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**University of Aboubakr Belkaïd – Tlemcen –**

**Faculty of TECHNOLOGY**

# MASTER THESIS

Presented for obtaining a MASTER Degree

**En** : Automation

**Major** : Automation and Industrial Engineering


**By**: **F**eryel **B**ENABDALLAH

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## Subject

**Modelling, Conception and realisation of an anaerobic chemostat in consideration of its automatic control**

Publicly defended on 29 /09/2022, in the presence of the jury composed of:

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# *Abstract*

We focus in this master thesis on the modelling of anaerobic chemostat. In the first section the mathematical model AM2 of the anaerobic digestion is introduced, a detailed study of its equilibrium points and their stability is given, and numerical simulations of its dynamical behavior are performed.

In the second section, An attempt of making an anaerobic bioreactor (a laboratory pilot) from scratch is conducted, with the aim of producing biogas from wastewater and collect experimental data in order to calibrate the model in the future. Biogas was produced and measured on a period of 35 days, where we have obtained a cumulative biogas volume of around 2950 ml.

As this is considered to be a complex model, a different type of control has been proposed by Michel Fliess which is based on the calculation of the derivatives. In order to use this method, In the final section, we developed a free-model robust control for the AM2 system, based only on input and output measurements.Simulation results showed the efficiency of the control in regulation, where the biogas output accurately follows the input.

The purpose of this Master thesis is to introduce the AM2 model and conduct its mathematical study as a first step then try to apply the system in real life, in other words, conduct the conception of an anaerobic chemostat and lastly use the model-free method to control it.

Key words

Anaerobic digestion, Equilibriums, Modelling, Stability, Chemostat, Control.

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# *General Introduction*

Water is considered to be the most valuable resource that planet earth possesses since all living creatures depend on it for their survival. 70% of the earth's surface is covered in water however only 2.5% of it represents fresh water with 68.95% of that being in the form of ice and 30.16% being underground water. So, we can conclude that only a small fraction of the earth's hydrosphere is water that can be used by humans which makes this resource even more valuable. Unfortunately, many countries face shortages of fresh water which can lead to social, economic and political disruption. On the other hand, pollution and climate change have the potential of affecting the availability and quality of the already fragile resource. Therefore, it is of crucial importance to use bioreactors and WWTP for wastewater treatment in order to preserve environment and ecosystems by reusing the purified water in agriculture and industry. As all others physical systems, bioreactors should be modeled, supervised and controlled, which is the aim of this master project as we designed a laboratory anaerobic chemostat, chose and analyzed an accurate model for it and developed controls for optimizing biogas production.

Water can be treated multiple ways, however one of the most promising methods to treat wastewater is via biological technologies which have been knowing a lot of attention in recent decades. It is considered to be a natural process that uses microorganisms (bacteria) for degrading the organic substrate (pollution) by using their own life-sustaining activities.

The decomposition of the organic matter can be achieved in either the presence of oxygen and in this case we call it the "aerobic digestion" or in the absence of it and this case we call it the "anaerobic digestion". Practitioners have used the biological reaction where the soluble substrates' transformation into biomass and releases a biogas (methane) and implemented it in a bioreactor where they could control and observe the medium and the development of the bacteria.

The anaerobic digestion is a process that can be divided into four steps: Hydrolysis, Acidogenesis, Acitogenesis and Methanogenesis. These steps are well explained and presented in the first chapter. However, this process can be a slow process to start and could easily become unstable by disturbances and overloading organic matter. Therefore, it is essential to have a good mathematical model to predict process behavior for various functioning conditions and assure the success of the automatic control. An adequate model which is the simplest one from a mathematical point of view, contains rich information about the key state variables which enables us to predict the system's qualitative dynamic behavior

In the context of anaerobic digestion, the Anaerobic Digestion Model no1 (ADM1) model is seen to be the most completed phenomenological model containing more than thirty differential equations modeling the reactions and exchanges between the multiple species residing inside the bioreactor. However, in order to control the anaerobic digesters, a more simplified model called the AM2 model is used as it is seen to be more suitable. It is a two-stage model (acidogenesis and methanogenesis) composed of six differential equations. where four of its state space variables are the main ones.

So, in the first part of our master thesis, we have focused on presenting the AM2 model for the anaerobic digestion and we study its equilibriums and their stability. Later on, we moved to the application of the system in real life as we have realized an anaerobic chemostat and its parameters and followed its development and the production of the biogas that goes with it.

We have also dedicated an important fraction of this master thesis for the realization of various electronic components that comprise our system, which appear to play a distinct role in the module's proper operation. By proper operation, we refer to the good functioning of the chemostat and that requires multiple parameters to be respected such as the temperature and the homogeneous mixture. Thus, we made a temperature sensor connected to a heating loop and an agitator. In the realm of conception and realization, we found multiple options and ways to make various components theoretically. However, many of these methods proved to not work in the physical world. Hence, we have made and realized the different components after various trials.

The model-free control which was applied on the AM2 system, is based solely on the input and output of the system and would be updated on each control time range, which is chosen depending on the desired-to-be-controlled system. We will test the efficiency of a calculated control law without considering the system’s model.

The thesis is divided into four chapters as follows: in the first chapter we focus on the wastewater issues facing the world and the possibility of treating them using the anaerobic digestion. We introduce in the second chapter the AM2 model and we calculate its equilibriums and study their stability. In the following chapter we present our experiment, and we specify the components used and the steps taken to realize our anaerobic chemostat. Lastly, we offer an introduction to the model-free control proposed by Michel Fliess with a focus on the calculation of the derivatives that are useful for this type of control. We also take one step further and apply the mentioned previously control on the AM2 system that we work with.

# *Chapter I :Wastewater treatment using anaerobic digestion*

## I.1 Introduction :

Treating wastewater technologies have been gaining lots of attention in the recent years as the problem of pollution keeps rising.

Water pollution has become a major global issue and requires immediate attention to be directed towards and an ongoing evaluation of water resource policy in order to counter this problem.

Both developed and developing countries are facing the consequences brought from water pollution mainly diseases and in extreme cases deaths as pollution in water causes approximately 14000 people to die on a daily basis. The quality of water is influenced by many factors such as climate, soil type, flow conditions and human activity.

One of the methods that are drawing attention is the biological wastewater treatment by anaerobic digestion. Anaerobic treatment happens using microorganisms conduct their metabolism only in the absence of oxygen.

In this first chapter, we will present the issue of water pollution that is facing the globe and we will focus on one of the eco-friendly ways to treat polluted water which is the wastewater treatment process by anaerobic digestion.

## I.2 Water :

Water is undoubtedly the most important resource on our planet as all living things depend on it to survive. Some billion years ago, the first living cells were created in this miraculous resource and therefore it is considered to be the source of life on earth. The hydrosphere is believed to cover around 70% of planet earth's surface which translates to 361740000 $Km^2$. This might sound like a lot, however according to the World Hydrological Cycle Observing System (WHYCOS) only 2.5% of this entire surface represents fresh water with 68.95% of it being in the form of ice and permanent snow in the Antarctic, Greenland and mountainous areas and 30.16% being underground water. So, it is clear that the freshwater only covers a tiny fraction of the earth's hydrosphere.

Since the quality of the water that we use to either consume, fish in or water our plants directly impacts the quality of the life that we lead, shortages of it can cause social, economic and political disruption. So, it is evident that it is extremely important to address the various issues surrounding water and create sustainable water-related policies and services such as encouraging governments to follow the SDG put by the United Nations.

The pollution and climate change scenario can potentially have considerable effect on the availability of the extremely fragile water resources and can also cause environmental degradation.

## I.3 Pollution:

Pollution can be defined in various ways. One of the simplest definitions of water pollution specifically is that it consists of contaminating water with pollutants such as chemical substances, trash, bacteria… which makes it unusable for drinking, swimming and other activities.

With the rapid demographic and economic growth in the world, water quality and water pollution have become a serious issue that needs to be tackled.

A huge amount of non-biodegradable substances get dumped in waters around the globe daily, overwhelming the self-purification capacity of the living bodies of water. China is a great example of the current water pollution problem as 80% of Chinese urban rivers evince significant pollution levels.[1]

As a result to try and put an end to these issues, a lot of attention has been poured towards the control of water pollution and the upgrade of the quality of waters using technologies (phytoremediation, pre-reservoirs, bio-manipulation…)

***Figure I-1 : Water Pollution by liquid and solid waste***

| Regions | Organic pollution |
|---|---|
| Zhaoyuan, Songhua River | 133 kinds of organic compounds in 11 categories were detected. 11 organic compounds, which include 27 substitutive benzene compounds and 21 polycyclic aromatic hydrocarbons were quantified. |
| Beijing-Tianjin-Tangshan Region | 133 kinds of organic pollutants word detected. |
| Hebei Plain | the detection rate of organic chloride was 100%. the average concentration was 0.1 μg/l and the concentrations increased from Piedmont to the sea. |
| Beside a river in Shangdong | 10 organic pollutants which include phenols, aldehyde, alcohols, PAHs, alkanes, ketones and acids were detected. |
| The karst groundwater in Jinan city | 76 organic pollutants of which 60% were phthalic lipid and heterocyclic aromatic hydrocarbons were detected. The most seriously polluted areas were distributed in waterworks of the eastern and western suburbs, the groundwater in menjiazhuang, and Xiying, Wohu mountain an Jinxiuchuan reservoirs. 59 organic pollutants were detected in total. |
| The groundwater in sewage irrigation area of Beijing | 138 organic pollutants of which 23% belonged to the priority pollutants proposed by USEPA and our country are detected. |
| Suburban area of a city in north China | 36 organic pollutants of which including five single aromatic hydrocarbon,s 7 halogenated hydrocarbons, 8 organic pesticides and 16 polycyclic aromatic hydrocarbons were detected. |
| Urban and suburban area of Changzhou city | the main organic pollutants were chloroform, tricholoroethylene, tetrachlorozthylyne, toluene and benzene. |
| Urban and suburban area of Suzhou and Wuxi city. | The main organic pollutants are trichloroethylyne and tetrachloroethylene. |

***Table 1 : The status of organic contamination in groundwater in some areas in China***

## I.3.1 **Pollutants:**

A pollutant is a substance that is present at levels that could endanger organisms or violate environmental quality standards. These pollutants are divided into different categories:

### *I.3.1.1 Biological pollutants:*

They represent the major threat that low-income countries could face since they cause diseases that are rapidly manifested and can in some severe cases lead to deaths. According to **WHO (2004)**, diarrheal diseases account for an estimated 4.1% of the total daily global disease burden

and are responsible for 1.8 million deaths each year. 88% of that burden is estimated to be caused by unsafe water supply, sanitation, and hygiene. Some of these biological pollutants are:

#### I.3.1.1.1 Viruses:

Viruses are infectious units with diameters of about 16 nm to over 300 nm. Their small size makes them ultra filterable, i.e. they are not retained by bacteria-proof filters. Viruses have evolved over longtime period, and have adapted to specific organisms or their cells. Viruses do not reproduce by division, such as bacteria, yeasts or other cells, but they replicate in the living cells that they infect. In them, they develop their genomic activity and produce the components from which they are made. The enteric viruses most relevant to man are enteroviruses, Norwalk, rotaviruses, reoviruses, caliciviruses, adenoviruses, and hepatitis A viruses. Viruses discharged in polluted water can migrate long distances in soil and groundwater.[2]

#### I.3.1.1.2 Bacteria:

Bacteria are microbes with a cell structure simpler than that of many other organisms. Their control center, containing the genetic information, is contained in a single loop of DNA. [3]Many species of bacteria are not harmful to man. In fact, some even live inside humans forming intestinal colonies. In wastewater, pathogenic bacteria are always present but at a variable concentration, depending on the local health conditions.

#### I.3.1.1.3 Protozoa:

Protozoa are the group of parasites most closely associated with diarrheas. They are single-celled organisms (2–60 mm in size) that develop in two ways: as trophozoites and as cysts. Infections are produced when mature cysts are consumed. Cysts are resistant to gastric juices and transform themselves into trophozoites in the small intestine, lodging in the wall where they feed on bacteria and dead cells.

#### I.3.1.1.4 Helminthes eggs:

Helminthes are worms some of which are parasites in humans. Where helminthes are the origin of waterborne diseases, they are mainly transmitted through the consumption of contaminated food (crops, meat, or fish). Helminthes can also be transmitted through the oral–fecal route and, therefore, hygiene is important as a factor in their control. As helminthes are associated with turbid water, they normally are not a concern in drinking water.

#### I.3.1.1.5 Biological indicators:

Thermotolerant coliform bacteria (commonly referred as fecal coliforms) are the group most frequently used as indicators of fecal pollution because they behave in a similar way to most pathogenic bacteria in the environment, and, during treatment, they are abundant and easy to determine.

### *I.3.1.2 Emerging pathogens:*

Some pathogens that are not usually followed during conventional monitoring have been linked to outbreaks in developed countries. These pathogens have been called 'emerging' pathogens. They have led to new regulations as well as to improvements in water and wastewater treatment procedures.

#### I.3.1.2.1 Conventional parameters:

They are commonly used in order to design or select the processes that are suitable to treat wastewater and sludge worldwide, and they refer mainly to the organic matter content (measured as BOD or COD biological or chemical oxygen demand), or suspended solids. In general, they are similar worldwide except for the heavy metals content that in general; and especially for sludge; is notably lower in third world countries than in developed ones since there is a noticeable difference at the industrialization level.

#### I.3.1.2.2 Emerging pollutants:

The term (chemical) 'emerging pollutant' is used to describe a wide variety of complex organic chemical compounds that are candidates for future regulation and that have not usually been monitored. Merging pollutants have been detected in untreated wastewater, treated wastewater, surface water, groundwater, and even in drinking water of both developed and developing countries. The sources of emerging pollutants are diverse. They come from nonpoint sources, municipal wastewater (treated or non-treated), and industrial discharges.

## I.4 Reclaimed water applications:

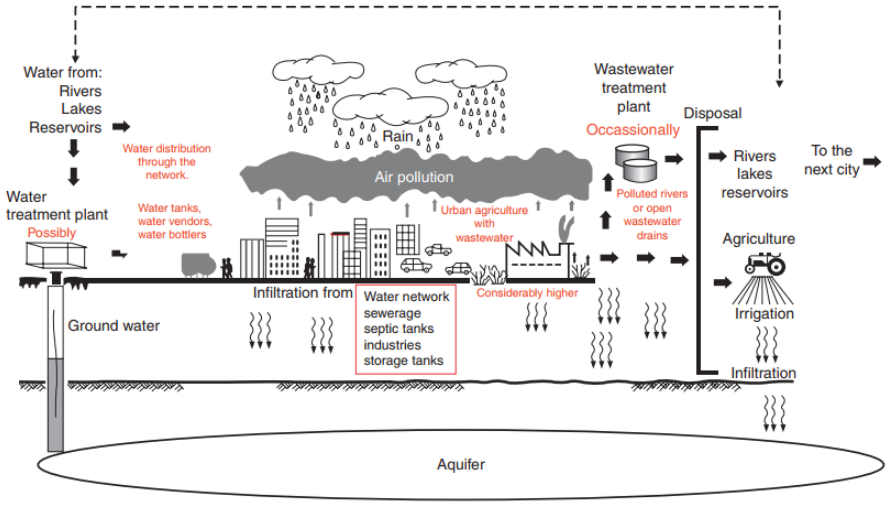


***Figure I-2 : Hydrological urban cycle***

In the planning and implementation of water reclamation and reuse, the reclaimed water application generally governs the type of wastewater treatment needed to protect public health and the environment, and the degree of reliability required for each sequence of treatment processes and operations. In principle, wastewater or any marginal quality waters can be used for any purpose as long as adequate treatment is provided to meet the water-quality requirements for the intended use. The dominant applications for the use of reclaimed water include: agricultural irrigation, landscape irrigation, industrial recycling and reuse, and groundwater recharge. Among them, agricultural and landscape irrigation are widely practiced throughout the world with well-established health protection guidelines and agronomic practices. From a global perspective, water reuse applications have been developed to replace or augment water resources for specific applications, depending on local water use patterns. In general, water reuse applications fall under one of seven categories: (1) agricultural irrigation, (2) landscape irrigation, (3) industrial reuse, (4) groundwater recharge, (5) environmental and recreational uses, (6) nonpotable urban uses, or (7) indirect or direct potable reuse. The relative amount of water used in each category varies locally and regionally due to differences in specific water use requirements and geopolitical constraints.

## I.5 Treatment technology:

Treatment technologies used for the production of reclaimed water typically follow conventional secondary treatment.

These technologies include depth and surface filters, membranes, carbon adsorption, disinfection, and advanced oxidation. The type of treatment processes that are selected to produce reclaimed water will depend on several factors, including the quantity and quality of reclaimed water required and the life cycle costs of the reclaimed water system. However, in terms of water quality, virtually any quality of reclaimed water that is desired can be produced using currently available technology. Membranes represent the most significant development as several new products are now available for a number of water and wastewater treatment and water reuse applications. Our main focus will be on **Biological technologies.**

### I.5.1 Biological technologies:

In the last few decades, a lot of attention has been directed towards controlling water pollution and improving the quality of water. Accordingly, various water pollution control technologies are being developed and applied. In our thesis we will focus only on biological technologies.

The biological wastewater treatment is a natural process that lies on microorganisms such as fungi, bacteria, yeasts, and algae to assist in decomposition of organic substances by using their own life-sustaining activities. These microorganisms consider wastewater to be a buffet of organic matter as they feed on the wastes, garbage and partially digested foods that exist in it. However, the pollutants must be soluble in water and non-toxic for the degradation to take place. The decomposition of the organic matter can be realized in either the presence of oxygen (aerobic digestion) or in the absence of oxygen (anaerobic digestion) which will be the focus of our study. These two digestion processes have fundamental differences in the technical and economic areas as shown in the following table:[4]

| **Anaerobic treatment** | **Aerobic treatment** |
|---|---|
| COD>1000 mg / l | High amount of excess sludge |
| Low amount of excess sludge | High energy demand |
| Energy generation by use of biogas | High required space |
| Low energy demand | Fully biological degradation |
| Low required space | |
| Sensitive against high sulfate and calcium concentrations | |
| No fully biological degradation | |

**Table 2*: Main characteristics of anaerobic and aerobic wastewater treatment***

- Anaerobic treatment: anaerobic microorganisms conduct their metabolism only in the absence of oxygen. Anaerobic processes are characterized by a small amount of excess sludge produced and low energy requirements. As biogas is produced during the degradation process, anaerobic processes produce an excess of energy.

  Biogas is a mixture of its principal components, methane and carbon dioxide, with traces of hydrogen sulfide, nitrogen, and oxygen. Biogas is energetically utilized mainly in internal combustion engines or boilers. In its function as a regenerative energy carrier, biogas replaces fossil fuels in the generation of process steam, heat, and electricity. The composition and quality of biogas depend on both effluent properties and process conditions such as temperature, retention time, and volume load.
- Aerobic treatment: aerobic microorganisms require oxygen to support their metabolic activity. In effluent treatment, oxygen is supplied to the effluent in the form of air by special aeration equipment. Bacteria use dissolved oxygen to convert organic components into carbon dioxide and biomass. In addition, aerobic microorganisms convert ammonified organic nitrogen compounds and oxidize ammonium and nitrite to

form nitrate (nitrification). The key factors for the success of an aerobic process are an adequate amount of nutrients in relation to the amount of biomass, a certain temperature and pH regime, and the absence of toxic substances. Aerobic processes are characterized by high volumes of excess sludge and higher energy demands compared to anaerobic processes. Furthermore, these reactors typically have large space requirements.

## I.6 Waste water disposal vs reintegration :

After the wastewater is treated, the next crucial step is to dispose of it. It is important to note that water needs to be returned to the environment or reused. In other words it needs to be reintegrated into the hydraulic cycles which reduces the negative results from taking water from nature beyond the quantity needed for ecological use.

We can reintegrate treated wastewater to the environment by discharging it either on land or in water bodies or by reusing it.

- Soil Disposal: This method consists of disposing of the water whether it is treated or non-treated into the soil as it has the ability to act as a treatment step if properly managed. Once the water is discharged into the land, it will evaporate and infiltrate to reach underground water bodies depending on the quality of the soil and the local conditions.
- Water Disposal: Effluents from plants can be used to increase the surface of water bodies. This can be done by diluting the effluent with fresh water and reusing it as a water source.
- Reuse: Another way of reintegrating water into the environment is simply by reusing it which is considered as an important way to fix the mismatch between the world's water supply and water demand.

On our planet, there is around 8500 $m^3$/ inhabitant.year water availability. However, this number is bound to vary depending on the region for example around 11% of the total world population live with no more than 1000 $m^3$/ inhabitant.year. Unfortunately, it is estimated that more people will start living under such water conditions in the next few years. Water can be reused in two different ways (unintentional and intentional).

### I.6.1 Unintentional reuse:

This kind of reuse describes situations where wastewater is mixed with the clean water supply unintentionally. It usually happens for agricultural irrigation, aquifer recharge and even for human consumption. Some examples of this type of reuse are mentioned in the table below.

| City | Recharged water | Groundwater uses |
|---|---|---|
| Hanoi, Vietnam | Sewer, storm water | Irrigation and drinking |
| Hai Yai, Thailand | Drainage canals, on-site sanitation facilities | Drinking |
| Ica Valley, Peru | Primary effluent | Drinking |
| Leon, Mexico | Mix industrial effluent | Irrigation and drinking |
| Merida, Mexico | Sewer, stom water | Drinking |
| Mexico city (southern part), Mexico | On-site sanitation facilities | Drinking |
| Santa Cruz, Bolivia | On-site sanitation facilities | |
| Sana'a, Yemen | Cess pits | Drinking |
| Tula Valley, Mexico | Untreated effluent | Irrigation and drinking |
| | | |
| **City** | **Recharged water** | **Groundwater uses** |
| Hanoi, Vietnam | Sewer, storm water | Irrigation and drinking |
| Hai Yai, Thailand | Drainage canals, on-site sanitation facilities | Drinking |
| Ica Valley, Peru | Primary effluent | Drinking |
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| Mexico city (southern part), Mexico | On-site sanitation facilities | Drinking |
| Santa Cruz, Bolivia | On-site sanitation facilities | |
| Sana'a, Yemen | Cess pits | Drinking |
| Tula Valley, Mexico | Untreated effluent | Irrigation and drinking |

**Table 3 :*Example of unintentional indirect potable reuse via aquifers***

## I.6.2 **Intentional reuse:**

This is the type where we use different processes to intentionally treat wastewater to make it reusable especially for agricultural uses, which is a convenient strategy for the following reasons:

- It is an easy option to increase controlled reuse when non-treated wastewater is already in use as it allows more profitable and safe products.

• It can be a low-cost option to manage wastewater and to reintegrate water into the environment.

• It allows the reclamation of nutrients (N and P, to increase soil fertility) and organic matter (to improve soil characteristics) at no cost.

• Particularly in (but not limited to) arid and semi-arid areas, it permits higher crop yields, as it allows crops to be sown year-round due to higher water availability.

• Due to the availability and reliability of water, crops with better profitability can be selected.

• It avoids discharging pollutants to surface water bodies (which have a considerably lower treatment capability than soils).

• It is possible to recharge certain type of aquifers through infiltration.

• It can be part of a strategy to secure food and increase poor people's income in water-scarce areas.[5]

### I.6.3 Foundation of water reuse:

Insufficient water supplies and low water-quality represent serious concerns for humankind. Various factors have contributed to these issues such as continued population growth, contamination of water, unbalanced distribution of water resources, and frequent droughts caused by extreme climate change. Water reuse helps realize two different things:

(1) The treated effluent is used as a water resource for beneficial goals resulting in decreasing drinkable water demands.

(2) Once the effluent is reintegrated into the environment, it improves the overall water quality in the receiving water body.

Water reuse is based upon three principles: (1) providing reliable and adequate treatment of wastewater to meet the strict requirements for the intended reuse applications, (2) protecting public health, and (3) gaining public acceptance.

## I.7 Bioreactors:

According to the Compendium of Chemical Terminology a bioreactor is an apparatus used to carry out any kind of bioprocess; examples include fermenter or enzyme reactor.[6] It is considered as a vessel that contains a nutrient medium composed of a mix of molecules, referred to as 'substances', upon which one or a group of microorganisms feed and grow. A population of these microorganisms is referred to as 'biomass'.

We use bioreactors mainly to modify an element biologically. In most cases, this operation is accompanied by the increase of biomass. It is important to note that only soluble substrates; in other words substrates that have created chemical bonds with water; are needed for the survival and development of the biomass.

Our thesis focuses on the biological reaction that represents the transformation of soluble substrates into a solid mass (biomass) and result into the releasing of biogas (methane).

### I.7.1 **Types of bioreactors:**

Bioreactors are divided and classified depending on their mode of functioning, putting it differently the way in which they are filled with substrates.

Therefore, we can distinguish three types of bioreactors:

- Semi-continuous reactor (fedbatch): Where the inflow rate is different from zero but the outflow rate is zero. In this case, the reaction volume keeps increasing over time. A fedbatch is perfect for producing biomass as it can be supplied with substrates depending on the needs of the microorganisms. It is also useful to avoid the inhibition due to the accumulation of the substrates.
- Closed reactor (batch): Where we introduce the substrates and the biomass at the starting time and stop supplying and withdrawing from the system. As a result, the reaction volume stays constant over time. This kind of reactor is used mainly in pharmaceutical, agri-food and chemical industries.
- Continuous reactor: Where the volume inside the bioreactor remains constant as the inflow and outflow rates are identical. This type of bioreactor is the most commonly used in industries as it processes a large amount of elements arriving non-top as in the case of processing water. The vessel that is used to grow biomass in a continuous way is called a chemostat.[7]

## I.8 **Chemostat:**

It is a device that was created back in the 1950s by Jacques Monod and by Aaron Novick and Leo Sziland.

In a chemostat, it is possible to control the microbial growth by interfering with the flow rate and keep a constant substrate concentration, as well as provide continuous control of the pH, temperature and oxygen levels.

The most important source of uncertainty when modeling a biological process using a chemostat is modeling the rate of the microorganisms' growth.

As mentioned previously, there are two types of digestion in the bioreactors, aerobic and anaerobic. However in our experiment we used the second type of digestion.

***Figure I-3 : The realized chemostat***

## I.9 Anaerobic digestion:

### I.9.1 Anaerobic digestion at a glance:

Anaerobic digestion is the biological process of converting elements using a complex microbial ecosystem of organic or inorganic substrates in the absence of oxygen. During the conversion, the organic matter is transformed to methane, carbon dioxide and biomass.

Treating wastewater using the anaerobic way of digestion has more advantages compared to the aerobic one and that is mainly because there are no power requirements for air supply, production of sludge requiring treatment and disposal is much lower and the methane production can be used for the production of energy.

Aerobic digestion has the ability to yield around ten times more energy with a higher microbial matter. It is efficient in breaking down waste elements. With free oxygen, bacteria can derive energy from the break-down of food molecules since bacteria use oxygen. For example, in a very well aerated space, there is a fast breakdown of the organic materials. However, when placing material in an environment with no oxygen, it produces less considerable heat, breaks down slowly and most of the energy remains locked in the form of biogas (methane).

### I.9.2 Biogas technologies :

Digesting the organic matter anaerobically provides many benefits such as generating renewable energy, reducing greenhouse gasses, reducing the use of fossil fuels, creating new jobs and closing the nutrient cycle. Anaerobic digestion converts organic waste matter into a valuable resource while reducing solid waste. Using biogas as a renewable energy source helps improve the energy balance,preserve the natural resources by reducing deforestation and protect the environment by reducing pollution and the use of fossil fuels.[8]

### I.9.3 Calorific biogas value:

The calorific value of the biogas depends mainly on the source of energy used as it is demonstrated in the following table as well as the weight of the source corresponding to $1m^3$ of biogas:

| **Fuel Source** | **Approximative Calorific Value** | **Equivalent to 1m³ Biogas (approx.. 6 kWh/m³)** |
|---|---|---|
| Biogas | 6-6.5 kWh/m³ | |
| Diesel, Kerosene | 12 kWh/m³ | 0.50 kg |
| Wood | 4.5 kWh/m³ | 1.30 kg |
| Cow dung | 5 kWh/kg dry matter | 1.20 kg |
| Plant residues | 4.5 kWh/kg dry matter | 1.30 kg |
| Hard Coal | 8.5 kWh/m³ | 0.70 kg |
| Propane | 25 kWh/m³ | 0.24 m³ |
| Natural gas | 10.6 kWh/m³ | 0.60 m³ |
| Liquefied petroleum gas | 26.1 kWh/m³ | 0.20 m³ |

***Table 4 :Clofiric value of diffrent fuel [9]***

Approximately 10 Kg of biowaste are used to produce 1 m^3 of biogas which contains around 21.6MJ of energy.

## I.9.4 Process of anaerobic digestion of biowaste:

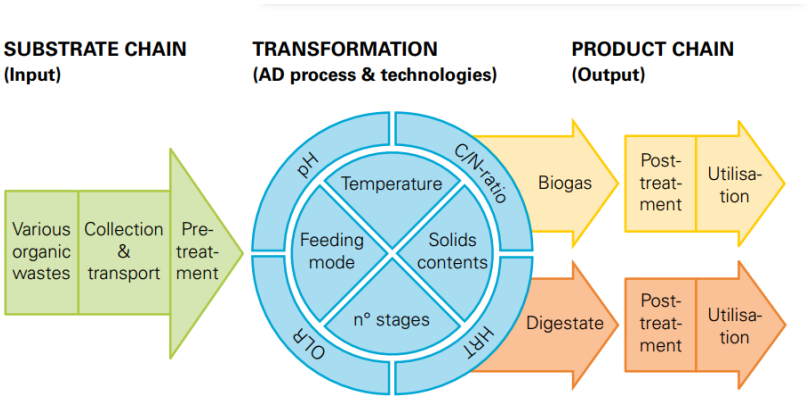



**Figure I-4 *: Process Chain of anaerobic digestion.****[10]***

The process of the anaerobic digestion can be divided into three sub-processes:

- Substrate process: Where the bio waste is generated, collected, transported and supplied to the digestion facility and pre-treated before feeding it to the reactor.
- Transformation process: Where the feed-stock is biologically and chemically transformed to a value product.
- Product process: Where the outflow from the reactor is post-treated, refined into an improved value product and then distributed and used.

## I.9.5 **Substrate process:**

### *I.9.5.1* ***Substrate sources:***

We call the biomass that is appropriate for digestion "substrate" or "feedstock". Back in the days, liquid wastes were treated anaerobically, with or without suspended solids, such in the case of sewers, industrial wastewater and sludge water. However, treating solid waste like agricultural and municipal solid started to attract attention in the 1960's. The following table shows the diverse feedstocks from agricultural, industrial and municipal sources.

| **Municipal** | **Agriculture** | **Industry** |
|---|---|---|
| • Organic fraction of municipal solid waste ("biowaste")<br>• Human excreta | • Manure<br>• Energy crops<br>• Algal biomass<br>• Agro-industrial waste | • Slaughterhouse waste<br>• Food processing waste<br>• Biochemical waste<br>• Pulp and paper waste |

***Table 5 : various feedstock from diffrent sources.***

- Biogas resulting from solid sources:

The amount of methane resulting from the anaerobic digestion of solid waste depends on various factors like the kind and composition of the feedstock, temperature and mixing as shown in the following table.

| **Substrate** | **Methane Yield (L/ Kg VS)** |
|---|---|
| Palm oil mill waste | 610 |
| Municipal solid waste | 360-530 |
| Fruit and vegetable wastes | 420 |
| Food waste | 396 |
| Rice straw | 350 |
| Household waste | 350 |
| Swine manure | 337 |
| Maize silage and straw | 312 |
| Food waste leachate | 294 |
| Lignin-rich organic waste | 200 |

**Table 6***:Biogas yield recorded from anaerobic digestion of organic solid waste*

- Pre-treatment: Most substrates require pre-treatment that includes sorting the non-biodegradable material such as metals, plastic and glass, reducing the particle size to

avoid blockage of the inlet pipe and adding water before the mixture is fed to the culture inside the bioreactor. This step is important as it enhances the degradation of volatile solids and thus increases the production of the biogas.

### *I.9.5.2 Biological and chemical process of anaerobic digestion:*

Biomethanation or biomethanisation are the two other names by which we can call anaerobic digestion. This process describes the biochemical degradation of complex organic material by multiple bacterial activities in the absence of oxygen.

The two most important products of anaerobic digestion are biogas and a cocktail of bacterial biomass and inert organics (effluent).

The anaerobic process of decomposing the organic matter occurs in a process divided into four steps as shown in the following figure:

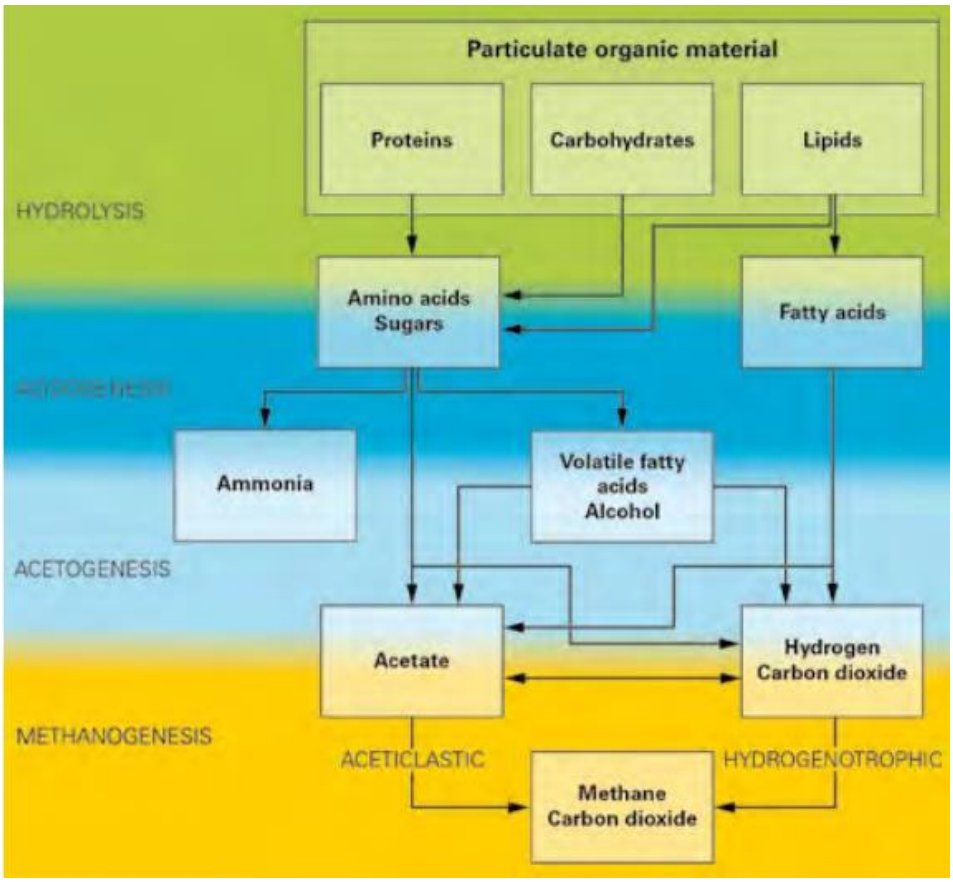



***Figure I-5: Schematic biodegradation steps of complex organic matter****[11]*

- Hydrolysis:

  This is the first and the slowest step of the degradation process. The term hydrolysis is used to describe the solubilization of complex particulate materials which can be composed of a mixture of components or a composite compound. The bacteria transform complex organic

matter i.e proteins, carbohydrates and lipids (fats) into amino acids, monosaccharide and fatty acids. This transform is of high importance as particulate organic materials are simply too large to be directly absorbed and used by microorganisms as substrate/food source.

- Acidogenesis:

  In the second stage, acidogenic bacteria convert the soluble organic monomers of sugars and amino acids to ethanol and acids (such as propionic and butyric acid), acetate, H2 and CO2. The degradation of amino acids also leads to production of ammonia.

- Acetogenesis:

  In this third stage both long chain fatty acids and volatile fatty acids and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. During this reaction the BOD (biological oxygen demand) and the COD (chemical oxygen demand) are both reduced and the pH decreased. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the partial pressure is low enough to thermodynamicallyallow the conversion of all the acids. Hydrogen scavenging bacteria lead to a lower partial pressure. Thus the hydrogen concentration in a digester is an indicator of its "health".

- Methanogenesis

  During this final stage, methanogenic bacteria convert the hydrogen and acetic acid to methane gas and carbon dioxide. Methanogenesis is affected by conditions in the reactor. such as temperature, feed composition and organic loading rate. The gaseous product, biogas, consists mainly of methane (CH4) and carbon dioxide (CO2), but also contains several other gaseous "impurities" such as hydrogen sulphide, nitrogen, oxygen and hydrogen. It is important to note that biogas with methane content higher than 45 % is flammable; the higher the CH4 content the higher the energy value of the gas.

| **Components** | **Symbol** | **Concentration ( Vol-%)** |
|---|---|---|
| Methane | $CH_4$ | 55-70 |
| Carbon dioxide | $CO_2$ | 35-40 |
| Water | $H_2O$ | 2 (20°C)- 7 (40°C) |
| Hydrogen sulphide | $H_2S$ | 20- 20000 ppl (2%) |
| Nitrogen | $N_2$ | <2 |
| Oxygen | O2 | <2 |
| Hydrogen | $H_2$ | <1 |
| Ammonia | $NH_4$ | <0.05 |

**Table 7** ***: Typical composition of biogas from biowaste***

The rate and efficiency of the anaerobic process is affected by the waste type and the operational parameters as described in the following section.

### *I.9.5.3 Operational parameters:*

The rate at which the microorganisms grow is of vital importance for the anaerobic digestion process. The operating parameters of the digester are therefore controlled so as to enhance the microbial activity and thus increase the anaerobic digestion efficiency. The most crucial parameters are mentioned down below:

- **Temperature:**

Although anaerobic digestion is supposedly feasible under all climatic conditions, when the temperatures are below $15°C$ (which is considered to be a low temperature) the process of digestion does not function satisfactorily. Under cold climatic conditions either a heating system should be used to increase the temperature or a larger digester has to be built to increase retention time. Not only is the mean temperature an important parameter for the AD process but large temperature variations, such as those between day and night, or seasonal variations, can also adversely affect the performance of an anaerobic digestion system.

There are two ideal temperature ranges for the performance of anaerobic bacteria; one at 30 – 40 °C for mesophilic microorganisms which is the case of our thesis and one at 45–60°C for thermophilic microorganisms. Operation of a digester in the mesophilic range is more stable, as these microbial communities can tolerate greater changes in environmental parameters and consume less energy. Inhibition by ammonium is less critical in the mesophilic range as compared to thermophilic conditions due to the lower content of free ammonia at lower temperatures. On the down side however, the mesophilic microorganisms are slower and thus a longer retention time in the digester is needed to maximize biogas yield. Despite some advantages of AD at higher temperatures, operating the digester at thermophilic ranges is generally considered less feasible in a developing country context due to the additional energy inputs required as well as the lower stability of the process.

- pH

The optimum pH for a generally stable AD process and high biogas yield lies in the range of 6.5 – 7.5. During digestion, the processes of hydrolysis and acidogenesis occur at acidic pH levels (pH 5.5 – 6.5) as compared to the methanogenic phase (pH 6.5 – 8.2). Lime is commonly used to raise the pH of AD systems when the process is too acidic. Alternatively, sodium bicarbonate can also be used for pH adjustment. Lime however frequently leads to precipitations and clogging of pipes when used in larger quantities. Sodium bicarbonate and sodium hydroxide are fully soluble and usually do not lead to precipitations.

- Carbon to nitrogen ratio:

The relationship between the amount of carbon and nitrogen in organic materials is represented by the C:N ratio. The C:N ratio is an important parameter in estimating nutrient deficiency and ammonia inhibition. Optimal C:N ratios in anaerobic digesters are between 16 and 25 A high C:N ratio is an indication of rapid consumption of nitrogen by methanogens, which then results in lower gas production. On the other hand, a low C:N ratio causes ammonia accumulation and pH values then may exceed 8.5. Such conditions can be toxic to methanogenic bacteria. Although methanogenic bacteria can adapt to very high ammonia concentrations this only happens if concentrations are increased gradually allowing time for adaptation. Optimum C:N ratios can be ensured by mixing different feedstock materials, with high C:N ratio ,organic solid waste for example, and low C:N ratios like sewage or animal manure.

- Inoculation and start-up:

When starting the digester for the first time, the digester needs to be inoculated with bacteria necessary for the anaerobic process. Diluted cow dung (optimally 1:1 ratio with water) is an ideal inoculate. Typically, the minimum cow dung required for good inoculation amounts to 10% of the total active reactor volume. In general, the more cow dung used for inoculation, the better. During the start-up phase, the bacteria population needs to be gradually acclimatized to the feedstock. This can be achieved by progressively increasing the daily feeding load which allows time to achieve a balanced microorganism population. Initial overloading presents a risk to the overall anaerobic process. Overloading results from either feeding too much biodegradable organic matter compared to the active population capable of digesting it, or rapidly changing digesters conditions (sudden change in temperature, accumulation of toxic substances, flow rate increase...). Such disturbances specifically affect methanogenic bacteria, whereas the acidogenic bacteria, which are more tolerant, continue to work, and produce acids. This eventually leads to an acidification of the digester which inhibits the activity of methanogens. Such an imbalance of acidogenic versus methanogenic bacteria can result in digester failure. Addition of manure can avoid this as it increases the buffer capacity, thereby reducing the risk of acidification. The gas that is produced in the first weeks after start-up is mainly carbon dioxide (CO 2). This gas is not flammable and can be released. After a few days the methane content of the gas will have sufficiently increased to a level that can sustain a flame (CH4 > 45 Vol.-%) and lead to high quality biogas (55 – 70 Vol.-%).

- Mixing:

The purpose of mixing and stirring inside the digester is to blend the fresh material with digested one and thus inoculate the fresh material with microbes. Such mixing avoids temperature gradients within the digester and also prevents scum formation. Scum and foam is a result of filamentous microorganisms in the digester. Low concentrations of substrate in AD plants lead to an increase in the growth of filamentous bacteria compared to flocculating bacteria. Scum in digesters should be avoided as it can result in blockage of the gas pipe or potentially lead to a foaming over of the digester. This results in displacement of slurry into pipes, machines and devices resulting in subsequent malfunction or corrosion. Loss of bacteria is usually a minor problem as they regrow. A constant top layer of 20 – 60 cm of foam is usually ergarded as "stable" in large-scale systems and is acceptable or easy to manage. A thicker impermeable scum layer however may prevent gas release from the liquid and eventually also lead to failure.

- Inhibition:

When planning and operating a biogas plant, aspects which inhibit the anaerobic process need to be considered. Some compounds at high concentrations can be toxic to the anaerobic process. Generally speaking, inhibition depends on the concentration of the inhibitors, the composition of the substrate and the adaptation of the bacteria to the inhibitor. Some of the typical inhibitors that we could name are: Oxygen, hydrogen sulphide (H2S), organic acids, free ammonia, heavy metals, tannins/saponins/mimosine and others hazardous substances such as disinfectants (from hospitals or industry), herbicides, insecticides (from agriculture, market, gardens, households) and antibiotics. Ammonia nitrogen is often referred to as one of the common inhibiting substances of anaerobic digestion. Ammonia inhibition can take place at a broad range of concentrations. In anaerobic reactors the total inorganic nitrogen consists mainly of ammonia (NH3) and the protonised form of ammonium (NH4+). At normal pH ranges the biggest share of the total inorganic nitrogen is in the form of ammonium. With increasing pH value and temperature the share of ammonia increases. The undissociated ammonia form diffuses through the cell membranes and inhibits cell functioning by disrupting the proton and potassium balance inside the cell. This inhibition will cause an imbalance and accumulation of intermediate digestion products such as volatile fatty acids (VFA) which can result in acidification of the digester.

## I.10 Conclusion:

The anaerobic digestion is such a suitable way to treat wastewater biologically as it has more advantages compared to the aerobic one and that is mainly because there are no power requirements for air supply, production of sludge requiring treatment and disposal is much lower and the methane production can be used for the production of energy.

As we mentioned above, it is of great importance to take the anaerobic operational parameters into account as they directly influence the rate at which the microorganisms grow. These parameters are the temperature which should be ideally around 37C, pH level, carbon to nitrogen ratio, the inoculation and start up phase, the mixing process and lastly the inhibition phenomena.

In our next chapter, we will focus on presenting a mathematical model for the chemostat where we will study the model and calculate its equilibriums and their stability.

# *Chapter II The Mathematical Analysis of the AM2 Model*

## II.1Introduction :

Modeling can be understood as simply a representation of the selected aspects of a domain of interest. There are many ways to define a model, it can be defined as a physical, mathematical or a logical representation of a system.

In our context of control systems engineering, a model representing a system and its environment is of vital importance to the engineer who must specify, design, analyze nd verify the systems. Modeling is considered to be the first step to take to estimate, observe, control and diagnostic a process. It is important to note that based on the dynamic model that the conception, analysis and the implementation of surveillance and control methods. A variety of system models are used to represent different types of systems for different modeling purposes. In the bioprocesses case generally and in the anaerobic digestion specifically, it is important to use of mass balance law to derive the mathematical model describing the process dynamic.

In the context of an anaerobic digestion process, the most important obstacle that could be faced is the possible accumulation of the Volatile Fatty Acids produced during the acidogenesis phase in the bioreactor and therefore destabilize the process. For this particular reason, the modeling, control and supervision tools are necessary for the optimization of the anaerobic digester functioning.

The anaerobic digestion models could be classified into two categories:

1. Big dimensions models which were developed by practitioners to replicate the phenomenological behavior of the system.
2. Simplified models developed to control the system describing in a small number of steps and with a limited dimension the anaerobic digestion.

The Anaerobic Digestion Model nO1 (ADM1) model is considered to be the most completed phenomenological model of the anaerobic digestion containing more than thirty differential equations modeling the bioreactions and chemical exchanges between the multiple species residing inside the bioreactor.

However, in order to control the anaerobic digesters, a more simplified model called the AM2 model is used as it is seen to be more suitable. It describes anaerobic digestion by two-stage

(acidogenesis and methanogenesis) it has six state space variables where four of them are the main ones.

In this chapter, we introduce the AM2 model for anaerobic digestion and we calculate its equilibriums and their stability as well in order to extract vital information about the principal variables of the process, which are considered to be the substrates and the biomasses. We also perform numerical simulations in order to illustrate the dynamic behavior of the system.

## II.2 Biological reactions' modeling:

As mentioned in the first chapter, bioreactors generally and chemostats specifically, consist of an enclosed device in which the feedstock is provided and from which the biological reaction's occur. Let us assume that all necessary components for the growth of the microorganisms are present in our chemostat. Their ability to ingest the substrates and the velocity with which the chemostat's medium is renewed are the only deciding factors when it comes to the development of the microorganism's velocity.

At a specific time't', the growth's kinetics depends directly on its own density. In other words, its development is exponential until the feedstock or the space start decreasing which means when the concentration of the biomass is twice as high, then the velocity would be twice as important as well. During the transition phase, it is possible to observe that as either the space or the resource become scarce and limit the development or growth. These limiting resources can be the carbon, nitrogen, even the light, or the concentration of the oxygen.

Throughout this manuscript, it is essential to note that we keep referring to the substrate as 'S' and the biomass as 'X' as well as their concentrations ( mass per unit volume ).

## II.3 Biological processes and reaction scheme:

We refer to a reaction scheme when describing desired processes that need to be formalized during a specific biological reaction. The latter could be considered as the transformation of substances catalyzed by the presence of microorganisms.

The following formula called Reaction Scheme, schematizes the growth of a microorganism 'X' on a substrate 'S':

$$S \rightarrow X$$

No units are needed as 'X' and 'S' are used to describe a qualitative transfer of matter. In order to complete the information we would have to add other products, for example, the production of CO2. In this case, the reaction will be represented as follows:

$$S \rightarrow X + CO_2$$

We can get a bit more specific by adding reaction yields and kinetics. However, it is necessary to note that yields are not present to balance the reaction in the same way we use them in chemistry. In this kind of biological reaction, the yields are obtained through trials with regards to the growth of the biomass which means we would have established that such an amount of substrate is necessary to produce such an amount of biomass. Therefore, the following scheme:

$$k_1 S \xrightarrow{\rho(.)} X + k_2 CO_2$$

Which can be translated to " $k_1$ substrate units results in the growth of biomass accompanied by the production of $k_2$ units of *CO2* at rate $\rho(.)$".

It is important to note that the yields can be normalized by putting $k_1$ or $k_2$ in the unit so that only one yield parameter is to be considered. This parameter is expressed by

$$\frac{1}{Y} = \frac{K_1}{K_2}$$

In the form used previously, the reaction scheme can specify that only one biological process is involved (in this case the microorganism's growth). However, once we consider the formalization, it is possible to represent various processes such as the biomass' mortality.

In this case, we can complete the previous scheme with a second equation:

$$k_d X \xrightarrow{X} X_d$$

Which explains the fact that the active biomass compartment feeds a dead biomass compartment "$X_d$" with a rate $k_d$.

Mortality is not the only biological process of interest. Down below, we give few examples of some other processes considered in the microbiological modeling:

- Maintenance is expressed as the use of a section of the resources to convert it into energy to be used by the biomass. It is often modeled with a negative term which describes a disappearance of substrate without microbial growth.
- Endogenous respiration represents a situation where the biomass itself becomes its own substrate. To put it differently, the dead biomass would be recycled and used. This

would be modeled by adding a negative mortality term and a positive term in the dynamics of the substrate. Since the substrate that appears is less than the biomass that disappears, this term is usually neglected due to the fact that mortality and maintenance are modeled by the same modifications to the equations.

- Flocculation is the arrangement of biomass into groups. It is known that microorganisms tend to naturally agglomerate in flocs and biofilms.

With all the key points mentioned above, let us move on to a modeling of a simple biological reaction.

## II.4 The equations of a chemostat:

Before we establish the chemostat's equations, it is important to specify a couple of conventions for the notations that will be used throughout our thesis. They were based on a common notion of automatic control (system input). We consider the chemostat to be an enclosed system with two supply and withdrawal devices, including pumps that enable us to set inflow and outflow rates and consequently it becomes possible to identify the system's variables. These variables are the two feed and effluent flow rates and the concentration of feed. The volume of the reactor and the concentrations of both the substrate and the biomass are represented by non-independent equations where changes in the input variables will lead to changes in the system state variables.

To establish the equations of the chemostat, we apply the mass balance law for modeling '*S*' and '*X*'. We consider the chemostat's volume to be '*v*' equipped with an inlet to supply it with feedstock and an outlet to withdraw the reaction mixture. To assure that all conditions are respected, we assume that the mixture is homogeneous and the environmental conditions (temperature and pH) are constant.

$S_{in}$ will denote the concentration of '*S*' in the feedstock, $Q_{in}$ and $Q_{out}$ the inflow and outflow rates respectively ( volume per unit of time ) and *Y(.)* the yield of the conversion of substrate into biomass ( mass of substrate consumed per mass of biomass produced ). In order to avoid using terms in $\frac{1}{Y}$, we will use the coefficients $k_i$ coefficients in the reaction schemes.

For a period of time 'dt', a mass balance can be achieved according to which the variation in the mass of an element (S and *X*) is the result between the mass of that element that has been brought into the system added to the produced mass of this element minus the consumed quantity minus the extracted quantity.

## Variation in the mass = mass brought into the system - extracted quantity + produced mass - consumed quantity

Variation in the mass = $r_i$ - $r_o$ + $r_p$ - $r_c$

$$Y = \frac{amount\ of\ cells\ produced}{amount\ of\ substrate\ consumed}$$

$r_c = \frac{rp}{Y}$ with $r_p$ : rate of the amount of cells produced = $\rho(.).v$

With the previous principle applied we can obtain the following equations:

$$\begin{cases} \dfrac{dv}{dt} = Q_{in} - Q_{out} \\ \dfrac{d(sv)}{dt} = r_i - r_o + r_g - r_c \\ \dfrac{d(sv)}{dt} = Q_{in}S_{in} - Q_{out}S - \dfrac{\rho(.)}{Y(.)}v \\ \dfrac{d(xv)}{dt} = r_i - r_o + r_g - r_c \\ \dfrac{d(xv)}{dt} = \rho(.)v - Q_{out}X \end{cases}$$

It is crucial to note that $\rho(.) = \mu(.)x$ where $\mu(.)$ is called "specific growth velocity" or "kinetics". We consider $Q_{in}$ and $Q_{out}$, in the continuous mode, to be equal ($Q_{in}$=$Q_{out}$). Therefore the output rate is different from zero and the chemostat's volume remains constant ($v(0) = v(t) = V$). By denoting $D = Q_{in} / v$ ($t^{-1}$), which is called the dilution rate, it yields that:

$$\begin{cases} \dfrac{dv}{dt} = Q_{in} - Q_{out} \\ \dfrac{ds}{dt} = D(s_{in} - S) - \mu(.)x \\ \dfrac{dx}{dt} = (\mu(.) - D)x \end{cases}$$

This model is what we call the simple chemostat model with one substrate and one biomass.

## II.5 Anaerobic digestion model AM2:

### II.5.1 Introduction to the AM2 model:

Anaerobic digestion can be operated with various feedstocks in a flexible manner in order to better integrate such systems in dynamic networks, like electricity grids and local carbon cycles, which are oriented to the seasonal availability of substrate.[12]

Temporary process instabilities occur from alternating process conditions, however, a poor process performance can typically be solved by adjusting the feedstock load and composition,[13] if the problem is diagnosed correctly and promptly. In order to describe the complex digestion to produce biogas, various suitable models were suggested. The description of the biological stages with changes in the monod-type kinetic equations for the consideration of the inhibition of volatile fatty acids (VFA) on methanogenesis were the basis for various models.[14] Approaches, which considered two bacterial groups, namely acid and methane producing microorganisms[15], were applied. Also, those that considered four populations were applied as well and they managed to influence and inspire further developments predicting the change of VFA, pH-value, and biogas production.

According to the objectives for which the anaerobic digestion models were developed, they can be divided into two categories:

- Large dimension models developed by practitioners to reproduce the phenomenological behavior.
- Simplified models developed for the control, describing macroscopically the anaerobic digestion in a small number of steps and with a limited dimension.

The anaerobic digestion model No 1 or ADM1 is the most completed and used model of the anaerobic digestion. It was used for several applications, such as studies of biodegradability of wastes or substrates like olive mill wastewater[16], municipal solid with activated sludge wastes, agro-wastes as apple, pear, orange, rape, sunflower, pig manure, and glycerol wastes[17], and others like maize silage, grass, and cattle manure, which show reliable results. The ADM1 was applied for state prediction from online measurements with pattern recognition.[18] The modeled biogas process was predicted with an accuracy of 90 %. [19]

The ADM1 is a complex model with 32 differential equations representing the reactions and exchanges between the different species in the medium. Unfortunately, due to its large dimension, its use to estimate, control and supervise the anaerobic digesters is not appropriate. In order to control the anaerobic digesters, a more suitable model called the AM2 is introduced and used. In this model, only two bacterial populations are considered, namely the acidogenic and methanogenic microorganisms and therefore it would use six differential equations.

## II.5.2 **Description of the AM2 model:**

The AM2 model is a simple model able to reproduce the dynamic's performance and take into account the destabilization phenomena of the anaerobic digesters caused by the build-up of VFA. It is considered to be one of the most suitable models for the control of these systems.
Developing the AM2 model is based on the hypothesis that bacterial populations involved in anaerobic digestion can be divided into two main groups of homogeneous characteristics and that anaerobic digestion can be described in a two-stage process.

In the first stage called acidogenesis, the consortium of acidogenic bacteria "$X_1$" converts the organic matter "$S_1$" into VFA "$S_2$" and carbon dioxide "$CO_2$". In the second step called methanogenesis, the methanogenic populations ``$X_2$" transform "$S_2$ " into methane "$CH_4$ " and carbon dioxide "$CO_2$".
The biological reactions are represented through the following reaction schemes:

- Acidogenesis with reaction speed $r_1 = \mu_1(S_1)X_1$ ( $\mu_1(S_1)$ is the growth rate of "$X_1$" on "$S_1$"):

$$k_1 S_1 \xrightarrow{r_1} X_1 + k_2 S_2 + k_4 CO_2 \qquad \text{II-1}$$

- Methanogenesis with a reaction speed $r_2 = \mu_2(S_2)X_2$ ($\mu_2(S_2)X_2$ is the growth rate of "$X_2$" on "$S_2$"):

$$k_3 S_2 \xrightarrow{r_2} X_2 + k_5 CO_2 + k_6 CH_4 \qquad \text{II-2}$$

The total chemical oxygen demand (COD) is the sum of $S_1$ and $S_2$. As mentioned above, the most important issue surrounding anaerobic digestion is the eventual build-up of VFA "$S_2$" in

the bioreactor during the methanogenesis which has the potential of destabilizing the process by making the bioreactor's medium acid. In order to represent the inhibition phenomena, we will use the law of Haldane to describe the growth rate of the methanogenic populations $\mu_2(S_2)$:

$$\mu_2(S_2) = m_2 \frac{S_2}{\frac{s_2^2}{k_i} + S_2 + K_2} \qquad \textit{II-3}$$

Where:

$m_2$: Maximum growth rate of $X_2$ on $S_2$.

$K_2$: Semi-saturation constant in the absence of inhibition.

$K_i$: Inhibition constant.

On the other hand, the growth rate of the acidogenic populations $\mu_1(S_1)$ is expressed using Monod's law:

$$\mu_1(s_1) = m_1 \frac{s_1}{s_1 + K_1} \qquad \textit{II-4}$$

Where:

$m_1$: Maximum growth rate of $X_1$ on $S_1$.

$K_1$: Semi-saturation constant associated with $S_1$.

## II.5.3 **Mathematical equations of the model:**

The general AM2 model contains four main state variables :

- $S_1$: The concentration of the organic matter to be degraded.
- $X_1$: The concentration of the acidogenic biomass population.
- $S_2$: The concentration of the volatile fatty acids (VFA).
- $X_2$: The concentration of the methanogenic biomass population.

Applying the same principle of mass balance we used to establish the chemostat's general equations:

$$\begin{cases} \dot{S}_1 = \frac{Q_{in}}{V} S_{1in} - \frac{Q_{out}}{V} S_1 - X_1 \, \mu_1(S_1) \\ \dot{X}_1 = \mu_1(S_1) X_1 - \frac{Q_r}{V} X_1 = (\mu_1(S_1) - \frac{Q_r}{V}) X_1 \\ \dot{S}_2 = \frac{Q_{in}}{V} S_{1in} - \frac{Q_{out}}{V} S_1 + X_1 \, \mu_1(S_1) - \mu_2(S_2) X_2 \\ \dot{X}_2 = \mu_2(S_2) X_2 - \frac{Q_r}{V} X_2 = (\mu_2(S_2) - \frac{Q_r}{V}) X_2 \end{cases} \qquad \textit{II-5}$$

As we are interested in the continuous bioreactors only then we note:

$Q_{in} = Q_{out} = Q_r = Q$

And we consider: $\frac{Q}{V} = D$ ( the dilution rate)

Initially, the AM2 model was developed for fixed-bed reactor, i.e only a part of biomasses αX can leave the bioreactor. Our equations become:

$\dot{S}_1 = D(S_{1in} - S_1) - k_1 \mu_1(S_1) X_1$ *II-6*

$\dot{X_1} = (\mu_1(S_1) - \alpha D) X_1$ *II-7*

$\dot{S}_2 = D(S_{2in} - S_2) + k_2 \, \mu_1(S_1) X_1 - k_3 \mu_2(S_2) X_2$ *II-8*

$\dot{X}_2 = (\mu_2(S_2) - \alpha D) X_2$ *II-9*

Where:

D: The Dilution rate ([$j^{-1}$]).

α ∈ [0,1] : The parameter that represents the fraction of the biomass that has not been retained in the bioreactor.

$S_{1in}$: The concentration of $S_1$ in the feedstock ([g/l]).

$S_{2in}$: The concentration of $S_2$ in the feedstock ([mmol/l]).

$K_1$: The yield of the consumption of $S_1$ by $X_1$ ([g/g]).

$K_2$: The yield of $S_2$ production by $X_1$ from $S_1$ ([mmol/g]).

$K_3$: The yield of S2 consumption by $X_2$ ([mmol/g]).

The two kinetics $\mu_1(.)$ and $\mu_2(.)$ will be taken into consideration for the mathematical analysis of the model. Therefore, it is important to note the following:

$\mu_1$ is a function of $S_1$:

- $\mu_1(0) = 0$.
- $\acute{\mu}_1(S_1) > 0$ for $S_1 \geq 0$.
- $\mu_1(\infty) = m_1$.

$\mu_2$ is a function of $S_2$:

- $\mu_2(0) = 0$ and $\mu_2(\infty) = 0$.
- $\mu_2(S_2)$ reaches a maximum $\mu_2^M > 0$ for $S_2 = S_2^M$.
- $\acute{\mu}_2(S_2) > 0$ if $0 \leq S_2 < S_2^M$.
- $\acute{\mu}_2(S_2) < 0$ if $S_2 > S_2^M$.

## II.5.4 **Equilibriums calculations:**

The different equilibrium are calculated by putting the derivatives (II-7) and II-9) to be null. We obtain the following equations:

$$(\text{II-7}) \rightarrow X_1 = 0 \text{ or } \mu_1(S_1) = \alpha D$$
$$(\text{II-9}) \rightarrow X_2 = 0 \text{ or } \mu_2(S_2) = \alpha D$$

- Case 1: $X_1 = 0$, $X_2 = 0$.

The case where $X_1 = 0$ and $X_2 = 0$ at the same moment is always possible. That is what we call the total "washout" of the bioreactor and it is due to the system not being adequately controlled, insufficient substrate or organic overload.

- Case 2: $\mu_1(S_1) = \alpha D$, $\mu_2(S_2) = \alpha D$

We considered various semi-cases for this:

- If $\alpha D < \mu_{1max}(S_1)$ : $\mu_1(S_1) = \alpha D$ got one solution $\lambda_1(D)$.
- If $\alpha D \geq \mu_{1max}(S_1)$ : $\mu_1(S_1) = \alpha D$ has no solution (and we consider $\lambda_1(D) = +\infty$).

- If $\alpha D = \mu_{2max}(S_2) : \mu_2(S_2) = \alpha D$ got two solutions $\lambda_2^1(D)$ and $\lambda_2^2(D)$ with ($\lambda_2^1(D) < \lambda_2^2(D)$).
- If $\alpha D > \mu_{2max}(S_2) : \mu_2(S_2) = \alpha D$ got no solution (and we consider $\lambda_2^1(D) = +\infty$ if $\lambda_2^2(D) < S_{1in}$. We consider:

$$S^*_{2in}(D) = S_{2in} + \frac{K_2}{K_1}(S_{1in} - \lambda_1(D)). \qquad II\text{-}10$$

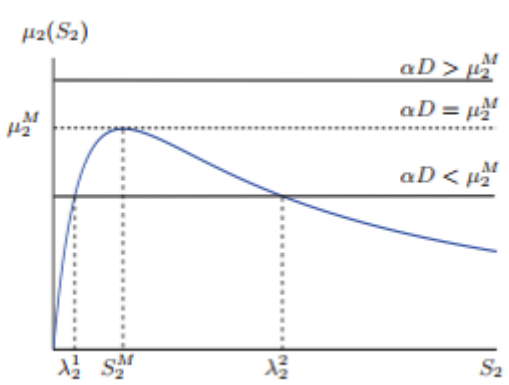



***Figure II-1 : Possible solution of $\mu_1(S_1) = \alpha D$***

This is the total concentration of the VFA available for the methanogenic reaction. It is equal to the sum of the $S_{2in}$ in the input of the bioreactor and the $\frac{K_2}{K_1}(S_{in} - \lambda_1(D))$ concentration produced by the acidogenic reaction in the steady state.

The cases mentioned above are represented in the following figures:

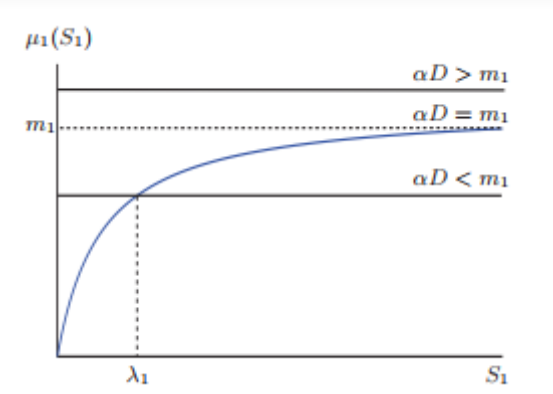



***Figure II-2 : Possible solution of $\mu_2(S_2) = \alpha D$***

The solutions mentioned above result in the obtaining of the following equilibriums that depend on D except in the washout case.

- $E_0 = (S_{1in}, 0, S_{2in}, 0)$, the washout which always exists and does not depend on D.

- $E_1(D) = (S_{1in}, 0, \lambda_2^1, X_2^1(D))$ where $X_2^1(D) = \frac{1}{\alpha K_3}(S_{2in} - \lambda_2^1(D))$.
- $E_2(D) = (S_{1in}, 0, \lambda_2^2, X_2^2(D))$ where $X_2^2(D) = \frac{1}{\alpha K_3}(S_{2in} - \lambda_2^2(D))$.
- $E_3(D) = (\lambda_1(D), X^*_1, S^*_{2in}, 0)$ where $X^*_1(D) = \frac{1}{\alpha K_1}(S_{1in} - \lambda_1(D))$.
- $E_4(D) = (\lambda_1(D), X^*_1, \lambda_2^1(D), X_2^{1*}(D))$ where $X_2^{1*}(D) = \frac{1}{\alpha K_3}(S*_{2in} - \lambda_2^1(D))$.
- $E_5(D) = (\lambda_1(D), X^*_1, \lambda_2^2(D), X_2^{2*}(D))$ where $X_2^*(D) = \frac{1}{\alpha K_3}(S*_{2in} - \lambda_2^2(D))$.

Proof of calculations. Let's take equations ( II-7) and (II-9), we calculate the equilibriums as follows:

1. When $X_1 = 0$ and $X_2 = 0$ and let's replace them in the equations (II-6 ) and ( II-9) and we get $S_1 = S_{2in}$. From this we get the equilibrium $E_0$.
2. When $X_1 = 0$ and $X_2 \neq 0$, we obtain $S_1 = S_{1in}$ from the equation ( II-6 )and from (II-9 ) we get $X_2^i(D) = \frac{1}{\alpha K_3}(S_{2in} - \lambda_2^i(D))$ after calculating the two solutions $\lambda_2^1$ and $\lambda_2^2$ of $\mu_2(S_2) = \alpha D$ with i=1,2. The equilibriums from these calculations are $E_1(D)$ and $E_2(D)$.
3. When $X_1 \neq 0$ and $X_2 = 0$, we use the solution $\lambda_1(D)$ of the equation $\mu_1(S_1) = \alpha D$ obtained from II-7 and we calculate $X_1^*(D)$ and from II-8 we obtain $S_2^*(D) = S_{2in} + \frac{K_2}{K_1}(S_{1in} - \lambda_1(D))$. The equilibrium for this case is $E_3$.
4. When $X_1 \neq 0$ and $X_2 \neq 0$, we have $\lambda_1(D)$ from II-7 and from (II-9) we have $\lambda_1^i(D)$ with i = 1, 2. From II-6 and II-9 we got $X_1^*(D)$ and $X_2^{i*}(D)$. In this case, the equilibriums are $E_4$ and $E_5$.

The equilibrium $E_0$ is the one representing the washout of $X_1$ and $X_2$ of the bioreactor. $E_1^i(D)$ with i = 1,2 is the equilibrium that describes the washout of the acidogenic biomass $X_1$. The equilibrium $E_4(D)$ is the one that fits the washout of the $X_2$ biomass. $E_5(D)$ and $E_6(D)$ are the inner equilibriums where $E_5(D)$ is considered to be the operational function point of the bioreactor.

## II.5.5 **The system's stability study**

In order to study the stability of the equilibriums, we have simply to study the eigenvalues of the jacobian matrix of the system ( II-6) – ( II-9) :

$$J = \left[\begin{array}{cc|cc} -D - k_1\acute{\mu}_1(S_1)X_1 & -k_1\mu_1(S_1) & 0 & 0 \\ \acute{\mu}_1(S_1)X_1 & \mu_1(S_1) - \alpha D & 0 & 0 \\ \hline k_2\acute{\mu}_1(S_1)X_1 & k_2\mu_1(S_1) & -D - k_3\acute{\mu}_2(S_2)X_2 & -k_3\mu_2(S_2) \\ 0 & 0 & \acute{\mu}_2(S_2)X_2 & \mu_2(S_2) - \alpha D \end{array}\right]$$

$$= \left[\begin{array}{c|c} J_{11} & 0 \\ \hline J_{21} & J_{22} \end{array}\right]$$

Where we consider :

$$J_{11} = \begin{bmatrix} -D - k_1\acute{\mu}_1(S_1)X_1 & -k_1\mu_1(S_1) \\ \acute{\mu}_1(S_1)X_1 & \mu_1(S_1) - \alpha D \end{bmatrix} \qquad \textit{II-11}$$

$$J_{22} = \begin{bmatrix} -D - k_3\acute{\mu}_2(S_2)X_2 & -k_3\mu_2(S_2) \\ \acute{\mu}_2(S_2)X_2 & \mu_2(S_2) - \alpha D \end{bmatrix} \qquad \textit{II-12}$$

The eigenvalues of the matrix J are the same eigenvalues of blocks $J_{11}$ and $J_{12}$.

- For the equilibrium $E_0$:

$$J_{11} = \begin{bmatrix} -D & -k_1\mu_1(S_1) \\ 0 & \mu_1(S_1) - \alpha D \end{bmatrix} \qquad \textit{II-13}$$

$$\textit{And} \quad J_{22} = \begin{bmatrix} -D & -k_3\mu_2(S_2) \\ 0 & \mu_2(S_2) - \alpha D \end{bmatrix} \qquad \textit{II-14}$$

The equilibrium $E_0$ is stable only if the eigenvalues of $J_{11}$ and $J_{22}$ are of negative real parts and for that to be realized the following conditions must be respected: $\mu_1(S_1) < \alpha D$ and $\mu_2(S_2) < \alpha D$ respectively.

- For the equilibriums $E_1$ and $E_2$:

$$J_{11} = \begin{bmatrix} -D & -k_1\mu_1(S_1) \\ 0 & \mu_1(S_1) - \alpha D \end{bmatrix} \qquad \textit{II-15}$$

$$J_{22} = \begin{bmatrix} -D - k\acute{\mu}_2(\lambda\,{}^{i}_{2})X_2^i & -k_3\alpha D \\ \acute{\mu}_2(\lambda\,{}^{i}_{2})X_2^i & 0 \end{bmatrix} \qquad \text{II-16}$$

For the matrix $J_{11}$, it is clear that in order for the matrix to have eigenvalues of negative real parts the only condition to be taken into consideration is that $\mu_1(S_1) < \alpha D$.

However for the matrix $J_{22}$ we consider the calculation of both its determinant and trace as follows:

$$det(J_{22}) = \alpha D k_3 \acute{\mu}_2(\lambda\,{}^{i}_{2}) X_2^i$$

$$tr(J_{22}) = -D - k_3 \acute{\mu}_2(\lambda\,{}^{i}_{2}) X_2^i$$

So for the equilibrium $E_1$, the matrix $J_{22}$ has eigenvalues of negative real parts only if $S_{1in} < \lambda_1$. Therefore, $E_1$ is locally asymptotic stable. However, for $E_2$, the eigenvalues are of opposite signs which means that $E_2$ is considered to be unstable.

- For the equilibrium $E_3$:

$$J_{11} = \begin{bmatrix} -D - k_1 \acute{\mu}_1(\lambda_1) X_1^* & -k_1 \alpha D \\ \acute{\mu}_1(\lambda_1) X_1^* & 0 \end{bmatrix}$$

$$J_{22} = \begin{bmatrix} -D & -k_3 \mu_2(S_{2in}^*) \\ 0 & \mu_2(S_{2in}^*) - \alpha D \end{bmatrix}$$

For the matrix $J_{22}$, the eigenvalues are of negative real parts only if $\mu_2(S_{2in}^*) < \alpha D$. However for $J_{11}$, we have to consider its determinant and trace.

$$det(J_{11}) = \alpha D k_1 \acute{\mu}_1(\lambda_1) X_1^* > 0$$

$$tr(J_{11}) = -D - k_1 \acute{\mu}_1(\lambda_1) X_1^* < 0$$

$E_3$ is considered to be locally asymptotic stable only if $S_{1in} > \lambda_1$ and $\lambda_2{}^1 > S^*{}_{2in} > \lambda_2$.

- For $E_4$ and $E_5$:

$$J_{11} = \begin{bmatrix} -D - k_1 \acute{\mu}_1(\lambda_1) X_1^* & -k_1 \alpha D \\ \acute{\mu}_1(\lambda_1) X_1^* & 0 \end{bmatrix}$$

$$J_{22} = \begin{bmatrix} -D - k_3 \acute{\mu}_2(\lambda\,{}^{i}_{2}) X_2^i & -k_3 \alpha D \\ \acute{\mu}_2(\lambda\,{}^{i}_{2}) X_2^i & 0 \end{bmatrix}$$

For the matrix $J_{11}$, the eigenvalues are of negative real parts only if:

$$det(J_{11}) = \alpha D k_1 \acute{\mu}_1(\lambda_1) X_1^* > 0$$

$$tr(J_{11}) = -D - k_1 \acute{\mu}_1(\lambda_1) X_1^* < 0$$

And for matrix $J_{22}$, we calculate the determinant and the trace as well:

$$det(J_{22}) = \alpha D k_3 \acute{\mu}_2(\lambda_2^i) X_2^{i*}$$

$$tr(J_{22}) = -D - k_3 \acute{\mu}_2(\lambda_2^i) X_2^{i*}$$

For the equilibrium $E_4$, the eigenvalues of the matrix $J_{22}$ are of negative real parts if $S_{1in} > \lambda_1$. Therefore $E_4$ is considered to be locally asymptotic stable in this case. However for $E_5$, the eigenvalues are of opposite signs and therefore the equilibrium is unstable.

## II.5.6 **Numerical Simulation of different equilibrium:**

In this section, we perform numerical simulations of system equilibria, by using for each case a set of parameters values such that the system converges toward the desired equilibrium.

- **Stability around of the equilibrium $E_0$:**

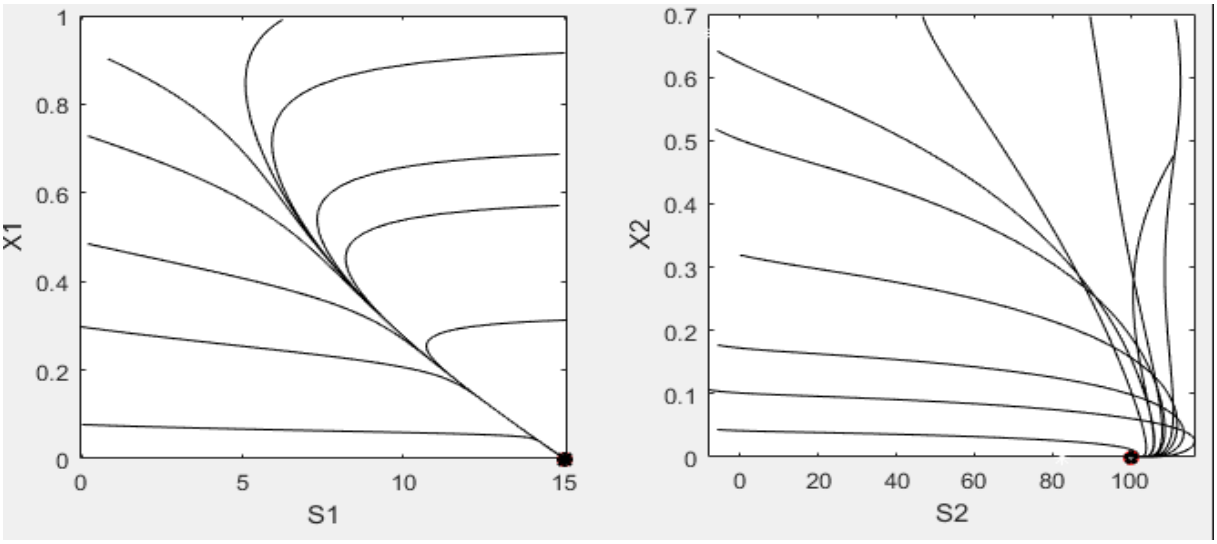



***Figure II-3 : Stability around of the equilibrium E0:***

In the first figure, we can visualize the stability of the Equilibrium E0. , where the system converges towards the washout whatever the initial conditions. For practionner, this equilibrium is not desired and should be avoided by using control. In this case, all bacteria are washed out, no degradation of substrate and we have a dead bioreactor.

## ➢ Stability around of the equilibrium E1 or E2:

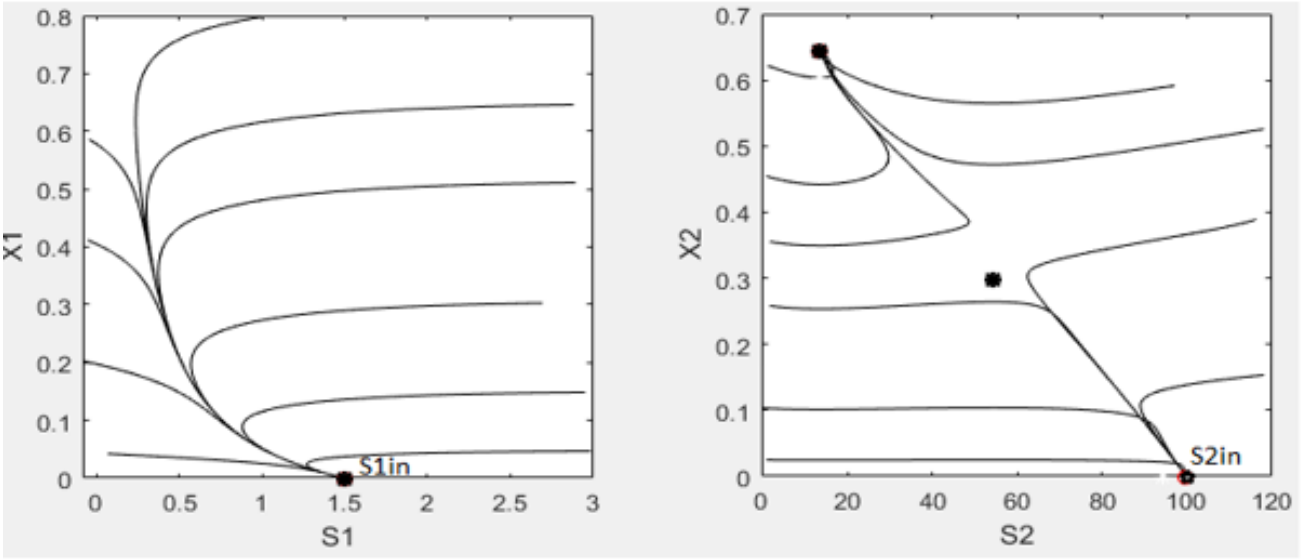



***Figure II-4 : Stability around of the equilibrium E1 or E2:***

In this case, we have no $X_1$ inside the bioreactor and S1 in not degraded in the first reaction. For the second reaction, which has only $S_{2in}$ as an input feedstock, according the initial condition, the system can converge toward:

- The washout equilibrium E2, where we have no X2 and S2 is not converted or,
- The interior equilibrium E2, where we have a consortium of X2 and S2 is converted into biogas.

From practical point of view, this case is not interesting because bacteria X1 in not active and hence there is no S2 production for the second reaction. It is difficult to ensure always an input S2in for the second reaction and hence, the second reaction will be stopped.

.

## ➢ Stability around of the equilibrium E3:

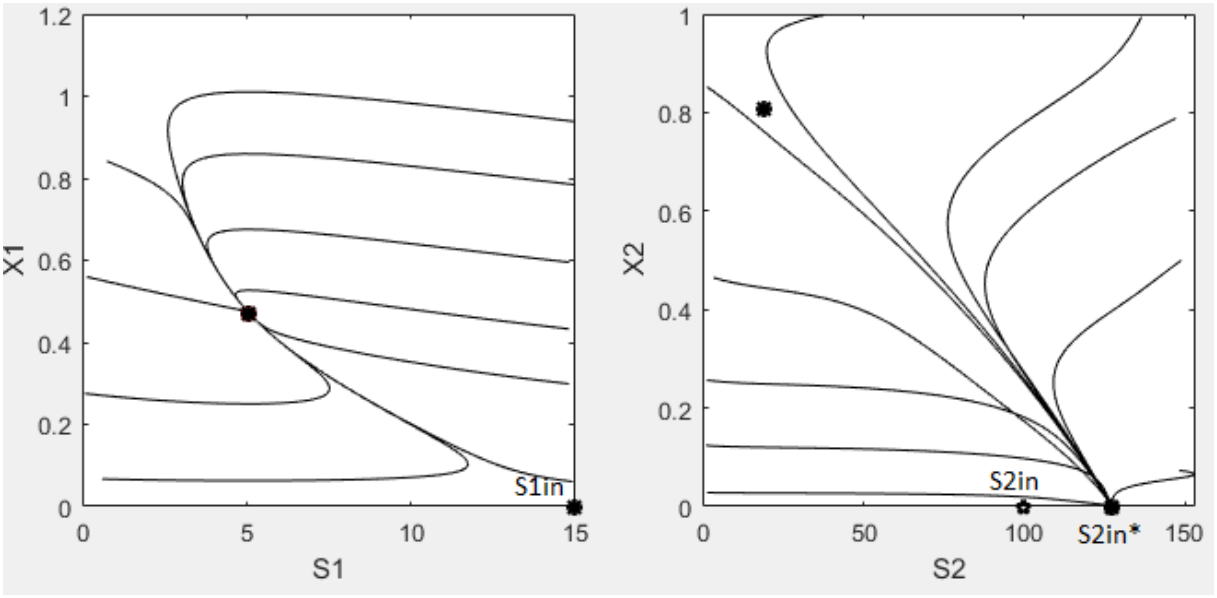



***Figure II-5 : Stability around of the equilibrium E3:***

In this case, only the biomass X1 can exist inside the bioreactor, i.e only the first reaction can be occurred and hence more S2 will be produced and cumulated. The biomass X2 is washed out and S2 is not converted, hence the reactional medium will be acid and the bioreactor becomes unstable.

## ➢ Stability around of the equilibrium E4 or E5:

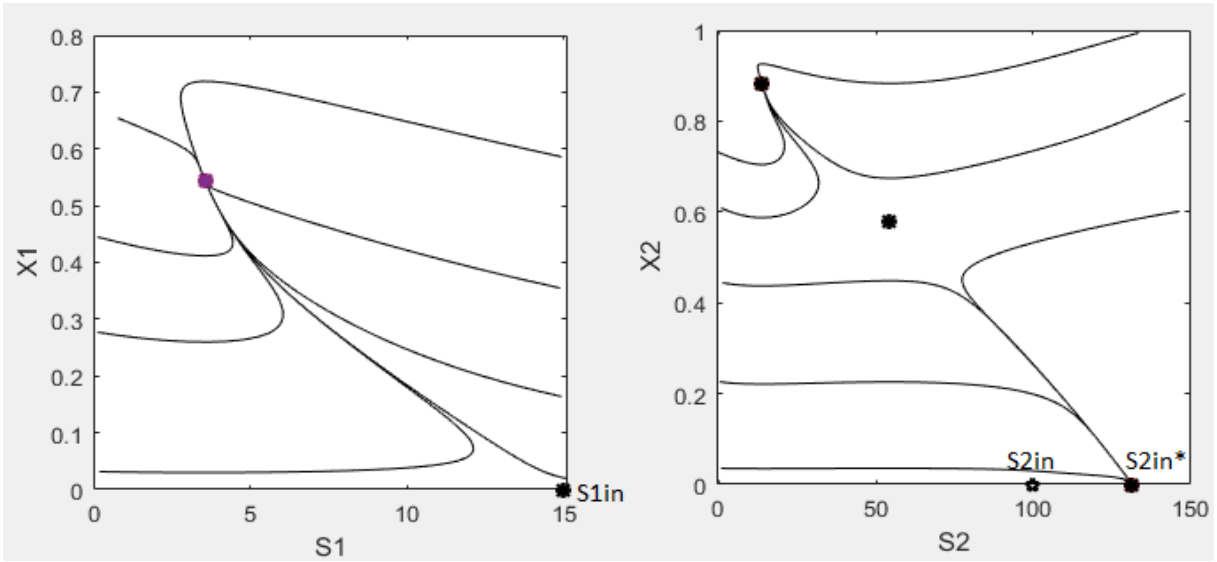



***Figure II-6 : Stability around of the equilibrium E4 or E5:***

This case is the most interesting in practice, because both bacteria X1 and X2 can co-exist inside the bioreactor arroud the equilibrium E4 and, the two reactions occur, giving a

degradation of S1, a conversion of S2 and a biogas production. The only task of practionner is to use a control such that the system converges toward the interior equilibrium E4.

## II.6 Conclusion :

The AM2 model is a four-dimension describing the anaerobic digestion by two stages, the acidogenesis and methanogenesis . It is considered to be the most suitable model to use in order to supervise and control the anaerobic system which have the tendency to be easily destabilized due to the accumulation of the Volatile Fatty Acids (VDA) inside the bioreactor. It is, therefore, of vital importance to analyze and study the equilibria of the system and to understand its dynamic behavior. The AM2 system can have six equilibria at most and, it can have a bistability behavior, where the interior equilibrium E4 assuring co-existence of X1 and X2 is the most important from practical point of view.

In the following chapter, we will discuss the realization and conception of an anaerobic chemostat ( small bioreactor).. We will also present the multiple steps and tools we used while building our system. In addition to the obstacles we faced in the physical world compared to simulation.

# *Chapter III Conception And realization of Chemostat*

## III.1 Introduction :

Theoretical research aids greatly in project realization, it allows us to do tests to determine what works and what does not work without actually realizing them, and it also aids in the detection of certain errors during the design phase.

For an easy manipulation of various electronic components, Arduino was the evident choice, not only for us but also for thousands of projects. Thus, for the editing of the electrical schematics we chose Proteus Professional software. Finally, our project was designed and programmed after conducting a general study on it.

This chapter will focus on the one hand on the simulation and on the other hand on the realization of the chemostat.

## III.2 Peristaltic Pumps :

A peristaltic pump is a positive displacement pump that transfers a wide variety of fluids using the principle of peristalsis, which is, in biology, a series of muscle contractions that transport food to various parts of the digestive system.

This pump has no valve and is inexpensive to maintain, equipped with a rollers or shoes that compress the tube or hose as they rotate, creating a vacuum that draws fluid through the tube. Providing an easy flow of particles and viscous fluids and eliminating the risk of the pump contaminating the fluid, or the fluid contaminating the pump.

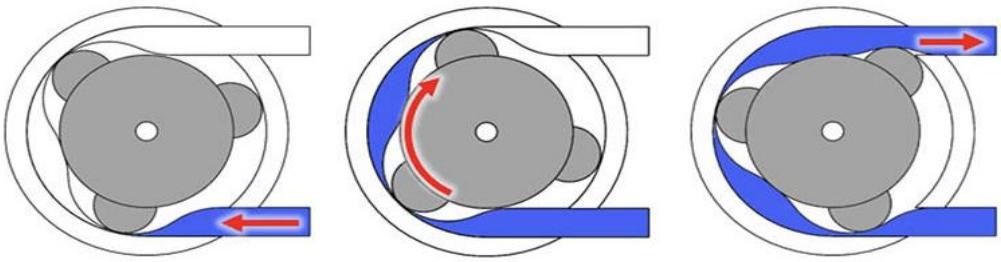


***Figure III-1*** : **Peristaltic Pumps** *[20]*

## III.3 Realization

In this project, we have built ourselves a peristaltic. Our task was to accomplish the following:

- The realization of a stator serving as a general frame, for this we used a PVC circle with a diameter of 8 cm. To ensure that the tube stays still in the frame, we have added the inner side of the PVC, a support, which is, also a circle made of PVC with a smaller diameter (6cm).

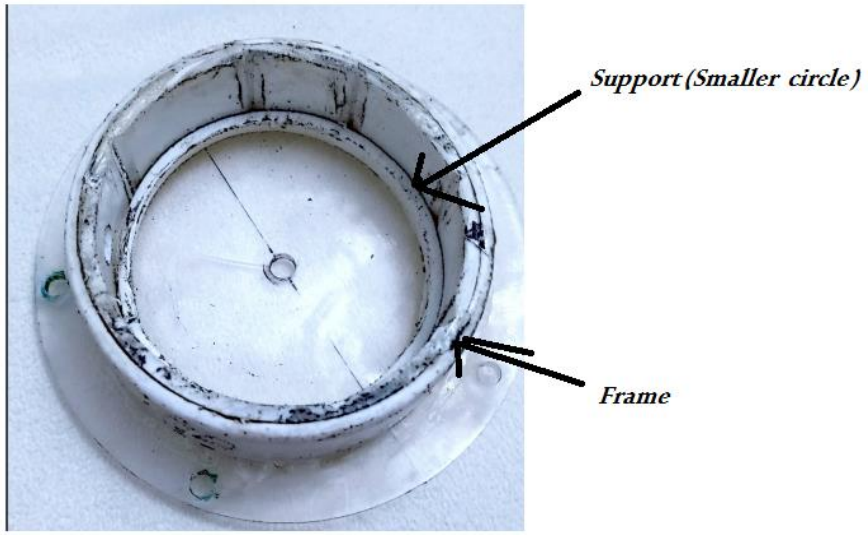


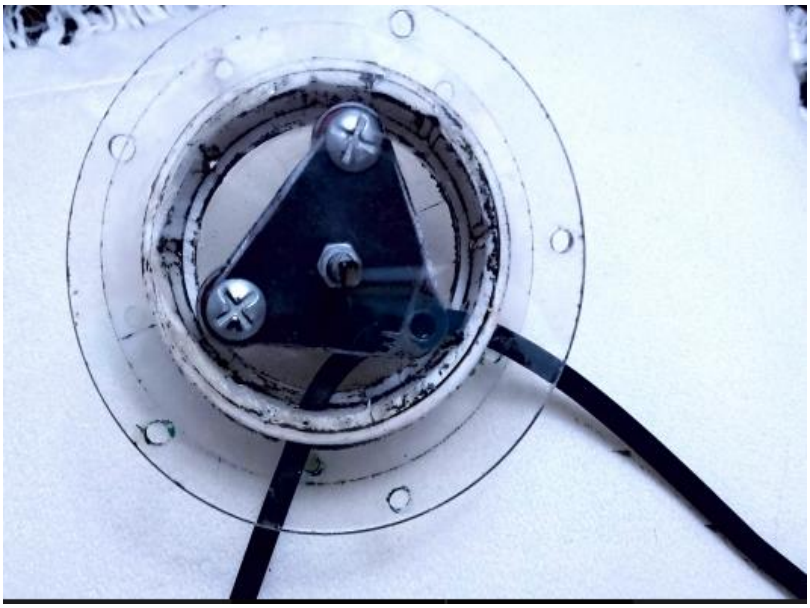

***Figure III-2 : General Frame***

The realization of a rotor using iron. This rotor shaft is attached to the motor, and is going to hold three bearings that will ensure the compression of the tube as they rotate.

***Figure III-3 : The Rotor***

We have also used a direct current motor ( DC motor ) that it is main job is to convert electrical energy into mechanical energy.

But unfortunately we couldn't use our pump because the power of the motor was much lower that the power needed for our pump to rotate.



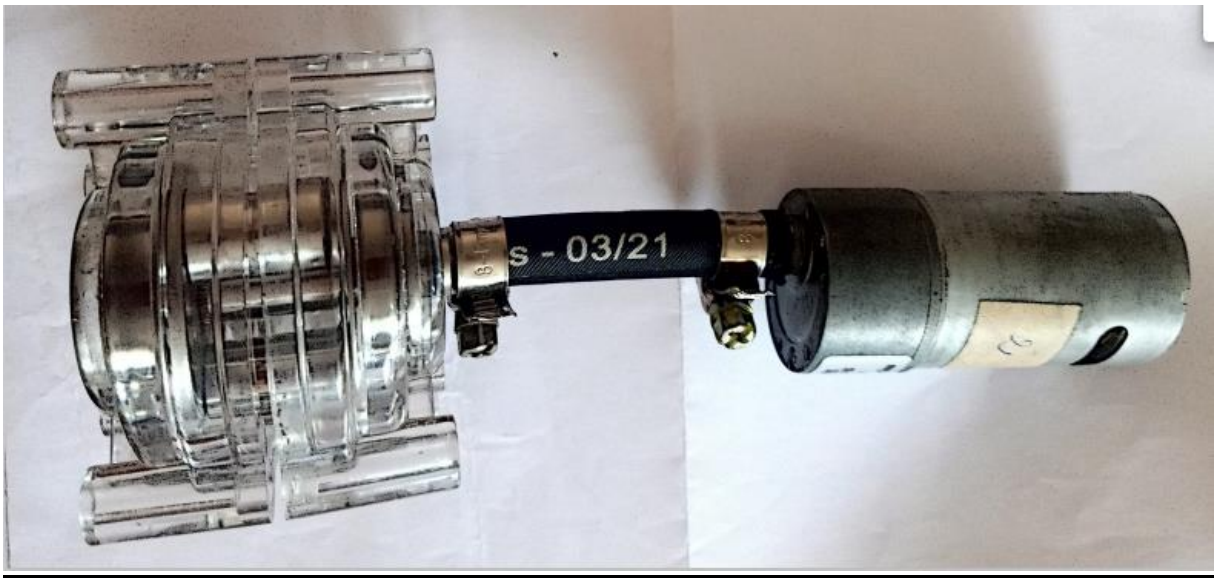



***Figure III-4 : Peristaltic Pumps***

## III.4 The Agitator:

Water treatment is one of the industries that needs to mix raw materials to have the production wanted. For our case, we have used a mixer composed of: an iron stick connected to a propeller. This combination will allow us to work and knead a large capacity of raw materials.

While the realization of the agitator we have faced a couple of issues: the stick was either very heavy or light that causes the instability of the whole mechanism. In addition to the fact that the stick was so long and the motor shaft was so short making the coupling very hard.

Due to this, we had to add another shorter stick that helps in the maintenance of the motor shaft and the stick as well.

***Figure III-5 : The Agitator***

## III.5 Biogas measurement:

As we have already mentioned, the digestion of the organic matter anaerobically provides many benefits such as generating renewable energy, the biogas.

Therefore, we have chosen the “water bottle” method to measure the gas production.

This method is to conduct the produced gas through a tube to a bottle filled with water that has an evacuation from where the water will be forced out every time the gas goes in.

***Figure III-6 : water bottle method for the Biogas measurement***

The biogas measurements of our project are shown in the following figures.

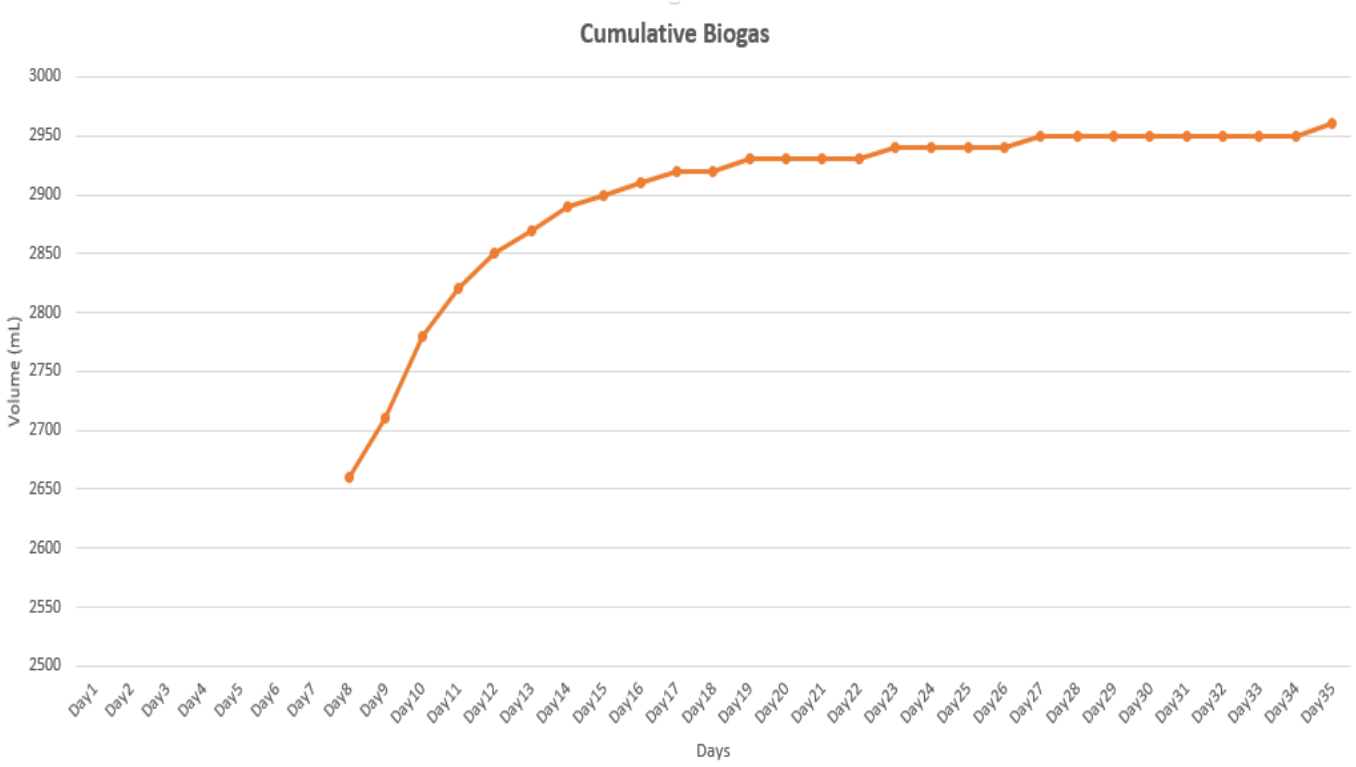



**Figure III-7 : Cumulative Biogas**

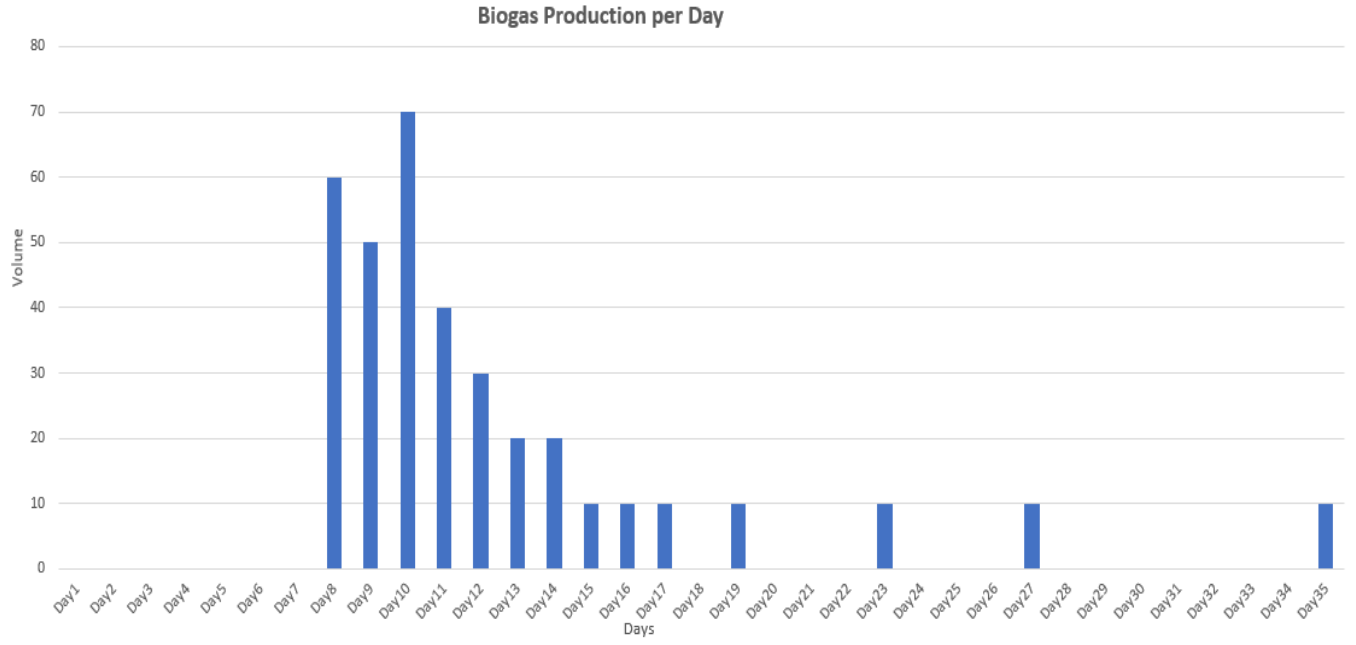



***Figure III-8 :*** **Biogas production per Day**

*Figure III-9 : The realized anaerobic chemostat*

## III.6 Theoretical study of the electronic circuit

### III.6.1 The Arduino Project History:

The Arduino project comes from a team of teachers and students from the Ivrea 1 School of Interaction Design (Italy). They encountered a major problem during this period (before 2003 - 2004): the tools needed to create interactivity projects were complex and expensive (between 80 and 100 euros). These often too high costs made it difficult for students to develop many projects and this slowed down the practical implementation of their learning.Until then, prototyping tools were mainly dedicated to engineering, robotics and technical fields. They are powerful but their development processes are long and they are difficult to learn and use for artists, interaction designers and, more generally, beginners. Their focus was on making equipment cheaper and easier to use. They wanted to create an environment close to Processing.

Activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board. To do so you use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing.[21]

Definition and constitution of an Arduino UNO board:

The Arduino Uno is a microcontroller board based on the ATmega328 (It is an ATMEL microcontroller from the 8-bit AVR family). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

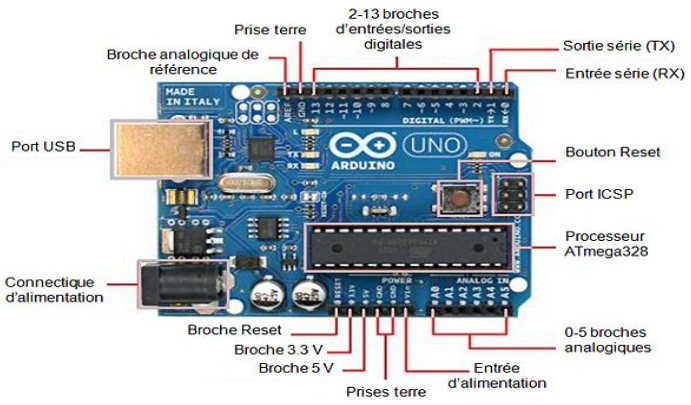



**Figure III-10 : Description of the Arduino UNO board** *[22]*

IDE Arduino is the software that will allow us to program our Arduino. The Interactive Development Environment (IDE) is an application contains everything required to edit a program, check its syntax before uploading it to an Arduino board, which will program the microcontroller.The IDE is very simple to use and continues to expand its capabilities as it evolves.

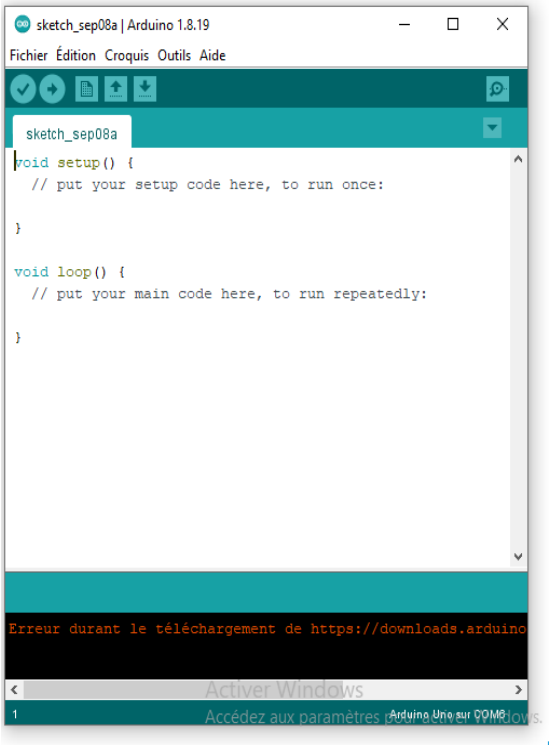



***Figure III-11 : IDE Arduino***

## III.6.2 **PT100:**

RTDs: Resistance Temperature Detectors and they are temperature sensors that contain a resistor whose resistance value changes as its temperature changes. They due to their reputation for accuracy, repeatability, and stability.

In this project, we have used The Pt100 2 wires, as it is the most common RTD and the most available.

The PT100 is a temperature probe made up of a platinum filament, which can be surrounded by a glass rod or not, whose characteristic is to change resistance according to the temperature. Their resistivity is 100 ohms at 0°C and increases as the temperature rises. Depending on the application, different sizes and shapes are available.

The choice of connection method, and thus the type of electronic interface, is determined by the ease of installation, acceptable cost, precision, and availability... A platinum probe can be connected in three different ways: two wires, three wires, or four wires

2 Wires: Simple, but line resistance influences accuracy.

3 Wires: Most commonly used in industry because it reduces systematic errors caused by line resistances.

4 Wires: Assembly technique used in laboratories for allowing for the complete elimination of errors caused by line resistance as well as conductor temperature variations.

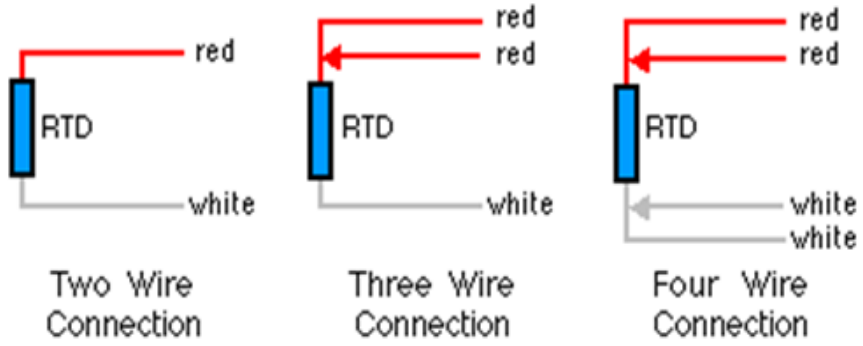



***Figure III-12 : The PT100 Wires****[23]*

In this project, we have used The Pt100 2 wires, as it is the most common RTD and the most available.

***Figure III-13 :PT100***

## III.6.3**LM324:**

### *III.6.3.1 Definition :*

LM324 series are low−cost, quad operational amplifiers with true differential inputs. They have several distinct advantages over standard operational amplifier types in single supply applications. The quad amplifier can operate at supply voltages as low as 3.0 V or as high as 32 V with quiescent currents about one−fifth of those associated with the MC1741 (on a per amplifier basis). The common mode input range includes the negative supply, thereby eliminating the necessity for external biasing components in many applications. The output voltage range also includes the negative power supply voltage.

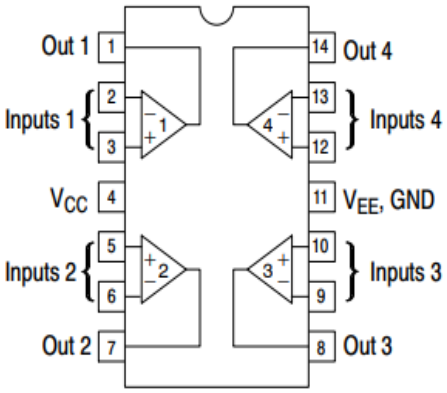



***Figure III-14 : Top view of the pin connection of LM324****[24]*

#### III.6.3.1.1 Advantages:

– Eliminates Need for Dual Supplies

– Four Internally Compensated Op Amps in a Single Package

– Allows Direct Sensing Near GND and VOUT also Goes to GND

– Compatible With All Forms of Logic

– Power Drain Suitable for Battery Operation

– In the Linear Mode the Input Common-Mode, Voltage Range Includes Ground and the Output Voltage

– Can Swing to Ground, Even Though Operated from Only a Single Power Supply Voltage

– Unity Gain Cross Frequency is Temperature Compensated [25]

***Figure III-15 : LM324***

## III.6.4**Relay:**

### *III.6.4.1 What is a relay ?*

A Relay is a simple electromechanical switch that is controlled with a low power direct or alternating voltage. While ordinary switches are used to manually close or open a circuit, similarly, a relay is a switch that connects or disconnects two circuits. Yet, it uses an electrical signal to control an electromagnet, which in turn connects or disconnects another circuit, rather than a manual operation. Also used to drive high power mains loads, up to 10 or 16 amperes.

### *III.6.4.2 How a relay works ?*

When electricity flows through a cable, it creates a magnetic field, causing it to become a magnet. By using the process called electromagnetism, we can then have a remotely controllable actuator.When current is sent into the coil, a magnet then begins to appear due to the polarized magnetic field induced by the electric current, which then actuates the switch of

the power circuit which will then supply the desired component (headlights, flashing lights, starter, etc.).

### *III.6.4.3 Pinout of a relay:*

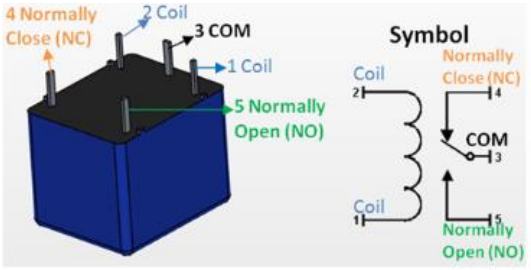



***Figure III-16 : Relay Pinout***

-Coil End 1: Used to trigger(On/Off) the Relay, Normally one end is connected to 5V and the other end to ground -

-Coil End 2 :Used to trigger(On/Off) the Relay, Normally one end is connected to 5V and the other end to ground.

-Common (COM): Common is connected to one End of the Load that is to be controlled.

-Normally Close (NC): The other end of the load is either connected to NO or NC. If connected to NC the load remains connected before trigger.

-Normally Open (NO) : The other end of the load is either connected to NO or NC. If connected to NO the load remains disconnected before trigger.[26]

### *III.6.4.4* ***Relay for Arduino:***

In the Arduino universe, the relay is used when we need to drive a component that consumes relatively large currents. We therefore find it in robotic applications, thermostats controlling electric heaters…

The current flowing in the coil is of the order of a hundred mA. Yet, a digital pin of the Arduino, configured as an output, can only deliver a maximum of 40 mA. It is therefore necessary to amplify this output current using a bipolar transistor.

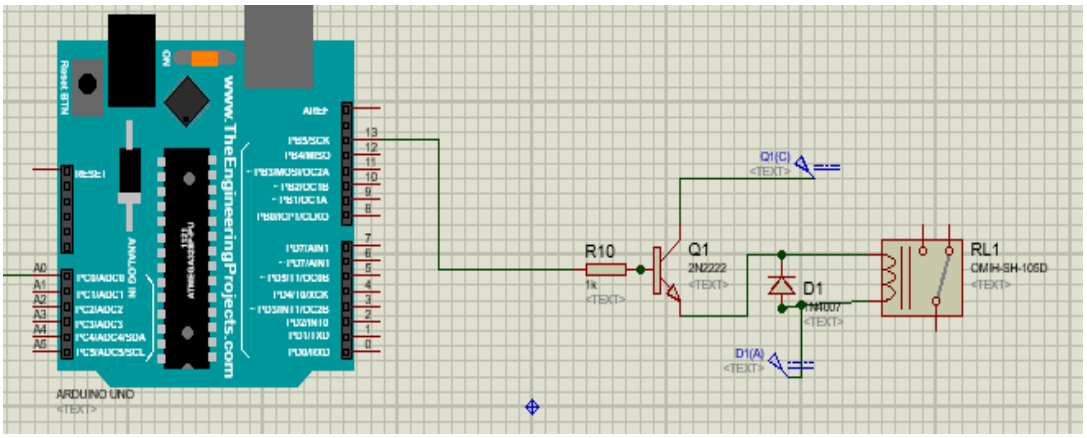



***Figure III-17 : Relay for Arduino***

When the transistor Q1 switches from saturated to blocked state, the diode D1 protects it. During this transition, the energy stored in the coil must be evacuated by this diode. Without it, the transistor's collector would receive hundreds of volts. That would damage it. This diode is known as a freewheeling diode.

### *III.6.4.5 Module relay :*

It's a ready made card, it includes a relay, a control transistor, 2 LEDs, three 1KΩ resistors and a 3-pin connector (GND, Vcc, IN)

Vcc: to power the relay

GND :GROUND and it is the negative.

IN : allows us to control the relay

In this project, we have used a 4 Module relay


***Figure III-18 : Module relay***

## III.6.5**LCD:**

Liquid Crystal Display or LCD is a flat, electronic device generally used as a screen in televisions, computers, smartphones and display signs for producing still and movable images.As the name goes, LCD is composed of liquid crystal particles. Liquid crystals generally do not emit light on their own rather they are illuminated by a fluorescent backlight. Liquid crystals were discovered back in the 1800s and over the following years underwent several modifications that deemed them suitable for a wide variety of applications.[27]


*Figure III-19 :LCD*

## III.6.6**I2C LCD adapter:**

An I2C LCD adapter is a device that contains a PCF8574 microcontroller chip. This microcontroller is an I/O expander that uses a two-wire communication protocol to communicate with other microcontroller chips. Anyone can use this adapter to control a 16x2 LCD with only two wires (SDA, SCL). It saves many arduino or other microcontroller pins. It includes a potentiometer for controlling the LCD contrast. The I2C address is 0x27 by default. This address can be changed by connecting A0, A1, and A2. thus, We connect the Arduino and I2C Lcd Adapter by connecting GND to GND, 5V to VCC, A4 to SDA and A5 to SCL.


*Figure III-20 : I2C LCD adapter*

## III.6.7**Electric resistance heaters:**

The electric resistance heaters are used in a variety of processes where the temperature of an object or process needs to be raised. In our case, for example, the mixture must be reheated each time its temperature drops below 30° .The electric heating element generates heat by converting electrical energy. The heat is then transferred to the process using various heat transfer methods.

*Figure III-21 : Electric resistance heaters*

## III.6.8**Simulation part:**

### *III.6.8.1 Proteus Professional :*

Proteus Professional is an electronics software suite. Developed by Labcenter Electronics. This software suite is made up of two main pieces of software: (ISIS, ARES, PROSPICE) and VSM.

ISIS: it is a software from Proteus Professional, best known for editing electrical schematics. Furthermore, the software allows you to simulate these diagrams, which allows you to detect certain errors during the design stage.

The ARES: is an routing and editing tool that perfectly complements ISIS. An electrical diagram created in ISIS can then be easily imported into ARES to create the electronic card's PCB (Printed circuit board).

This software suite is well-known in the electronics industry. It is used by many businesses and training organizations, including high schools and universities. In addition to its other benefits, such as its ease of understanding and use, the Virtual prototyping tool aids in the reduction of hardware and software costs when designing a project.

### *III.6.8.2 Project circuit on Proteus:*

The following figure represents the circuit of our project under Proteus, which functions in accordance with our project's concept.

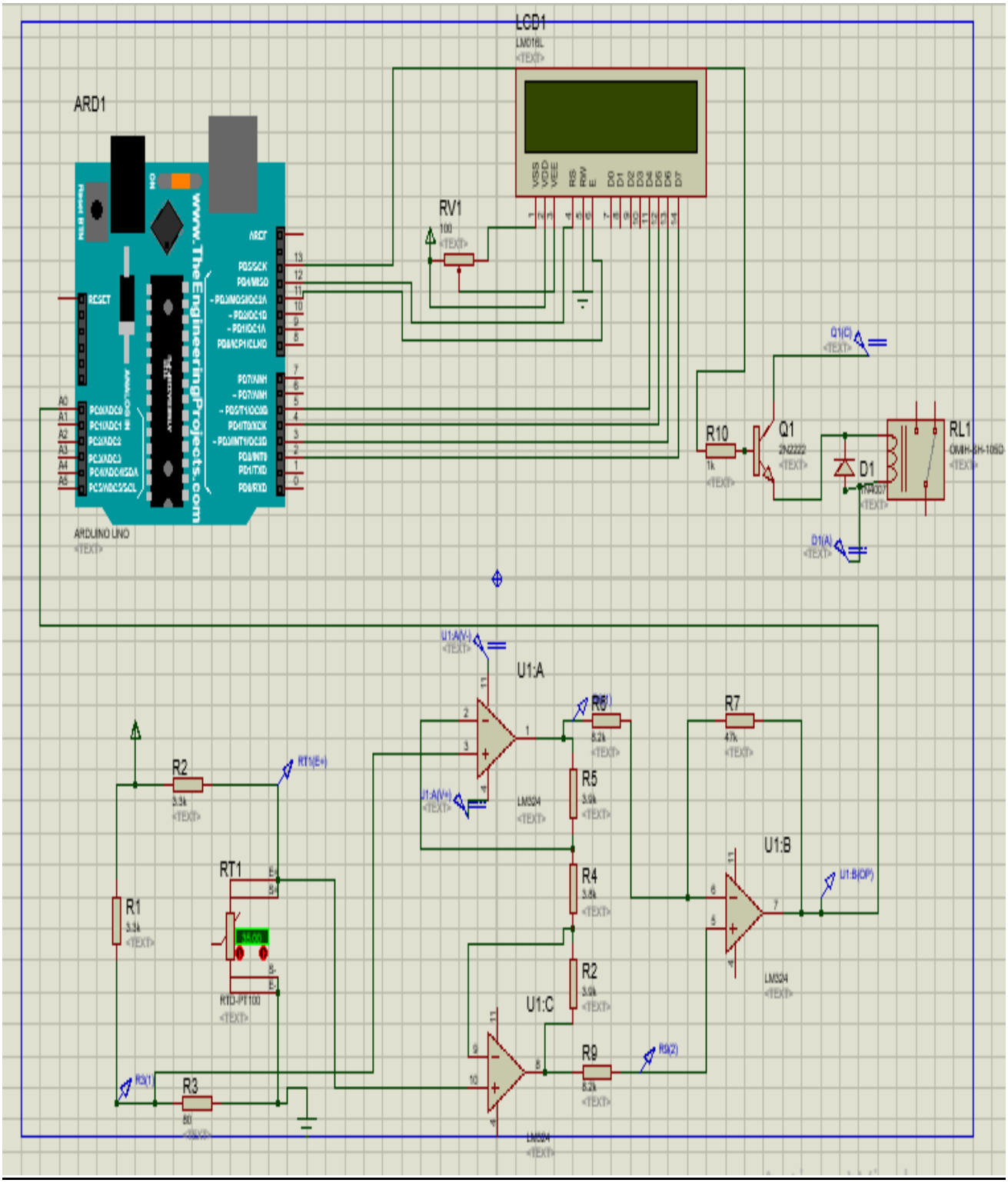



*Figure III-22 : Project circuit on Proteus*

We have realized the above-shown circuit with the sole purpose of measuring the chemostat's mixture temperature and control it in a way to keep it at a certain degree as it is essential for the survival of the biomass living in the medium explained in chapter 1.

### *III.6.8.3 Temperature measurement:*

In this project, we used the RTD PT100 to measure the temperature because they are much more linear than thermocouples and, in cases of limited ranges and accuracy, can be considered to be linear. Therefore, we have made several circuits.

## III.6.8.3.1 Conditioner section:

- **The tension divider bridge**

❖ **Project circuit on Proteus**

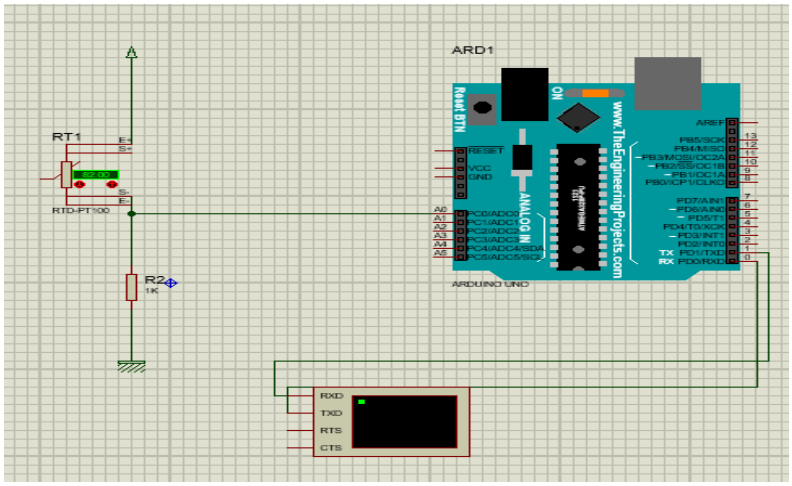



***Figure III-23 :Tension divider bridge circuit***

The first essay that we have conducted with the intention of measuring the temperature was using the tension divider bridge as a sensor using PT100. This bridge is composed of two resistance in series, one of them is the PT100 and the other one is a resistor chosen after calculations. However, the implementation in real life using the values obtained theoretically did not give logical results. The "linear" equation for calculating the resistance of a Pt100 probe as a function of temperature is: $Rt = \alpha * T + Ro$

With Rt = resistance at t°C, Ro = resistance at 0°C (100 Ω), α = temperature coefficient of the probe (0.385Ω/Ω/°C) and T = the temperature in °C.

❖ The simulation program on Proteus:

The project program on Proteus, displayed in the memory appendix.

➢ LM35

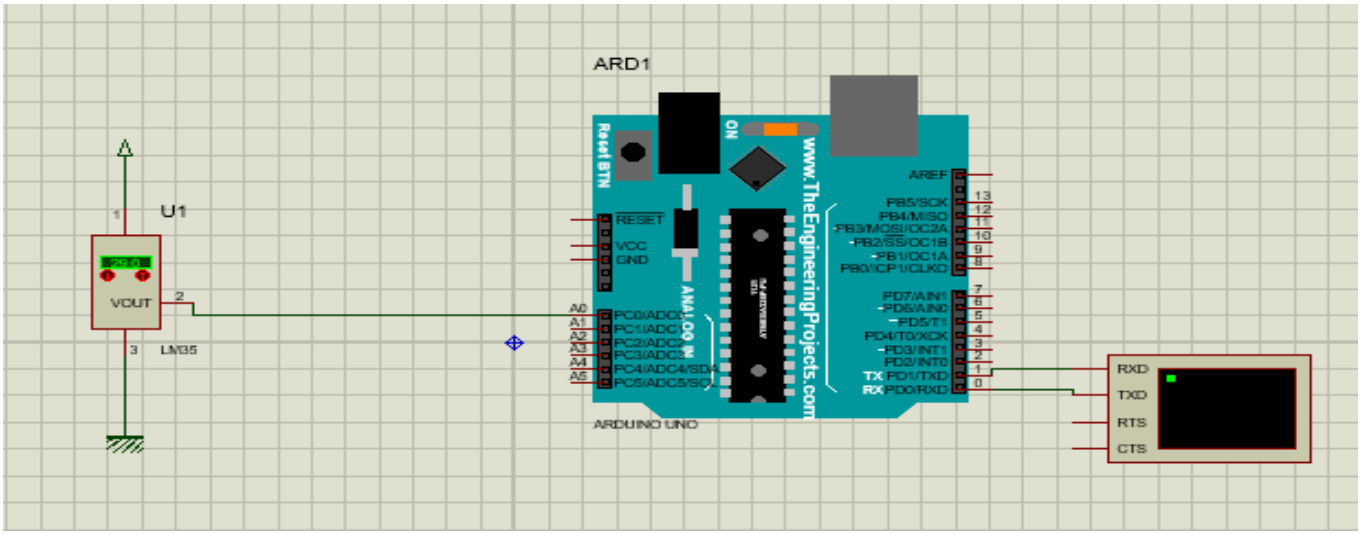



***Figure III-24 : LM35 Circuit***

The LM35 is a sensor that is reliable when it comes to measuring temperature. However, the downside is that we needed a sensor to measure the water's temperature and the mentioned previously sensor cannot be dipped in liquids consequently we could not use it for our experiment.

➢ Wheatstone bridge and LM324 amplifiers:

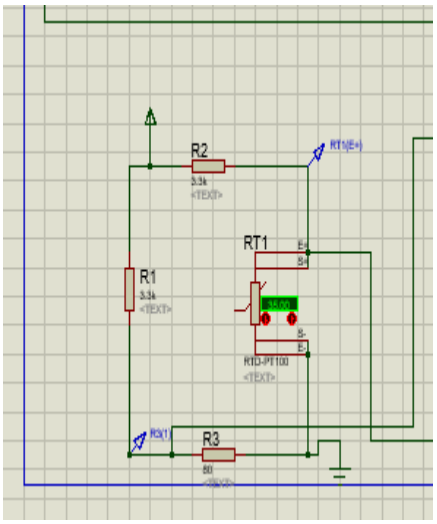



***Figure III-25 :* Wheatstone Bridge**

After various essays, we decided to use the wheatstone bridge to measure the temperature. One of the crucial reasons why we used this bridge was because we needed our measurements to have an initial point of 0°C which was only possible when conducting the experiment in real life thanks to it. Additionally, the wheatstone bridge assures the conversion of a passive sensor into an active one. It also guarantees the stability and linearity of the system.

### III.6.8.3.2 The amplification section:

- LM324:

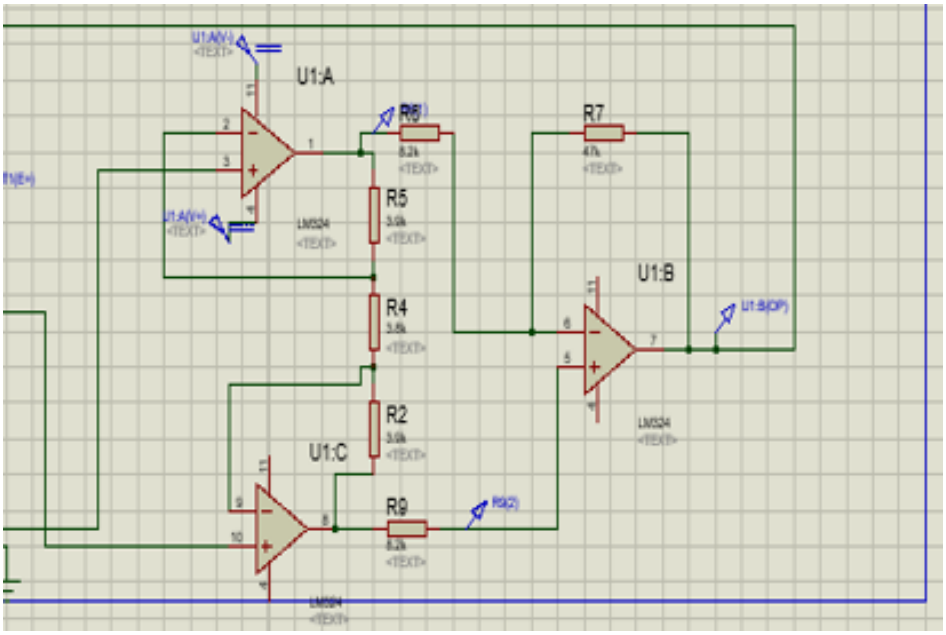



***Figure III-26*** : **LM324 circuit**

We have used the LM324 amplificator to enable us to obtain the curves which proves the system's linearity. We have also used in our trials an AD620 as an amplificatory however the LM324 has proved to be more reliable in the implementation.

❖ PCB circuit:

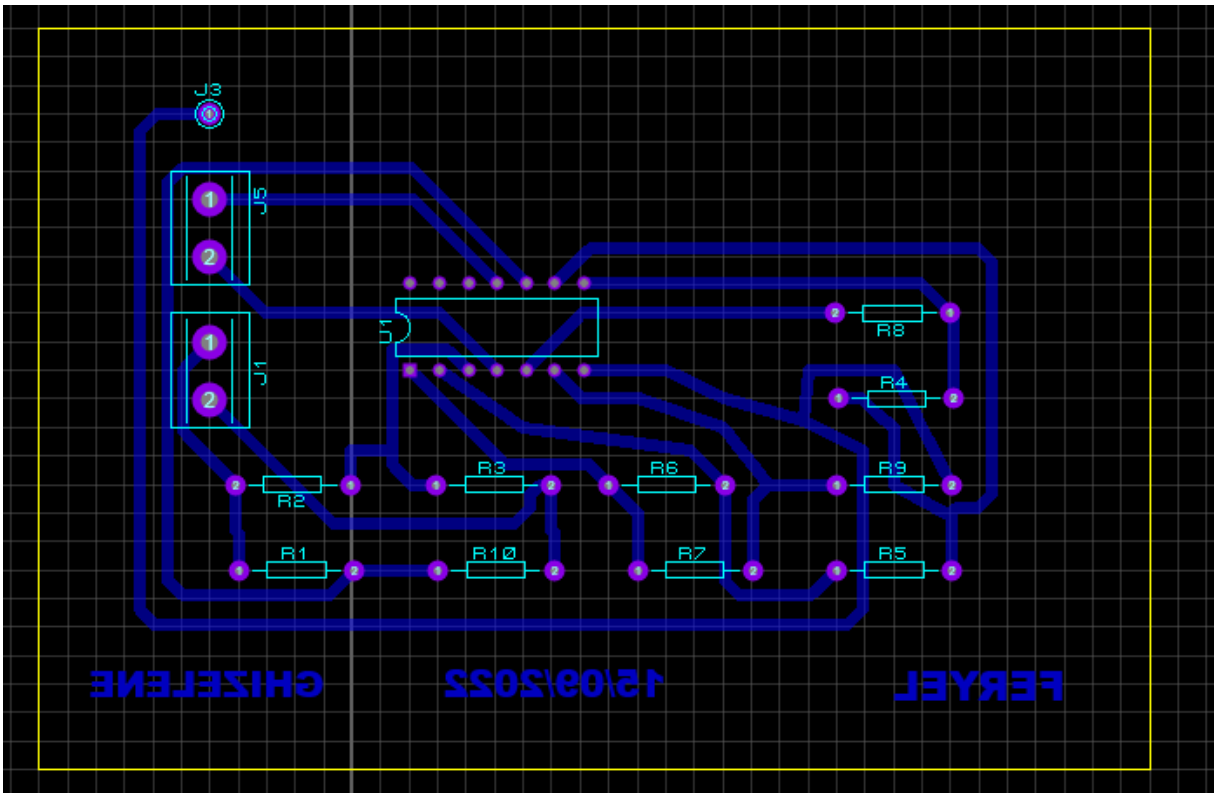



*Figure III-27 : The PCB circuit*

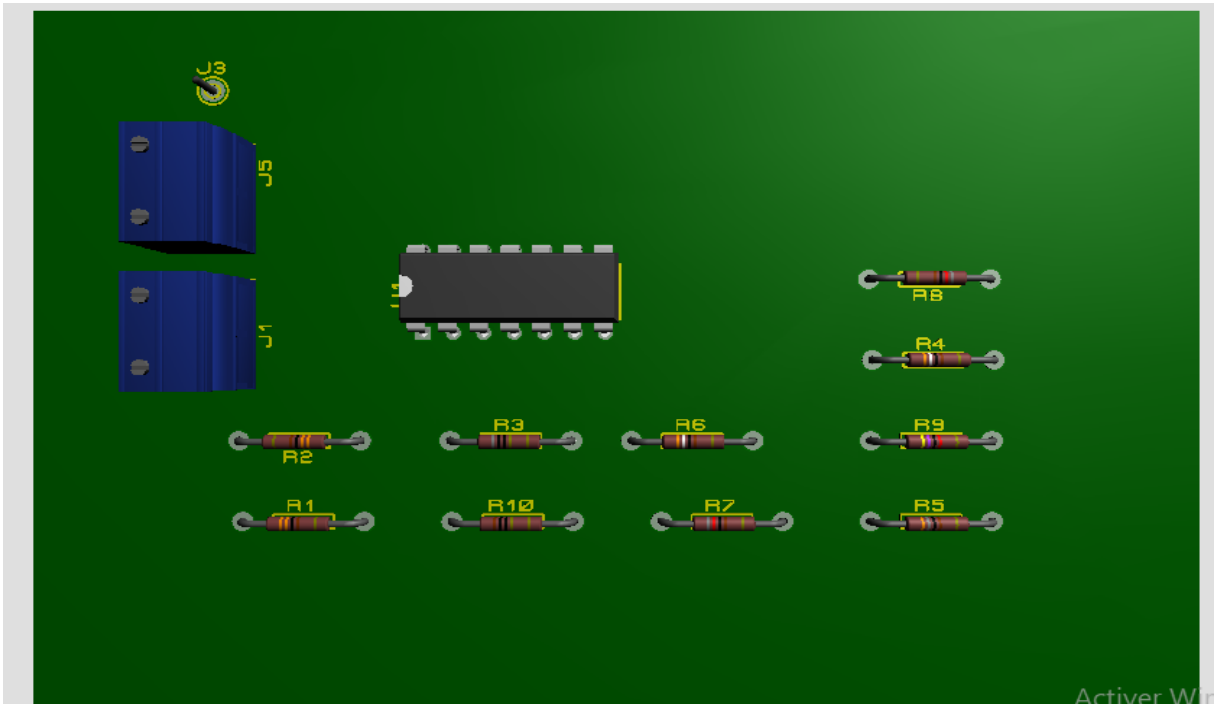



***Figure III-28 :* 3D view of the PCB circuit**

### III.6.8.3.3 Analog / digital conversion and display section:

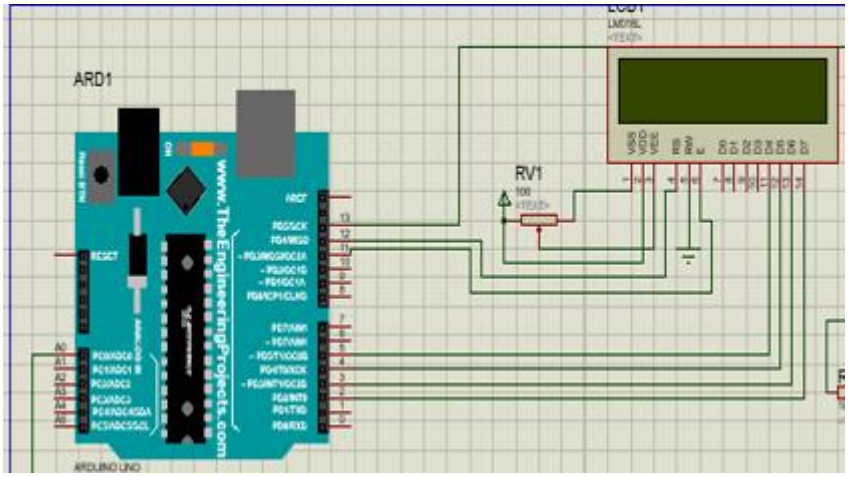



*Figure III-29 : Analog / digital conversion and display section*

For this section we have used Arduino as a tool to convert the analog information into a digital one which will later be displayed on the LCD screen showing the temperature captured from the water in °C.

### III.6.8.3.4 Control loop:

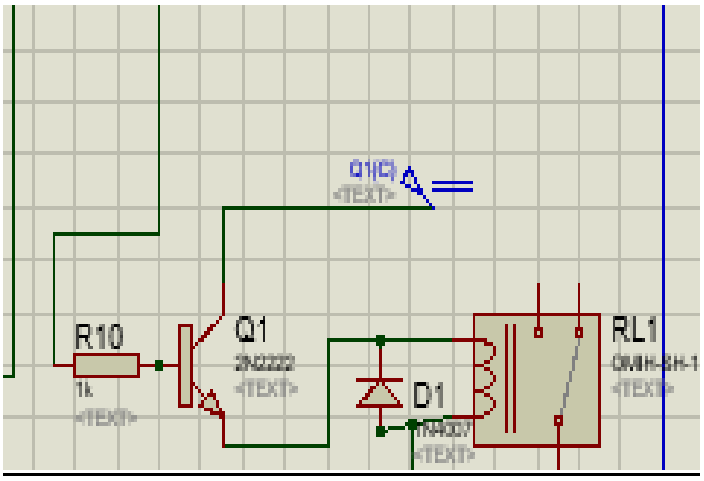



*Figure III-30 : Control loop*

The information will be received by the control loop and will be regulated via the relay which will open and close depending on the temperature. We could have used a different type of control such as PID, however our system did not require such control.

- ❖ The simulation program on Proteus:

The project program on Proteus, displayed in the memory appendix.

## III.7 Conclusion:

In summary, we have provided an overview of the technology of the various electronic components that comprise our system. Each appears to play a distinct role in the module's proper operation. The study of electronic components is critical for understanding the operation of all electronic devices.

We used both Proteus software and Arduino, which enabled us to test multiple circuits and codes until we were able to choose the most suitable and adequate ones depending on the accuracy of the results received. This was followed by realizing the mentioned above simulation in the physical world which gave satisfying results as they were almost identical to the theorical study.

# *Chapter IV Model-free control of the AM2 system.*

## IV.1 Introduction:

Reliable models of the physical system are essential for an efficient automatic control. Models are often created by a series of simplifications and their parameters are usually uncertain. In such case, the control developed is sometimes only effective for the nominal model. However, it is of great importance for engineers that the control continues to function on the real system whose behaviour may differ from that of the initial model. Therefore, we go back to so-called robust regulators to deal with this problem.

Another efficient way to face this challenge is using the model-free control which is considered to be a control that does not need the system's model but uses only its input and output measurements. In this chapter, we apply a model-free control to the AM2 system for optimizing the biogas production. We will use data of the dilution rate (input) and the biogas (output) to establish the control.

We also offer a simulation of the application of the model-free control on the AM2 system introduced in the chapter 2.

## IV.2 Automation:

Automation is a term used to describe technology applications where human input and interference are minimized. There are various types of automation as listed below:

· Basic automation: This kind of automation takes simple, rudimentary tasks and automates them. It is all about digitizing work by using tools to streamline and centralize routine tasks, such as using a shared messaging system instead of having information in disconnected silos. Robotic process automation is also considered to be a type of basic automation.

· Process automation: This is the type of automation that manages business processes for uniformity and transparency. Typically, dedicated software and business apps handle it. It is possible to increase productivity and efficiency using process automation.

· Integration automation: It is the type that describes when a machine has the ability to mimic human tasks and repeat them once their rules are defined. A good example of this would be digital workers which are software robots that are trained to work with humans in order to perform specific tasks.

· Artificial intelligence automation: This level of automation is considered to be the most complex one. Once we add the feature of "AI" then that means that machines have the ability to "learn" and make certain decisions based on their past experiences and situations they were put in and analysed.

### IV.2.1 **Automation systems:**

An automation system is an integration of sensors, controls, and actuators designed to perform a function with minimal or no human intervention.

Most automation systems are derived from manual processes such as drilling, cutting, welding, and so on. These systems use robotic arms to manipulate the movement of the tool that performs the original function. Other applications, particularly in the field of process control, use automation to monitor and control process parameters. This is done by manipulating the operation of equipment such as heaters, motors, pumps, and compressors or by opening or isolating process lines using control valves. Automation systems are available in different configurations even for one specific function. The most common applications of automation systems are but not limited to: assembling, cutting, welding, packaging, measuring, process control.

### IV.2.2 **The advantages of automation systems:**

The most important objective for which an automation system is developed is to reduce human intervention as a human operator is not prone to mistakes and errors which can be the reason to various problems. Therefore, producing an automation system can produce substantial benefits on profit, production rate, safety and quality. Some of the advantages of using an automation system are but not limited to: more consistent production, increased repeatability, precision and accuracy, increased product quality, better working conditions and lower operating costs.

## IV.2.3 Understanding an automation system:

A system is defined as an assembly of components in a way that can lead to the production of a function or a given task. It can possess one or multiple input signals and one or multiple output signals as well. We can distinguish two categories of systems according to their number of inputs and outputs or as we call them mono-variables and multi-variables systems respectively as shown in the following figure:

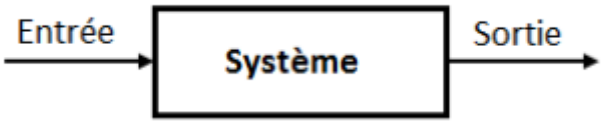



**Figure IV-1 : Mono-variable System**

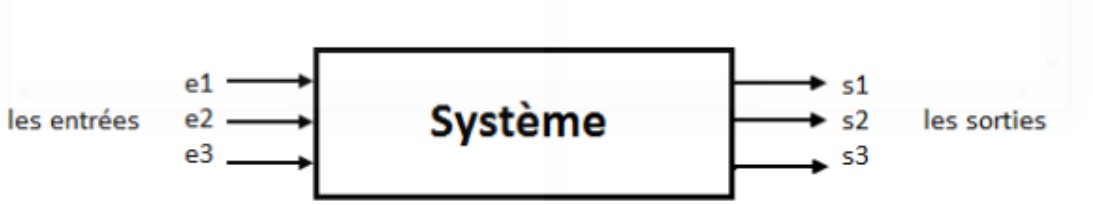



**Figure IV-2 :Multi-Variable System**

## IV.2.4 Controlling an automation system:

An automation system's objective is to satisfy a bunch of specifications in terms of stability, speed, precision, and robustness. The control assures that these performances are realized based on the measures obtained from the output of the system captured with sensors or estimated with observers as well as by taking action using actuators of the system.

Depending on the nature of the command, we are able to realize the following functions:

- The command is chosen to be constant, and the controller needs to keep the output equal or as close as possible to the reference input.
- The command is a variable signal that has to be followed by the output with a null or a small error.

## IV.2.5 Types of system's controls:

Control systems can be done through either open-loop or closed-loop. The key difference between the two is feedback.

- Open-loop control:

  We consider any system where the control signal is non-dependent on the output signal (no feedback from output sensor) to be an open-loop system as it is shown in the following figure.


**Figure IV-3 :Open-loop control.**

In an open loop, the command's device pilots the system but does not assure its automatic control. We usually tend to use this kind of system when:

- We prioritize low cost as it is inexpensive.
- There are rare or no changes in the output, for instance, some cooling pumps.
- There are extremely rare process disturbances.

  - Closed loop control :

It is a system where the control signal depends one way or another on the output signal. Inn other words, there is a feedback where the signal of the output is continuously compared to the input signal and therefore, the system is continuously corrected until the two signals are equal or close to each other. The following figure explains the structure of the closed-loop control.

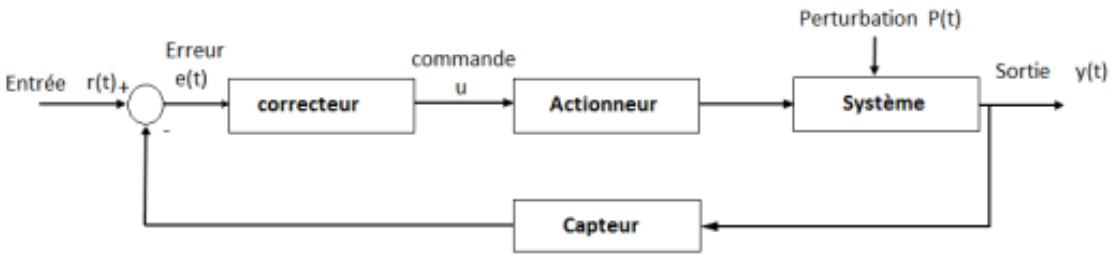



**Figure IV-4 :Closed-loop control.**

## IV.3 Why do we need a model-free control:

Model-based control usually present a couple of drawbacks that are mainly the fact that its efficiency depends largely on knowing the dynamics of the system and that it assumes all state variables are available. [28]

Therefore, for the sake of simplifying things, a control that does not depend on a model is introduced in this chapter. Model free control is considered to be an alternative approach in order to control systems that are somehow complex by representing them in a more simplified way known as "ultra-local model" and using algebraic estimation methods to create a simple controller to track the set-point trajectory. This type of control is not based on the global model of the system, but only on the measurements taken in the inputs and outputs of the system. The control is continuously renewed by using a valid local model on a short period of time.

The free-model control is a new approach introduced by M.Fliess and Al. Elle in their publication in 2013 where we look for a valid model on a large range of operations. [29]

## IV.4 Global and local models:

What we mean by a global model is a model that is as valid as possible in time. It describes the connection between the output of the system depending on its input using physical laws.

Any physical system is described using differential equation between its input *u* and its output *y*, of general order *n*:

$$y^{(n)} = f(t, y, \dot{y}, \dots\dots, y^{(n-1)}, u, \dot{u}, \dots\dots, u^{(m)}) \qquad IV\text{-}1$$

This model presents a couple of downsides:

- Unknown model (uncertain parameters, approximated or neglected dynamics, …).
- Disrupted system, measurements with noises, uncertain inputs….

Therefore, to deal with these challenges; practitioners proposed using a model-free control which consists of replacing the complex and unknown model IV-1) by an ultr- local one valid for a short time window as shown in the following figure.

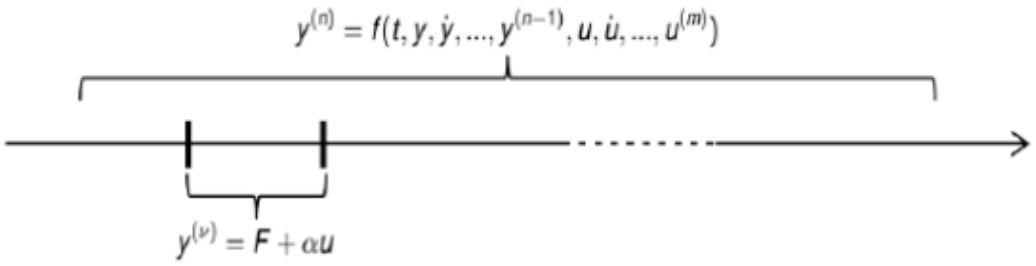



**Figure IV-5 : Model-free control**

The ultra-local model or the "phenomenological" model is represented by the equation IV-2):

$$y^{(v)} = F + \alpha u \qquad \textit{IV-2}$$

Where:

- u: the single control variable.
- y: the single output variable.
- $y^{(v)}$: the derivative of order $v \geq 1$ of y.
- $\alpha \in \mathbb{R}$ is a non-physical constant parameter. It is chosen in a way that $\alpha u$ and $y^{(v)}$ are of the same magnitude.
- $F$: is continuously updated and is supposed to contain all the unknown and disrupted parts of the system and is estimated based on the inputs y and outputs u on every considered time window.

  The function F is estimated from derivative of the output measurement and the past control as shown by equation (IV-3).

$$F_{est} = {y_{est}}^{(v)} - \alpha u \qquad \textit{IV-3}$$

## IV.5 Principles of calculations of the model-free control:

The control's principle is explained by the following figure where two time intervals are taken into consideration:

- Time interval of control T on which the local model is considered, and which is updated at k.T, k=1, 2, .., n. The control is applied on the system every kT.
- Time interval of measurements δt during which we measure the output of the system and therefore estimate $y^{(v)}$ .

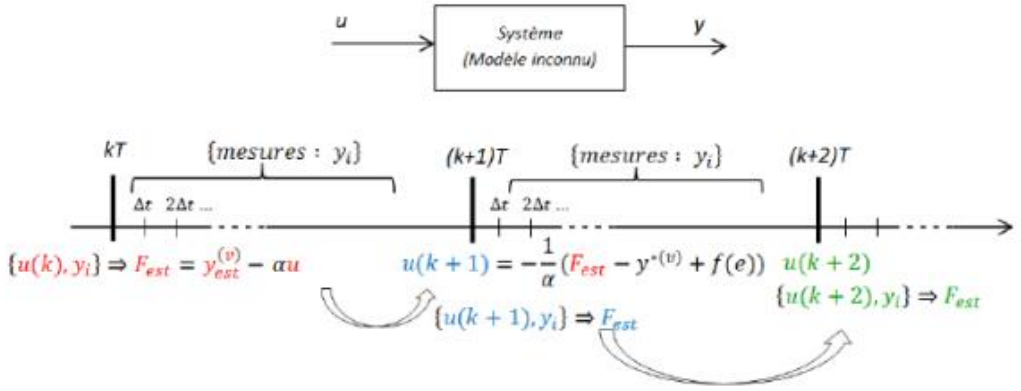



**Figure IV-6 : Principles of calculations of the model-free control**

In order to calculate the free-model control, we proceed as shown down below:

- We define the ultra-local model:

$$y^{(v)} = F + \alpha u \qquad \textit{IV-4}$$

- We estimate the derivative ${y_{est}}^{(v)}$ in order to estimate the function F. As mentioned above, F contains not only the unknown structure of the system but also the part that contains all the noise. It is continuously updated using:

$$F_{est} = {y_{est}}^{(v)} - \alpha u \qquad \textit{IV-5}$$

  Calculate the control input y. On every control time range T, the control is given by:

$$u = -\frac{1}{\alpha}(F_{est} - y^{*(v)} + f(e)) \qquad \textit{IV-6}$$

- $y^*$ is considered to be the reference trajectory which the output y has to follow.
- $f(e)$ is a causal or non-anticipative function that depends on the past and present of the tracking error e= $y - y^*$

Let's combine now the two equations:

$$y^{(v)} = F + \alpha u \qquad \textit{IV-7}$$

$$u = -\frac{1}{\alpha}\left(F_{est} - y^{*(v)} + f(e)\right) \qquad \textit{IV-8}$$

We obtain:

$$e^{(v)} + f(e) = 0 \qquad \textit{IV-9}$$

We have to choose $f(e)$ in a way that assures the good follow of the trajectory $y^*$ or that a perfect tracking is asymptotically ensured. In other words:

$$\lim_{t \to +\infty} e(t) = 0 \qquad \textit{IV-10}$$

This equation is considered to be too general which can cause challenges when leading to easily implementable tools. This challenge can be corrected using adjustable intelligent proportional-integral-derivative controller (iPID).

### IV.5.1 **Intelligent PIDs:**

Most often, we use the proportional-integral-derivative controller (iPID). Therefore, we choose:

$$f(e) = k_p e(t) + k_i \int e(t)dt + k_d \dot{e}(t) \qquad \textit{IV-11}$$

The gains values $k_p$, $k_i$and $k_d$ are adjustable using the essay and failure method.

In order to choose the suitable corrector for our system, let's take the case of a mono-variable system. Note that the ultra-local model is expressed as follows:

$$y^{(v)} = F + \alpha u \qquad \text{IV-12}$$

Most often we stick with $v = 1$ or $v = 2$. Let's assume that $v = 2$ then equation *IV-2* becomes:

$$\ddot{y} = F + \alpha u \qquad \textit{IV-13}$$

We use the intelligent proportional-integral-derivative controller or iPID to close the loop:

$$u = -\frac{F - \ddot{y}^* + k_p e + k_i \int e + k_d \dot{e}}{\alpha} \qquad \textit{IV-14}$$

Where:

- $y^*$ is the trajectory of reference.
- $e = y - y^*$ is the error of the tracking.
- $k_p$, $k_i$ and $k_d$ are the PID tuning gains.

Now, let's assume that $v = 1$ in equation *IV-15*, we get:

$$\dot{y} = F + \alpha u \qquad \textit{IV-16}$$

We use the intelligent proportional-integral controller also known as the iPI, we get:

$$u = -\frac{F - \dot{y}^* + k_p e + k_i \int e}{\alpha} \qquad \textit{IV-17}$$

A good estimation of F helps the controller get satisfactory performances. In most cases $k_i$ is set to be equal zero which leads to the use of an intelligent proportional controller also known as iP as shown here:

$$u = -\frac{F - \dot{y}^* + k_p e}{\alpha} \qquad \textit{IV-18}$$

## IV.6 Model-free control algorithme :

In order to establish a model-free control, it is important to follow a bunch of simple steps while considering the estimation of the output and its derivatives which has to be reliable. The mentioned above steps are as follows:

- Choose a value for $v = 1$ or 2 of the equation *IV-19).*
- Adjust α in a way that $y^{(v)}$ and $\alpha u$ have the same magnitude.
- Choose $y^*$ the reference.
- Estimate $y^{(v)}$ then calculate $F = y^{(v)} - \alpha u$.
- Apply a corrector iPI or iPID to the system according to the specifications while adjusting the parameters $k_p$, $k_i$ and $k_d$.

It is important to note that it is necessary to choose the two time ranges:

-T the control time which depends on the time constant of the system to be controlled,.

-δt the time interval of the data measurement.

## IV.7 Time derivatives estimation:

The model-free control is essentially based on a good estimation of the derivatives of the output of the system. If the estimation is not correct, then the results obtained would undoubtedly be incorrect as well which can only be proof of the crucial importance of choosing the suitable method to calculate the derivatives.

There are multiple methods however most of them are either too sensitive to noises or hard to implement.

Therefore, in order to find a way to overcome the mentioned above challenges, M. Fliess and al. have developed and introduced new methods which can estimate the derivatives using integrals which, as we all know, have the ability of filtering noises found in measurements as they are considered to be low-pass filter.

## IV.8 Derivatives estimation using M. Fliess and al method:

Let's assume that $y(t)$ to be a noisy observation of a signal called $x(t)$ with real values on a set of finite time ranges and that we would like to estimate its derivatives. We consider $x(t)$ as an N degree polynomial signal, which can be expressed using Taylor expansion around the point zero as follows:

$$x_N(t) = \sum_{v=0}^{N} x^{(v)}(0)\frac{t^v}{v!} \qquad \textit{IV-20}$$

The $x_N(t)$ Laplace transform is expressed like this:

$$x_n(s) = \sum_{v=0}^{N} \frac{x^{(v)}(0)}{s^{v+1}} \qquad \textit{IV-21}$$

The objective is to estimate $x^{(v)}(0)$, from then on we can find easily he derivatives estimations of the system's output $x(t)$ which is supposed to be noisy therefore we would consider an independent estimation.

Let's multiply the two parts of the equation IV-22 by $s^{N+1}$. This will help us obtain:

$$s^{N+1}X_N(s) = s^N x(0) + s^{N-1}\dot{x}(0) + \cdots + x^N(0) \qquad \textit{IV-23}$$

Let's suppose that $N = 3$ for example:

$$s^4X_N(s) = s^3x(0) + s^2\dot{x}(0) + s\ddot{x}(0) + x^3(0) \qquad \textit{IV-24}$$

Our objective is therefore finding $x(0)$, $\dot{x}(0)$, $\ddot{x}(0)$ and $x^3(0)$.

- $x(0)$ estimation: In order to obtain $x(0)$, we have to calculate the derivatives relatively to s of the equation IV-25 three times, the following equation is obtained:
  - First derivative:

$$4s^3X_N(s) + s^4\frac{dX_N(s)}{ds} = 3s^2x(0) + 2s\dot{x}(0) + \ddot{x}(0) \qquad \textit{IV-26}$$

  - Second derivative:

$$12s^2X_N(s) + 8s^3\frac{dX_N(s)}{ds} + s^4\frac{d^2X_N(s)}{ds^2} = 6sx(0) + 2\dot{x}(0) \qquad \textit{IV-27}$$

- Third derivative:

$$24sX_N(s) + 36s^2\frac{dX_N(s)}{ds} + 12s^3\frac{d^2X_N(s)}{ds^2} + s^4\frac{d^3X_N(s)}{ds^3} = 6x(0) \qquad \textit{IV-28}$$

We divide the equation [4.18] on $s^{\overline{N}}$, for our example let's consider that $\overline{N} = 5$:

$$\frac{24}{s^4}X_N(s) + \frac{36}{s^3}\frac{dX_N(s)}{ds} + \frac{12}{s^2}\frac{d^2X_N(s)}{ds^2} + \frac{1}{s}\frac{d^3X_N(s)}{ds^3} = \frac{6}{s^5}x(0) \qquad \textit{IV-29}$$

Let's apply the reverse Laplace transform on the equation IV-30 so we can return to the time domain:

$$6x(0)\frac{T^4}{4!} = \int_0^T \sigma^{\ 3}\ x(\sigma)d\sigma + 12\int_0^T\int_0^{\sigma 1}\sigma^2 x(\sigma)d\sigma d\sigma_1 + 36\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2} -\sigma x(\sigma)d\sigma d\sigma_1 d\sigma_2 + 24\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2}\int_0^{\sigma 3} x(\sigma)d\sigma d\sigma_1 d\sigma_2 d\sigma_3$$

Using mathematical tools, it is possible to simplify the double, triple and quadruple integrals more:

$$6x(0)\frac{T^4}{4!} = \int_0^T \sigma^3\, x(\sigma)d\sigma + 12\int_0^T (T-\sigma)\sigma^2 x(\sigma)d\sigma + 36\int_0^T -\frac{(T-\sigma)^2}{2!}\sigma x(\sigma)d\sigma + \ +24\int_0^T \frac{(T-\sigma)^3}{3!}x(\sigma)d\sigma$$

Where we can estimate $x(0)$.

- $\dot{x}(0)$ estimation: For us to estimate $\dot{x}(0)$, we have to calculate the second derivative of equation IV-31 relatively to s, we get:
  - First derivative:

$$4s^3X_N(s) + s^4\frac{dX_N(s)}{ds} = 3s^2x(0) + 2s\dot{x}(0) + \ddot{x}(0) \qquad \textit{IV-32}$$

  - Second derivative:

$$12s^2X_N(s) + 8s^3\frac{dX_N(s)}{ds} + s^4\frac{d^2X_N(s)}{ds^2} = 6sx(0) + 2\dot{x}(0) \qquad \textit{IV-33}$$

In order to estimate $\dot{x}(0)$, we have to eliminate the term $x(0)$. To do so, let's start by dividing the equation [4.21] by *s*:

$$12sX_N(s) + 8s^2\frac{dX_N(s)}{ds} + s^3\frac{d^2X_N(s)}{ds^2} = 6x(0) + \frac{2}{s}\dot{x}(0) \qquad \textit{IV-34}$$

Then we calculate the derivate relative to *s* from the obtained equation as shown below:

$$-\frac{2}{s^2}\dot{x}(0) = s^3\frac{d^3X_N(s)}{ds^3} + 11s^2\frac{d^2X_N(s)}{ds^2} + 28s\frac{dX_N(s)}{ds} + 12X_N(s) \qquad \textit{IV-35}$$

Later, we divide [2.23] by $s^4$ as follows:

$$-\frac{2}{s^6}\dot{x}(0) = \frac{1}{s}\frac{d^3X_N(s)}{ds^3} + \frac{11}{s^2}\frac{d^2X_N(s)}{ds^2} + \frac{28}{s^3}\frac{dX_N(s)}{ds} + \frac{12}{s^4}X_N(s) \qquad \textit{IV-36}$$

Right now, let us apply the reverse Laplace transform on equation IV-37 to enable us to return to the domain of time, we obtain:

$$-2\dot{x}(0)\frac{T^5}{5!} = \int_0^T -\sigma^3 x(\sigma)d\sigma + 11\int_0^T\int_0^{\sigma 1}\sigma^2 x(\sigma)d\sigma d\sigma_1 +$$
$$28\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2} -\sigma x(\sigma)d\sigma d\sigma_1 d\sigma_2 + 12\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2}\int_0^{\sigma 3} x(\sigma)d\sigma d\sigma_1 d\sigma_2 d\sigma_3$$

We can simplify the integrals more using mathematical tools as follows:

$$-2\dot{x}(0)\frac{T^5}{5!} = \int_0^T -\sigma^3 x(\sigma)d\sigma + 11\int_0^T (T-\sigma)\sigma^2 x(\sigma)d\sigma + 28\int_0^T -\frac{(T-\sigma)^2}{2!}\sigma x(\sigma)d\sigma +$$
$$12\int_0^T \frac{(T-\sigma)^3}{3!}x(\sigma)d\sigma$$

And this is how we can estimate $\dot{x}(0)$.

- $\ddot{x}(0)$ estimation:

  The first thing to do to estimate $\ddot{x}(0)$ is to calculate the first derivative relative to *s* of equation IV-38 , we get:

$$4s^3X_N(s) + s^4\frac{dX_N(s)}{ds} = 3s^2x(0) + 2s + \ddot{x}(0) \qquad \textit{IV-39}$$

In order to estimate the term $\ddot{x}(0)$, we have to eliminate $x(0)$ and $\dot{x}(0)$. Therefore, we have start by dividing the equation [4.25] by *s*, as shown:

$$4s^2X_N(s) + s^3\frac{dX_N(s)}{ds} = 3sx(0) + 2\dot{x}(0) + \frac{1}{s}\ddot{x}(0) \qquad \textit{IV-40}$$

Then, we calculate the derivative relative to s of equation (IV-41 )as follows:

$$\frac{2}{s^3}\ddot{x}(0) = \frac{d^3X_N(s)}{ds^3} + 10s^2\frac{d^2X_N(s)}{ds^2} + 22s\frac{dX_N(s)}{ds} + 8X_N(s) \qquad \textit{IV-42}$$

Later, we divide the equation [4.27] by $s^4$:

$$\frac{2}{s^7}\ddot{x}(0) = \frac{1}{s}\frac{d^3X_N(s)}{ds^3} + \frac{10}{s^2}\frac{d^2X_N(s)}{ds^2} + \frac{22}{s^3}\frac{dX_N(s)}{ds} + \frac{8}{s^4}X_N(s) \qquad \textit{IV-43}$$

Right now, we apply the reverse Laplace transform on equation (IV-44 )to enable us to return to the domain of time, we get:

$$2\ddot{x}(0)\frac{T^6}{6!} = \int_0^T -\sigma^3 x(\sigma)d\sigma + 10\int_0^T\int_0^{\sigma 1}\sigma^2\, x(\sigma)d\sigma d\sigma_1 + 22\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2} -\sigma x(\sigma)d\sigma d\sigma_1 d\sigma_2 + 8\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2}\int_0^{\sigma 3} x(\sigma)\, d\sigma\, d\sigma_2\, d\sigma_3$$

It is possible to simplify the integrals more using mathematical tools as shown:

$$2\ddot{x}(0)\frac{T^6}{6!} = \int_0^T -\sigma^3 x(\sigma)d\sigma + 10\int_0^T (T-\sigma)\sigma^2 x(\sigma)d\sigma + 22\int_0^T -\frac{(T-\sigma)^2}{2!}\sigma x(\sigma)d\sigma + 8\int_0^T \frac{(T-\sigma)^3}{3!}x(\sigma)d\sigma$$

From which we can estimate $\ddot{x}(0)$.

- $x^3(0)$ estimation:

Let's start by calculating the derivative relative to *s* of equation (IV-45) :

$$s^3 X_N(s) = s^2 x(0) + s\dot{x}(0) + \ddot{x}(0) + \frac{1}{s}x^3(0) \qquad \textit{IV-46}$$

Now, let us calculate the third derivative of the equation ( IV-47) relative to *s*:

$$-\frac{6}{s^4}X^3(0) = s^3\frac{d^3X_N(s)}{ds^3} + 9s^2\frac{d^2X_N(s)}{ds^2} + 18s\frac{dX_N(s)}{ds} + 6X_N(s) \qquad \textit{IV-48}$$

Then, let's divide the equation [4.30] by $s^4$:

$$-\frac{6}{s^4}X^3(0) = \frac{1}{s}\frac{d^3X_N(s)}{ds^3} + \frac{9}{s^2}\frac{d^2X_N(s)}{ds^2} + \frac{18}{s^3}\frac{dX_N(s)}{ds} + \frac{6}{s^4}X_N(s) \qquad \textit{IV-49}$$

Now, let us apply the reverse Laplace transform on equation (IV-50) in order to enable us to return to the time domain, we get:

$$-6x^3(0)\frac{T^7}{7!} = \int_0^T -\sigma^3 x(\sigma)d\sigma + 9\int_0^T\int_0^{\sigma 1}\sigma^2 x(\sigma)d\sigma d\sigma_1 + 18\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2} -\sigma x(\sigma)d\sigma d\sigma_1 d\sigma_2 + 6\int_0^T\int_0^{\sigma 1}\int_0^{\sigma 2}\int_0^{\sigma 3} x(\sigma)d\sigma d\sigma_1 d\sigma_2 d\sigma_3$$

From where we can estimate $x^3(0)$.

The examples mentioned above have presented and demonstrated how the calculation method works. The estimation of the derivatives is a fast and easy way, and it has many advantages such as:

- The estimated value is expressed using iterated integrals or a low-pass filter.
- It helps eliminate the noise.
- It presents no delays like the other classical filters.
- It is used to estimate the state, parameters and control…
- It uses Laplace transform to calculate.

## IV.9 Application of the model-free control on the AM2 system:

In this section of our thesis, we will use a closed loop of the model-free control on the AM2 system.

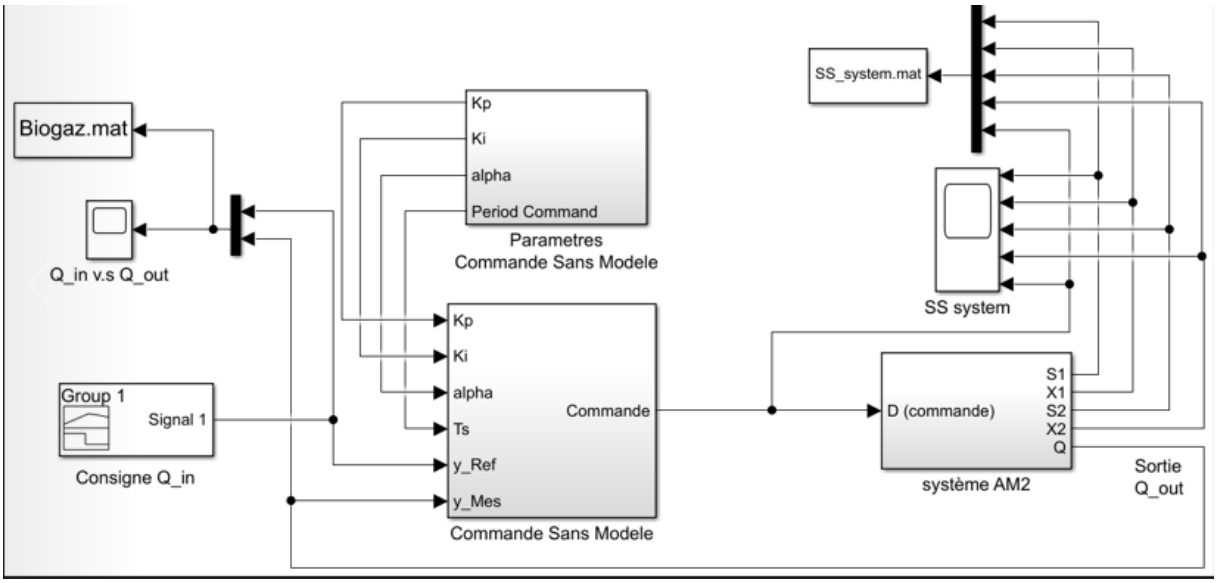



***Figure IV-7 : simulation of the model-free control***

We will also implement this control using MATLAB / SIMULINK to visualize the simulation's results.

The implementation of the model-free control is presented as shown below:

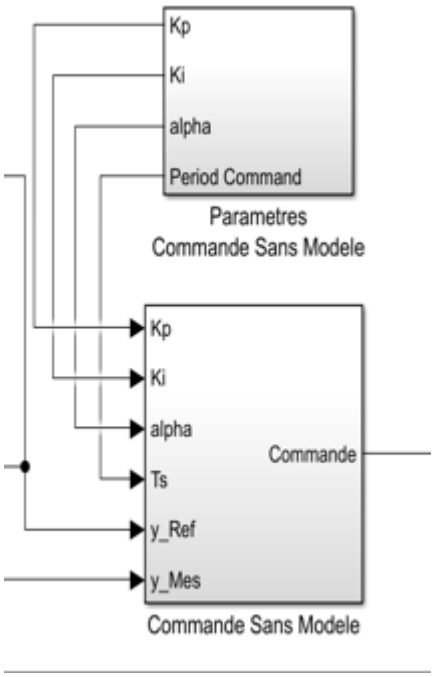



***Figure IV-8 The implementation of the model-free control.***

In which we have two blocks:

- One for choosing the control parameters:

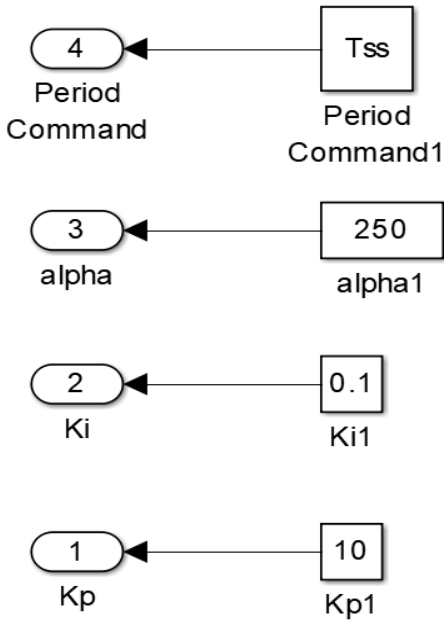



**Figure IV-9 : Block of the parameters**

- one for calculating the control signal:

The block provides the control at its output and receives the reference and measurement signals required for this control at its input.

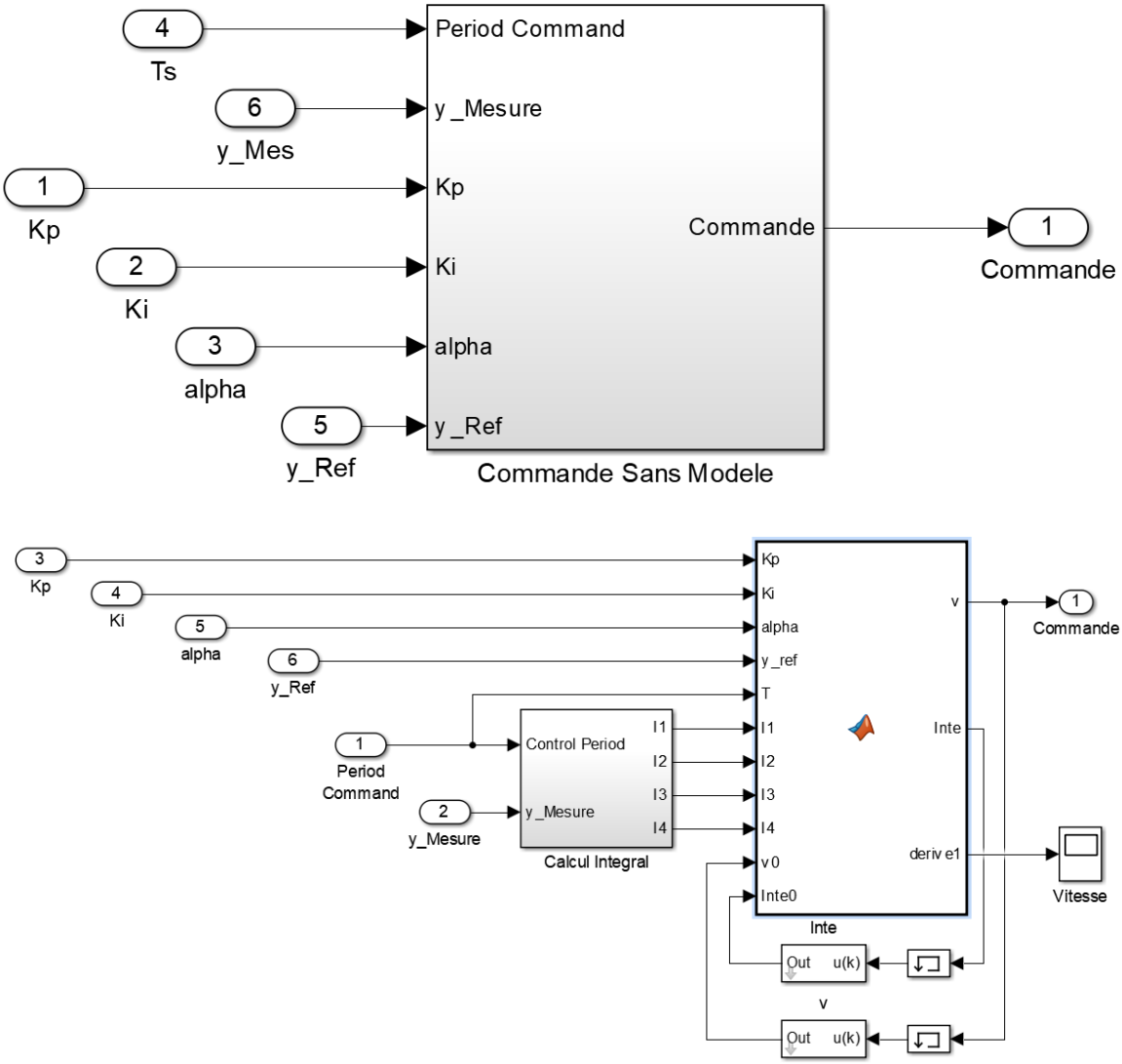



**Figure IV-10 : Block of control**

The model-free control, as we have explained previously, relies heavily on the good estimation of the output derivatives since an incorrect estimation leads to wrong results. In order to estimate the derivatives in the best way, the calculation of the integrals must be precised.

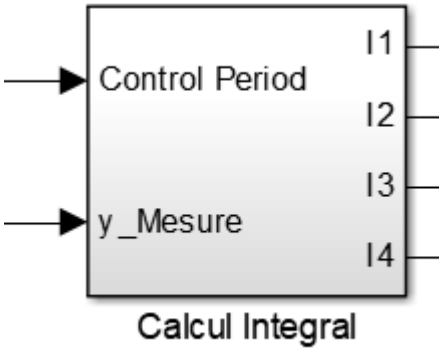



**Figure IV-11 : calculation of the integrals**

The control block of the AM2 system is shown as follows:

Our system can be clearly visualized in the block with D being the input and $S_1$, $X_1$, $S_2$, $X_2$ and $Q_{out}$ as outputs. In this block, we identify the AM2 system and the state variables as shown in figure…

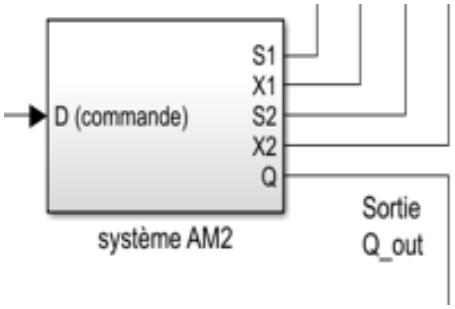



**Figure IV-12 : AM2 Système.**

The Simulink of the shown above MATLAB code of the AM2 system is presented in the following figure:

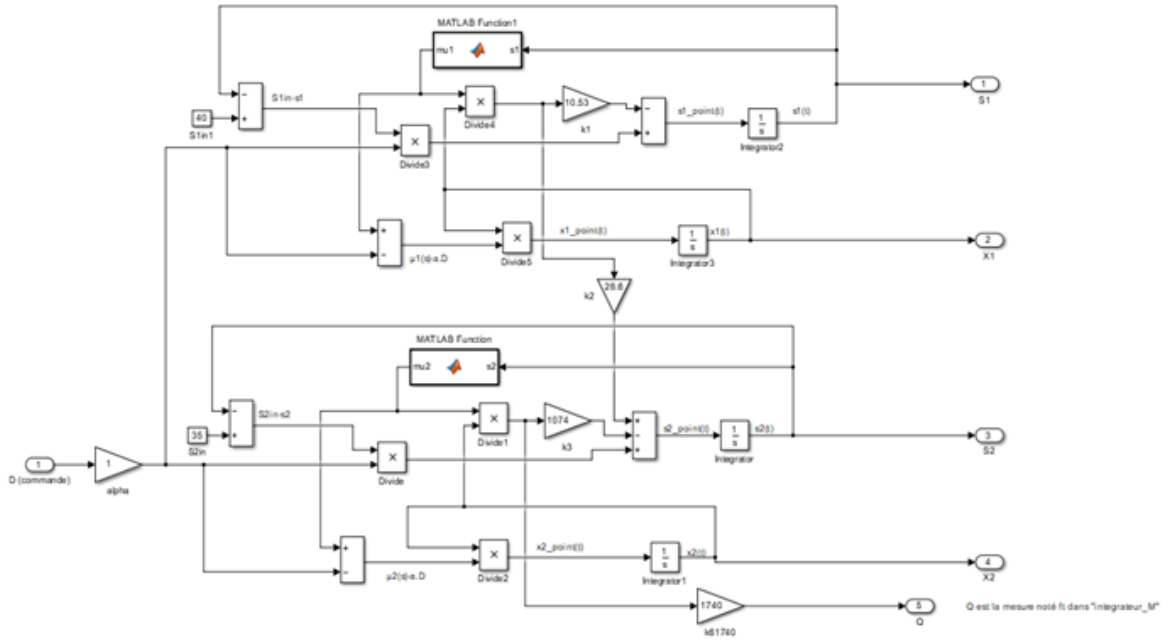



**Figure IV-13 : The Simulink MATLAB code of the AM2**

## IV.10 Simulation results in Regulation mode:

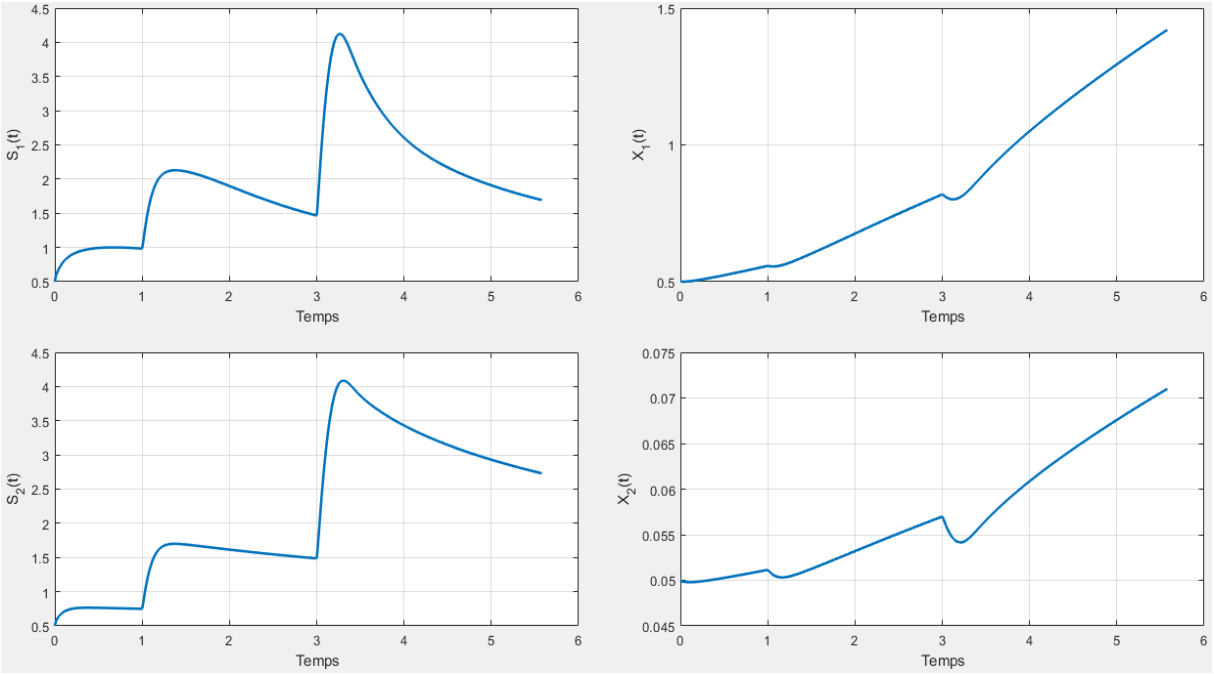



***Figure IV-14 :The development of the biomasses and the consumption of the substrates.***

The curves of $X_1(t)$ and $X_2(t)$ represent the development of the biomasses while $S_1(t)$ and $S_2(t)$ represent respectively the consumption of the substrates.

In figure ( IV-7 **)** we can visualize the production of the biogas as an output of the control block. The system is in a closed-loop as seen so it enables us to compare the output which is the biogas with the reference which we chose it to be a step signal between 5-10 and 10-20. We obtained the following figure:

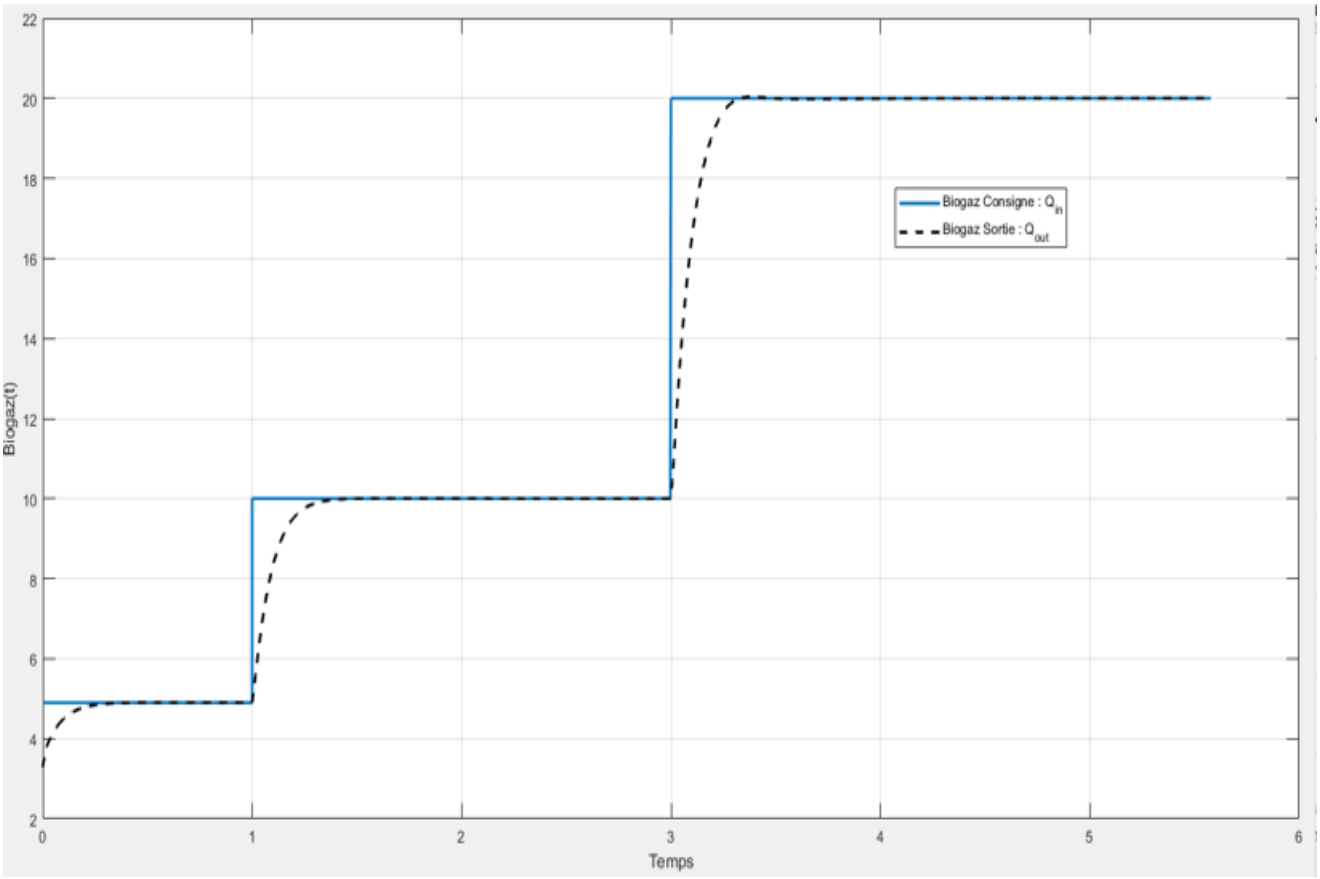



***Figure IV-15*** **: Visualize the production of the biogas**

We can notice that the output of the gas is following the reference with an insignificant error which is what we are seeking.

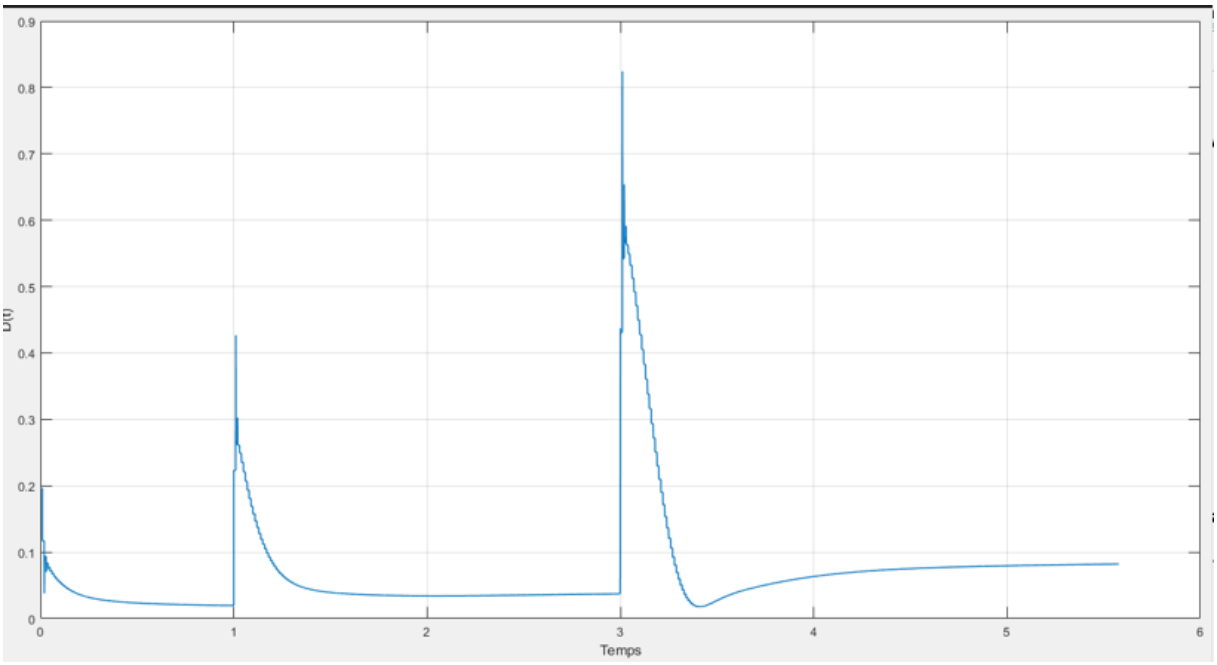



***Figure IV-16 :Control simulation***

The figure represents the evolution of the substrate  with time S1. As seen, it starts with an appropriate dillution rate  to start the system and it reaches high values every time the feedstock is introduced and decreases once it is consumed by the microorganisms unti it gets to its steady state after a period of time.

## IV.11 Conclusion:

In this chapter, we have presented the model-free control which can be applied to complex systems with finite dimension. The mentioned above control can be observed or considered as a contribution to the intelligent PID (i-PID) controllers or the intelligent PI (i-PI) controllers which facilitate the control even when the system is non-linear. The most important part is:

- The consideration and the update of the ultra-local model on a short period of time.
- The estimation of the output derivatives.

The model-free control is considered to be a technique dedicated to the calculation of the controller's parameters in real time. It is based on calculating the derivatives without having a

prior knowledge of the mathematical model of the system. It is a method that enables us to get rid of the identification of the system's parameters.

Furthermore, thanks to MATLAB / SIMULINK, we were able to observe and see through the application of the model-free control on our system that the mentioned before control is quite an interesting approach as it enables us to control our system. We have obtained a stable response in the output with a good precision and a fast response time.

This type of command is sturdy not only when it comes to disturbances but also when it comes to model's errors since it is not based on a mathematical model but is based on the good estimation of the derivatives which is reliable against noise filtering. This helps us to arrive to the conclusion that the model-free control guaranteed us the requirements of the specifications.

# *General conclusion*

## General conclusion:

Water resources are becoming more valuable as days pass since they have and are still affected negatively by pollution and climate change. It is, therefore, of crucial importance to look for innovative solutions to treat and reuse wastewater particularly in agricultural and industrial uses which are considered to be one of the biggest consumers of water.

The biological treatment of wastewater using aerobic or anaerobic digestion is one of the promising technologies that are knowing great attention. As the two methods were compared, the anaerobic digestion is seen to have more advantages compared to the other one and that is mainly because there are no power requirements for air supply, lower production of sludge requiring treatment and recovered biogas (methane) can be used for the production of energy.

The anaerobic digestion is a very complex biological process which involves microorganisms that evolve with time while feeding on the substrate and which can easily be destabilized. To avoid the process destabilization , it is vital to control it using a mathematical model that contains rich information about the main state variables and that describes their dynamic behavior well.

Multiple models were proposed for this type of digestion, however the AM2 model is considered to be the most suitable one for the control and observation purposes. In this master thesis, this mathematical model has been introduced in order to analyze and study its equilibrium and thus simulate the system behavior. An experimental dispositive was realized and a robust control was applied on the AM2 system.

Another type of control was offered called the model-free control which, as its name suggests, is a model that does not need to be calculated based on the system's model but uses only its input and output.

We have dedicated the first chapter to the introduction of the biological wastewater treatment using the anaerobic digestion. We presented of the advantages of this process and we were explained and detailed its stages (Hydrolysis, Acidogenesis, Acitogenesis and Methanogenesis).

In the second chapter, we introduced the AM2 model and made a detailled mathematical study of its equilibrium and their stability. This two-stages model (acidogenesis and methanogenesis) could have up to six equilibriums and it presents a global behavior of bistability. It can function around the inside operational equilibrium as well as the washout equilibrium. However, this

last behavior needs to be avoided in practice therefore the system needs to be supervised and controlled.

This was followed by the chapter which we dedicated most of our time as it is about the experiment. We have worked on realizing an anaerobic chemostat from scratch. We have detailed and explained every step taken in the conception of this laboratory bioreactor as well as the components chosen since unfortunately, we were limited to work with the components found at the university's laboratory and those we bought with our own means.

The last chapter focused on the development of a robust of control without using the system model, called the model-free control and its application on the AM2 system Our aim was to stabilize and optimize the biogas production using only input/output measurement, since we have not an appropriate model. Simulations results showed the efficiency of the developed control law, produced biogas best followed the set-point signal and, stability of the process was guaranteed.

Perspectives of this work include: 1) the instrumentation of the anaerobic chemostate with more sensors and actuators, especially peristaltic pumps, biogas and flow sensors, 2) data measurement of biogas, substrates and biomasses, 3) experimental implementation of the free-model control using input/output collected data and, 4) assembly of a laboratory benchmark to test more controllers in future.

# ***Appendix:***

- **The tension divider bridge**

```
int voltage = A0;

float R= 1000.0;
void setup() {
  /*pinMode(8, OUTPUT);*/
    Serial.begin(9600);
}

void loop() {
  float voltage = ((analogRead(A0)*5.0 )/ 1023.0);
float Rt =( ((5 * R)-( R * voltage))/(voltage ) );
float Temperature = (Rt- 100.0)/0.378;
  Serial.print( voltage);
Serial.print("v");
Serial.print(Rt);
Serial.print("ohm");
Serial.print( Temperature);
Serial.print("c");
Serial.println();
delay(2000);
}
```

- LM35:

```
#define sensorPin A0
void setup() {
 Serial.begin(9600);
}
void loop() {
int reading = analogRead(sensorPin);
float voltage = reading * (5000 / 1024.0);
float temperature = voltage / 10;
 Serial.print(temperature);
 Serial.println("C");
delay(1000); // wait a second between readings
}
```

- **Project circuit**:

```
#include <LiquidCrystal.h>
int sensorPin = 0;
int relay =13;
LiquidCrystal lcd(12, 11, 5, 4, 3, 2);
void setup() {
Serial.begin(9600);
pinMode(relay, OUTPUT);
}
void loop() {
  int reading = analogRead(sensorPin);
  float voltage = reading * 5.0;
  voltage /= 1024.0;
  Serial.print(voltage); Serial.println(" volts");
  float T = (voltage - 0.745) * 100;
   Serial.print(T); Serial.println(" degrees C");
  lcd.print("Temp = ");
  lcd.print(T);
  lcd.print(" C");
   if(T <= 32){
    digitalWrite(relay, HIGH);
```

```
  }
     else if(T >= 36){
   digitalWrite(relay, LOW);
  }
  else{
  }
// delay for the code
  delay(500);
  lcd.clear();
}
```

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