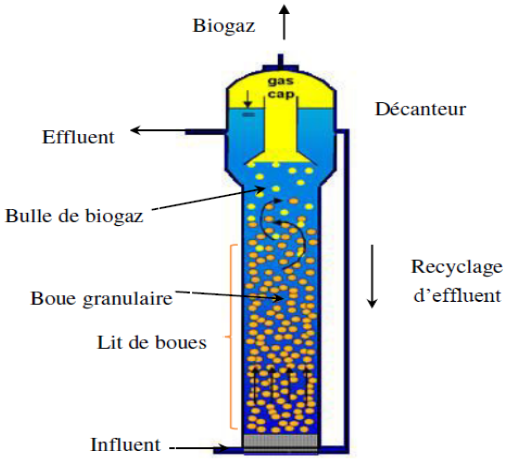


Figure 10. Diagram of an EGSB reactor (Mutombo, 2004 [25]).

3.2.9.4 IC REactor

Another key point of this IC reactor is that it circumvents the main problem of sludge evacuation encountered during the start-up period of the UASB.

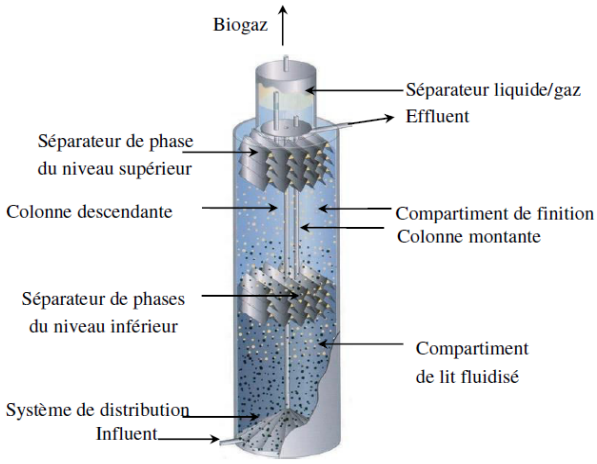


Figure 11. Schematic of an IC (Paques B.V.)

These so-called internal circulation reactors are in the form of cylinders of variable height (between 16 and 28 m high). They are composed of 2 UASB compartments connected one above the other. The first stage works at high load and the second at low load. The main characteristic of these reactors lies in the collection of biogas at each of the two stages. The gas collected in the first stage is conveyed by a pipe, called a "riser", to the top of the reactor by generating a gas-lift (gas pump) also pumping the sludge mixture (effluent + sludge) into the first stage. After separation of the sludge mixture and the biogas in the degassing tank located at the top of the

reactor, the effluent and sludge are directly returned to the base of the reactor via the central pipe, called the "downer" due to the difference in density between the riser and the downer. An internal recirculation flow is thus created, giving the reactor its name. The biogas leaving the top of the reactor is sent to the gasometer via a pipe.

3.2.9.5. Immobilized Sludge Reactors and Fluidized Bed Reactors

These are the so-called "third generation" (fixed sludge reactor) and "fourth generation" (fluidized bed reactors) reactors. Supports are placed between two perforated plates or two meshes to hold them in the reactor. These are ordered or loose plastic supports offering fixing surfaces on which bacterial films develop. As with UASB technology, the purifying biomass is kept in the reactor.

Furthermore, these reactors can be sensitive to suspended matter in the effluents that can clog the support used for the development of the biofilm. They may require backwashing steps and clarification of the effluent

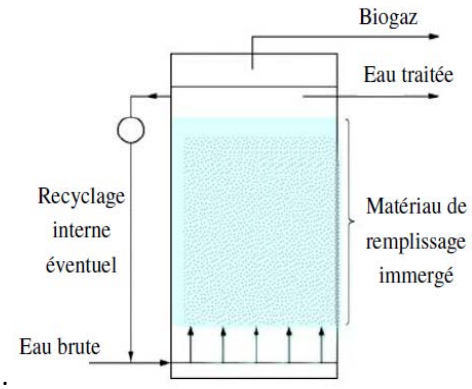


Figure 12. Immobilized sludge reactors

The technology of fluidized bed reactors is directly derived from reactors with sludge fixed on very small supports (sand, biolite, etc.) which have significant settling capacities) on which the purifying bacterial populations attach and develop

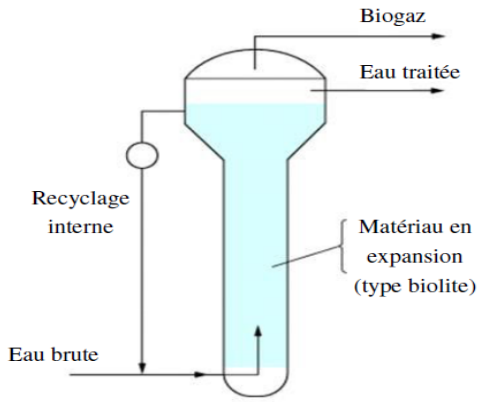


Figure 13. Fluidized bed reactors

4. Conclusion

The sizing techniques of a biodigester can be different from one digester to another, depending on the type of digester and also on the characteristics of the materials in place. [26,27,28,29] In the literature, we find several types of process and several categories of anaerobic reactors. In batch operation, a substrate is introduced into the digester in one go. Once the reaction is complete, the digester is completely emptied and a new series is restarted. This type of feeding is rarely used in industrial environments.Continuous operation is the most widely used in industrial environments. The reactors are fed permanently at a so-called "nominal" regime which generally corresponds to a constant material flow rate.Semi-continuous operation is a hybrid operating mode between continuous and batch operations. It corresponds to the alternation of filling, reaction, decantation and emptying cycles of the reactors. This mode allows some of the microorganisms to be preserved for the next cycle. It is well suited to small-scale digestion.For a given treatment mode, digesters are also differentiated by their mixing mode, which greatly influences the efficiency of the anaerobic digestion process. Overall, two mixing modes are considered: "stirred" reactors and "plug-in" reactors.The principle of the stirred reactor is to allow the material a general movement that ensures the total homogeneity of the digestion medium. This is generally the operating principle of wet reactors.For "plug-in" reactors, the digestion medium moves from the inlet (feed) to the outlet (drawdown). The absence of agitation prevents overall mixing of the reactor and the progress of the degradation process is therefore increasing throughout the reactor.In reality, industrial digesters operate on a mixed mixing mode between the stirred mode and the plug-in mode.

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Conflicts of Interest

"The authors declare no conflicts of interest."

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