Reverse Flow Combustor Design for a Flexible Fuel Micro Gas Turbine

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Acknowledgments

This thesis aims to sustain the development of micro gas turbines in a context where fuel-flexibility, mainly the possibility of utilization of renewable fuels is foreseen; a plausible future.

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Juliano R. Pappalardo

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Abstract

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After the analysis of three tendencies in the energy field: substitution of liquid and solid fuels by gaseous fuels for electricity production; advent of distributed electricity generation; and the possibility of integration in fuel-cell hybrid systems for electricity production, the micro gas turbine comes as the most promising solution. Aiming at sustainable solutions, the micro gas turbine is intended for flexible fuel utilization, thus biogas is considered as well as natural gas.

Biogas is produced via anaerobic digestion, the main types of reactors and feedstock are discussed. The resulting biogas composition is presented and besides a composition of 60% methane, 40% carbon dioxide, the purification for utilization in gas turbines is also featured.

With the objective of designing a compact reverse flow annular combustor operating with lean pre-mixed flames (for reduced nitrogen oxides emissions), initially for a 100 kW micro gas turbine, a preliminary design phase has been carried out where the combustor main dimensions (diameters, lenghts and passage widths) were determined. Lately it was suggested by the research team the design of a similar combustor for a 1500 kW MGT, the preliminary design has been adapted and the refinement phase proceeded.

The design refinement perfomance targets are: low pattern factor (obtained with proper dilution jets positioning and flow rate); contained liner temperatures (obtained with proper positioning of the splash rings that provide cooling air films) and low total pressure losses (obtained with a constant optimization of flow passages, avoiding recirculation and stagnation zones). The combustor should also be able to burn biogas or natural gas with a flame that does not touch the combustor liner or interferes with liner cooling. CH_4 and CO emissions should also result low.

The design methodology of the refinement phase included four main subjects, the improvement of a feature in one of them usually has brought a beneficial aspect in another, these main subjects are: injector improvement (for proper fuel pre-mixing); primary zone flow adequacy (for proper flame positioning and reduced recirculation zones in the combustion chamber); cooling adequacy (for the liner temperatures lying below the safety value of 1150 K) and dilution adequacy (for the pattern factor shall lie below 0.21).

Tangential injectors were adopted since they allow for a compact combustor and a reduced number of injectors. The disposition adopted is three injector in an upstream plane (β_1) and three injectors in a downstream plane (β_2).

CFD simualations models used are: energy equation; Reynolds-Averaged Navier-Stokes (RANS) with $k - \epsilon$ realizable model (since it deals with the presence of flows with complex secondary features), turbulent kinetic energy production limiter (avoid buildup in stagnation zones) and use of standard wall function (which limits total number of cells in the domain); Species transport with volumetric reactions with the turbulence-chemistry interaction modeled using Finite-rate/Eddy-dissipation, the mechanism chosen was methane-air 2-step.

Simulations workflow consisted in non-reactive simulations where fuel-premixing in the injector could be studied and optimized followed by reactive simulations and reactive simulation with conjugate heat transfer analysis across the liner walls.

A detailed analysis of results (total pressure, velocity, equivalence ratio, rate of reaction and temperature fields) for natural gas and biogas utilization has been produced. The total number of different combustors geometries is sixty-one.

The final combustor model satisfies the project requirements in terms of performance and emissions while respecting the given geometric constrains (based on turbine dimensions) and boundary conditions.

Keywords: sustainability; biogas; flex-fuel; multi-fuel; gas turbine; micro gas turbine; reverse flow annular combustor

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Part I

Introduction

Chapter 1

Energy tendencies

> "The more we study the major problems of our time, the more we come to realize that they cannot be understood in isolation. They are systemic problems, which means that they are interconnected and interdependent."
>
> *Fritjof Capra, The Web of Life*

In this introductory chapter we will explore two tendencies: the Increased burning of gases instead of liquid or solid fuels for electricity production and the advent of Distributed Electricity Generation.

Afterwards we present the technologies in the energy sector that are aligned with both tendencies and we mention a third tendency related to hybrid systems to identify the most promising among such technologies, the micro gas turbines.

We end the chapter indicating the motivation for the development of Flexible Fuel Micro Gas Turbines.

1.1 Tendency 1: Gaseous fuels use instead of liquid or solid fuels for electricity production

Gaseous fuels have cleaner burning with also lower carbon dioxide emission than solid or liquid fuels. Coal is associated with higher levels of polutants'

emissions than Natural Gas because:

- Natural Gas burning is associated with lower sulfur dioxide emissions, since sulfur is present in small amounts in Natural gas than in Coal;

- Carbon monoxide is produced during incomplete combustion and therefore is associated predominantly to liquid or solid fuels, Natural Gas emissions of CO is minimal;

- Liquid and solid fuels are also associated with Particulate Matter emissions which is null for the case of Natural Gas;

- Hydrogen fluoride is emitted in most coal burning sites, it is not emitted during Natural Gas burning since it does not contain fluorine;

- If present, mercury can be removed from natural gas prior to combustion, but it cannot be removed from the coal matrix.

With regards to global warming, natural gas emits lower amounts of carbon dioxide per unit of energy release. It can be verified by analyzing the stoichiometric combustion of methane (CH_4) (main constituent of Natural Gas), diesel[1] and coal[2] with oxygen. Such reactions and respective Lower Heating Values (LHV[3]) are shown below:

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[1]Among all liquid fuels, diesel is foreseen to show the highest increase in consumption during the period 2012 to 2040 (including biodiesel).[33] We assume the diesel to be composed solely by decane whose chemical formula is $C_{10}H_{22}$.

[2]Anthracite and bituminous coal account for most of the world's estimated recoverable coal reserves on a tonnage basis.[33] These coals have the highest percentage of carbon content, such that the chemical formula is approximated by pure carbon.

[3]Enthalpy of combustion is the amount of heat released from the system when 1 kmol of fuel is burned completely in a specified state (usually the standard state of $25°C$ and 1 atm) and products are brought to the same state. It is given by the formula $h_c = H_{prod} - H_{reac}$ where H is the sum of enthalpy of formation at standard state $(\bar{h}_f^\circ)$ and the sensible enthalpy relative to the standard reference state $(\bar{h} - \bar{h}^\circ)$. Assuming that water in the products is in vapor phase, the enthalpy of combustion subtracted the latent heat of the mass of water in the products at the combustion chamber temperature is called Lower Heating Value (LHV).[29]
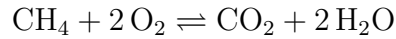
$$\mathrm{CH_4 + 2\,O_2 \rightleftharpoons CO_2 + 2\,H_2O}$$
$$LHV = 800.80 MJ/kmol_{\mathrm{CH_4}}$$
$$\mathrm{C_{10}H_{22} + 15.5\,O_2 \rightleftharpoons 10\,CO_2 + 11\,H_2O}$$
$$LHV = 6282.08 MJ/kmol_{\mathrm{C_{10}H_{22}}}$$
$$\mathrm{C + O_2 \rightleftharpoons CO_2}$$
$$LHV = 393.60 MJ/kmol_{\mathrm{C}}$$
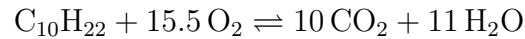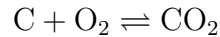
It's easy to verify that to obtain $1GJ$ of energy it's necessary $1.25kmol$ of methane, $0.16kmol$ of diesel or $2.54kmol$ of coal. Multiplying these values by the number of moles of carbon dioxide produced in each equation it's possible to see that to obtain such amount of energy, $1.25kmol$, $1.6kmol$ or $2.54kmol$ of CO_2 would be released. For this reason gaseous fuels, mainly natural gas, is usually preferred to coal or diesel, the main representatives of solid and liquid fossil fuels.

Other advantages of the use of Natural Gas instead of Coal are:

- Gaseous fuels can be produced from solid fuels with a certain conversion efficiency, the opposite doesn't apply;

- Power plants relying on gas are less expensive, faster to install and allow high efficient arrangements than coal-fired power plants;

1.2   Tendency 2: Advent of Distributed Electricity Generation

The second tendency is the advent of Distributed (Electricity) Generation promoted by the evolution of Local Economy[4] and the increased use of Renewable Sources.

1.2.1   Increased Use of Renewable sources

Along the centuries, human settlements became denser and larger not only due to mechanization of agriculture, but also because fossil fuels were used for electricity production. Such fuels have very high energy densities and therefore can be transported to power plants with relative easiness. Such power plants are usually located

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[4]Local Economy is an alternative to the centralized economy. In the local economy perspective, people prefer to spend their money in local products or services, giving attention to local producers.

far from urban areas and the electricity is distributed in a centralized way to increasingly dense and large urban areas.

New urban settlements that consider the use of renewable energy sources must be concerned about their inherently low power densities.

Inherently low power densities of RES   Figure 1.1 shows the ranges of power densities and sizes of claimed area by power conversion systems and end users. Some useful information can be extracted, for example, since the only renewable energy that can be installed together with the end user and hence claiming no further land are flat plate collectors and photovoltaics because they can be installed on roof tops. If photovoltaics become cheap enough such that its size range moves to the right in the diagram, they could supply the whole energy demand of a considerable range of houses. At present, flat plate collectors can supply the entire heat demand of a range of houses and a limited range of industries. Cities are composed by houses, supermarkets and high-rises each one having a power density and size range; many people live or work in high-rises and power densities become incompatible with flat plate collectors; supermarkets would have to reduce their power consumption to be supplied by flat plate collectors or photovoltaics. The overall power density required ranges from $6 - 10W/m^2$ in uncrowded low income cities to about $100 - 150W/m^2$ in affluent crowded megacities.

Any other energy conversion rather than flat plate collectors or photovoltaics will claim certain additional land[5].

All renewable resources are represented by light gray rectangles located in the bottom part of the diagram, showing they have low power densities.

Thermal power plants include coal, oil and gas fired plants and also nuclear power plants (i.e. all non-renewable sources). In coal fired power plants the power density range depends on electrical output of the plant, on the land occupied by it (boiler, generation buildings, cooling towers, switch-yard and eventual on-site coal storage), but also on energy content of coal, the type of mining (strip mining and underground mining claim different extensions of land and leave spoil banks with different sizes as well), the proximity of the extraction mine to the power plant (the area of eventual pipelines to carry coal sludge or dedicated railroad to carry processed coal must be accounted) and the necessity or not for building new High Voltage Transmission

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[5]For example, phytomass power density is a fuel power density. According to Vaclav Smil: "Most forests store no more than $200t$ of phytomass per hectare ($20kg/m^2$) and so even if all of it could be harvested, the yield would be more than $300MJ/m^2$. Because a clear-cut forest may take between 50–100 years to return to its pre-harvest state, the power density of wood harvests must be calculated by dividing the energy total by the time it takes to regenerate the phytomass. [...] the actual sustainable power density of wood harvests would be merely $0.2W/m^2$.[50]

Lines into which the electricity will be injected. If all these factors are favorable then power density ranges from $1000 - 3000W/m^2$; otherwise, power density of electricity coming from coal power plants ranges from $100 - 500W/m^2$, approaching that of best photovoltaics in sunny conditions, but still relatively high.[50]

If forecasts are correct and, indeed, the use of renewables increases, large areas must be claimed. Renewable energy production takes place evenly throughout its claimed area, rather than in a centralized plant. It seems therefore more viable to decentralize electricity production and allow Distributed Generation of power in smaller amounts to satisfy local needs.[6]

It is opportune to start next section with a definition of Distributed Generation and then describe how Centralized Electricity Production became mature, is having its drawbacks exposed and is giving space for the complementary Distributed Generation.

1.2.2 Distributed Generation

According to the European Directive 2009/72/CE: " 'distributed generation' means generation plants connected to the distribution system.". In turn, "'distribution' means the transport of electricity on high-voltage, medium-voltage and low-voltage distribution systems with a view to its delivery to customers, but does not include supply.".[47] In other words, Distributed generation occurs simply when generation plants are connected directly to the customers through a distribution line.

Centralized Generation of electricity (CG) has reached its maturity and drawbacks are being increasingly exposed. In addition, recent deregulation of the electricity market and new technologies favor its counter-part, the Distributed Generation of electricity (DG).

Maturity of CG For many decades, generation cost could be reduced by simply increasing the size of turbines,[7] the larger amount of power produced came with relatively low extra cost. In addition, larger machines do offer better efficiencies than smaller ones. However, steam and gas turbines seem to be close to the size limit. Efficiency increase in bulk electricity production (CG) can be attained with

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[6]Whenever possible, dense settlements should be surrounded by wind-farms, located close to small rivers from which hydrogeneration is forecast to increase in many countries (including Brazil), as well as having enough solar panels (either photovoltaics or flat plate collectors) and a Integrated Waste Management (IWM) focused on turning agricultural, industrial or urban organic wastes into energy (biogas or bioliquids). See chapter 2.

[7]Usually steam turbines.
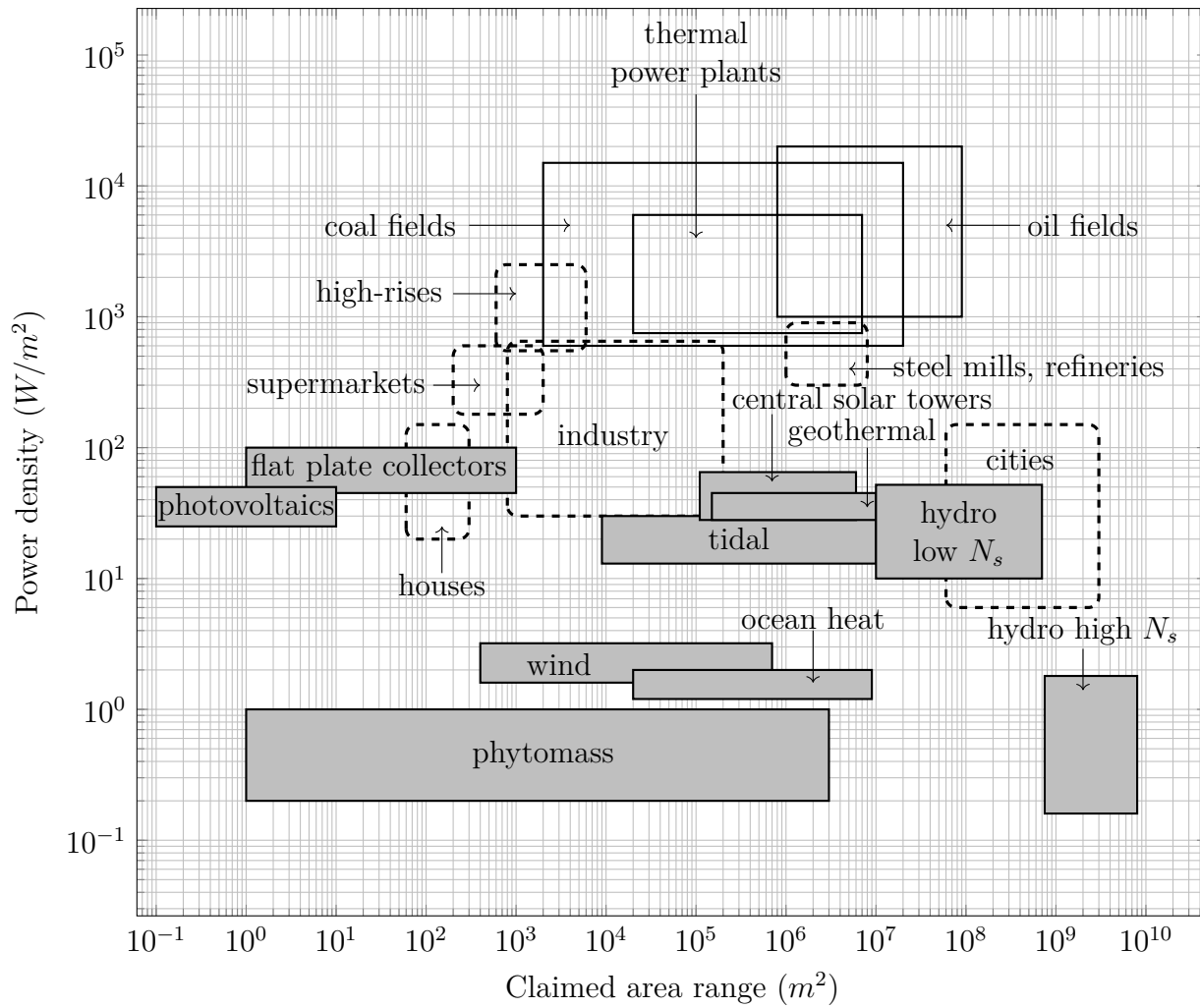
Figure 1.1: Claimed area *vs* power densities of thermal power plants, renewable energy conversions (including power density of coal and oil extraction) and of final energy uses. N_s is the specific speed of hydro-power plants. (Source: adapted from [50])

Combined Cycles, development of new materials and production techniques or improvements in aero-thermodynamics of components. In any case, the achievement of a size limit is a sign of maturity of the CG scheme, DG on the other hand can offer gains in efficiency through co-generation[8], in particular with CHP generation[9]. In CHP, heat is not produced using a dedicated boiler but using the rejected heat from the heat engine that is producing electricity and must be located as close as possible to the end-users since, due to heat losses, steam cannot be transmitted through long distances as electricity does.

When the large power plants were planned they were usually located far from cities which has been a solution for local environmental pollution, but now the concept of "moving outside (or out-sight)" is controversial since pollution has become a continental or even a global concern. That's another sign of the maturity of centralized generation, there is no much place left to "hide" bulk power plants. The use of renewable energy sources mitigates pollution problems, suggests the adoption of Distributed Generation and also promotes the concept of energy security[10].

Transmission & Distribution Losses   The main drawback of the centralized generation system is related to losses due to transmission and distribution of electricity along long networks. These losses, called Joule losses[11], can be reduced by upgrading transmission lines, power transformers, insulation or monitoring systems; by improving electric power dispatch planning and maintenance practices; and by modernizing metering systems. In addition, if part of the electricity demand is offered by Distribution Generation, such losses are also reduced since generating units are located much closer to end-users. In the OECD members, about $6-8\%$ of electricity produced in 2013 was lost in transmission and distribution. In non-OECD members, in the same year losses were about 10%.[33]

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[8]Simultaneous production of at least two useful energies.

[9]Combined Heat and Power generation (CHP) is the most common type of co-generation. It is the simultaneous production of electrical energy and thermal energy (hot water, steam or superheated steam) using the recovery of heat rejected form a heat engine cycle. Such heat can be used as energy source to cool air in absorption refrigeration systems, which may be more interesting in tropical localities.

[10]The International Energy Agency defines energy security as the uninterrupted availability of energy sources at an affordable price. Energy security has many aspects: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance.

[11]The Joule effect is the dissipation of active power into heat when current flows through a conductor or equipment possessing certain electrical resistances.

Deregulation of electricity market   Historically, monopolies (both privately or publicly regulated) controlled regionally the generation, transmission, distribution and retail of electricity to users. In some instances the distribution could be handled by different companies. In any case, vertically integrated monopolies were the norm. During this period, the availability of electricity increased unprecedentedly and reliability reached very high levels. Nonetheless, some economists said that the monopoly status of the electric utilities removed the incentive to operate efficiently and encouraged unnecessary investments.[40] They suggested that electricity prices would be lower and that the economy as a whole would benefit if the electricity was treated as a commodity and traded in the free market. Despite the complexity, the electricity provision could be deregulated following similar patterns in many western countries. New generation companies (GENCOS), transmission companies (TRANSCOS), distribution companies (DISCOS) and retailers could participate in more competitive models which may vary from the least deregulated - traditional monopoly vertically integrated utility - to the most deregulated, where small consumers can choose the retailers from which they buy electricity.[12]

Regarding eventual growing demand, in a monopoly the utility tends to overestimate the capacity needed to be installed, the customers usually pay for such unnecessary investments. On the other hand in a competitive scenario the generating companies forecast individually the capacity grow and carefully make investments, since it is their onus if unnecessary investments are made. In a monopoly, the transmission and distribution network could grow theoretically in a synchronized way to match the growing generating capacity. That's because the same company owns the generation units and transmission and distribution network. However, in the competitive scenario, the capacity growth projected by the GENCOS in not known years in advance by the TRANSCOS and a mismatch in capacity or location of transmission lines risk to happen.

GENCOS operating in a competitive market invest wisely in maintenance and upgrade policies such that the reliability attained with the previous monopolistic model is kept at high levels. For the same reason generation efficiency is presumably higher than in the monopoly scheme, however the maintenance of other system elements such as transmission lines, transformer and distribution lines are not synchronized anymore with power plant maintenance and losses due to congestion may

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[12]The different deregulated models or schemes denotes that the deregulation process occurs from the producer to the consumer level. The most simple deregulated model shows different GENCOS competing to supply to the, still centralized, wholesale purchasing agency from which all DISCOS forcibly buy. A more deregulated model shows DISCOS purchasing the electrical energy directly from the GENCOS in a wholesale market which takes the form of a pool or of bilateral transactions intermediate by an Independent System Operator which controls the transmission lines.[40]

reduce the system's overall efficiency. If the gains in efficiency of the deregulated electricity market compensate or the overall efficiency losses is still to be proved.[40]

The Distributed Generation benefits directly from the deregulation of electricity supply because it invites many small GENCOS to participate, which in some instances can act also as consumers. Electricity's share of residential sector energy consumption is predicted to grow from 61 percent in 2012 to 75 percent in 2040.[33] This forecast reflects that such demand can promote and benefit from DG from units located in residential areas. Furthermore, many rural areas wait for electrification in an attempt to promote better quality of life (DG is more suitable for rural electrification than CG).

New technologies   After the introduction of power electronics, asynchronous generation (present in substantial part of wind turbines) and direct current generation (present in photovoltaics and fuel cells) could be converted into alternate current with the proper grid frequency. This allowed recent renewable sources and/or smaller generator to provide part of electricity demand into the grid according to the DG scheme (connection of generators directly in the distribution network).

In the centralized, traditionally monopolistic, scheme for electricity production there are many large synchronous machines. Their rotational speed is carefully controlled in order to keep the grid frequency in an admissible range ($\pm 1\%$). This means that synchronous generation units rather than providing energy, provide also ancillary services[13]. Power electronics allow DG direct current or asynchronous speed generators to provide part of these ancillary services, for example: photovoltaics can aid Power Factor regulation and micro gas turbines reaching nominal power in a relative short-time can provide non-spinning reserve[14]. Other technologies allowed the lines to carry electricity in both directions, for example two-way transformers, they also promote the spread of DG.

Increasingly cheaper and accessible information and communication technologies (mainly composed by monitoring tools and sensors) allow remote monitoring, control and optimization of dispatches in microgrids[15] in what's called *smart-grids*. Micro-

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[13]Services that ensure reliability and support the transmission of electricity from generation sites to customer loads. Such services may include load regulation, spinning reserve, non-spinning reserve, replacement reserve, and voltage support. (Source: U.S. Energy Information Administration on-line glossary)

[14]The non-spinning reserve or supplemental reserve is the extra generating capacity that is not currently connected to the system but can be brought online after a short delay. In isolated power systems, this typically equates to the power available from fast-start generators.(Source: Wikipedia)

[15]An electricity grid system of electricity wires for a small area, not connected to a country's main electrical grid. (Source: Cambridge Dictionary)

and smart-grids are forming the knowledge bases for the expansion into Distributed Generation.

From an investor point of view, considering all the favorable scenario mentioned, the Distributed Generation represents a low risk investment. To guarantee that, the European Parliament and The Council of the European Union in the Directive 2009/72/CE determine that in order to "ensure effective market access for all market players, including new entrants, non-discriminatory and cost-reflective balancing mechanisms are necessary". Such balancing mechanisms are seen by the parliament and council as necessary until the electricity market is "sufficiently liquid", they include incentives and balancing tariffs and must be implemented by national regulatory authorities.

Brazilian scenarios In Brazil, in December 2015 a program for the development of distributed electricity generation was created ("Programa de Desenvolvimento da Geração Distribuída de Energia Elétrica - ProGD"). It aims at promoting the increase and implementation of distributed generation of electricity based on renewable sources or co-generation in public buildings (such as schools, universities and hospitals[16].), commercial buildings, industries and residences.[44]

According to the Brazilian Distributed Generation legislation, when a DG consumer produces (prosumer) and injects electricity into the grid he receives credits that can be used to pay electricity bills up to five years ahead or in his other properties. He does not receive money for such service. The literal translation of this system is "electrical energy compensation system". The prosumers are taxed only with respect to the net energy obtained from the grid. The ProDG directive introduced an important advantage: prosumers can form consortia or cooperatives, i.e. interested producers can gather in cooperatives or consortia to be able to participate in the scheme. A cooperative of producing pork meat or milk that has high biogas production potential could use micro gas turbines and benefit from this idea.

The ProDG program doesn't restrict the energy source used for DG, however, in 2016, the ProDG favored the importation of photovoltaics panels reducing the import taxes of related equipments. Notwithstanding, the internal market for other renewable sources can benefit from other politics, for example the BNDES responsible for financing large infrastructure projects in Brazil, including those for increasing the electrical installed capacity, has changed its criteria for accreditation of wind turbine equipment producers. After December 2012 the nacelle[17] and the hub have to be, at

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[16]The "National Bank for Social Development" (BNDES) was authorized to loan money with special rates to projects aimed at energy efficiency and Distributed Generation using renewable sources in public schools and hospitals (Law 13.203/15).

[17]Housing for the drive-train components of a wind turbine.

least, assembled in Brazil. Such new methodology has benefited the Brazilian wind sector, helping to create job opportunities.

As mentioned before, the ProDG favors also co-generation in Brazil. That is an important finding because when we consider the technologies that are aligned with both tendencies shown in this Chapter: "Gaseous fuels use instead of liquids or solid fuels" and the "Advent of Distributed Generation" and use a third tendency to identify which technology is the most suitable, the micro gas turbine comes as the most promising solution. They can operate in co-generative mode and benefit directly from ProDG program. Additionally, if micro gas turbines are designed to be able to burn biogas (fuel-flexibility) they can indirectly benefit from the recent National Policy on Solid Waste.

Such policy issued in Brazil imposes that open dumps be banned and public waste receives an adequate final destination. As "adequate final destination", the Brazilian policy defines as: "destination of residues that includes re-utilization, composting, the recuperation and energetic recovery or other admissible, previously authorized, destinations".[27] Brazil has 5564 municipalities and this policy promotes the investment in machinery and equipment used in the recycling process, reverse logistics systems[18] and landfills. The Department of Industrial Competitiveness of the Ministry of Development, Industry and Trade (MDIC) is in charge of the policy implementation, according to them, it includes the industrial design for waste reduction and non-generation, anaerobic digestion and plasma arc gasification technologies, mechanical sorting facilities for recyclables, and integrated municipal waste management strategies.

Energy recovery from Municipal Solid Wastes (MSW) can be done through landfill anaerobic digestion, dedicated anaerobic digesters, gasification or incineration (i.e. combustion). Regarding such recovery in Brazil, the national policy states that: "Technologies for energetic recovery of Municipal Solid Wastes can be used, given that the technical and environmental viability be demonstrated and that the toxic gases monitoring program approved by the environmental department be implemented."[27]

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[18]In Brazil, the producers, importers, distributors and retailers of some products are obliged to collect them back (using a reverse logistics system whose project and development is their responsibility) from the user. Such products are: Agrochemicals and containers thereof, batteries, tires, lubricant oils and containers thereof, fluorescent lamps, sodium or mercury vapor lamps and mixed, electronic products and their components.[27]

1.3 Technologies aligned with the Tendencies

Considered together, these tendencies indicate the development of gas burning conversion machines of small size. Up to date, the two promising options are: internal combustion engines (ICE) operating at Otto cycle and Micro Gas Turbines (MGT).

MGT are considered to be more expensive than ICE and may present lower electrical efficiency. However, in comparison to ICE of the same electrical power, MGT require less maintenance and operate at lower noise level, basically due to less moving parts. For this same reason, MGT dissipates less heat to the surroundings and thus its exhaust gases besides flowing at steady state (rather than intermittent which is the case in ICE) have higher enthalpy than ICE. Further, MGT are lighter and have probably lower footprint and are more fuel flexible than ICE, being able to use usual fuels (such as natural gas, propane and oil) or alternative fuels such as heavy oils, biodiesel, liquid gas, synthetic gas or biogas.

1.3.1 The third Tendency: Hydrogen economy

If we consider the future establishment of a hydrogen economy as a third tendency and regard electricity production using fuel cell hybrid systems, MGT remain as the most promising solution. That's because fuel cells work at steady state, supplying a continuous exhaust stream coming from the cathode. In high temperature fuel cells (MCFC or SOFC for example) such stream is considerably hot and can be expanded (steadily) in a gas turbine, or having the heat exchanged (steadily as well) with the stream coming from the compressor. In this context, fuel cells besides supplying direct electric current can be compared to combustion chambers: they are adiabatic, supply heat steadily but present a certain pressure drop. ICE are reciprocating engines that inherently work in non-steady flow, hence not applicable for such hybrid systems applications.

1.4 Sustainably obtained Renewable Fuels: the choice for biogas

Whenever the cost of electricity decreases as the conversion efficiency is improved, the demand for it tends to increase (as a consequence of the "law of demand"), consequently the resources are depleted in a faster rate,[19] as we hypothesize free market and absence of taxation by the government.[51]

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[19]Historically two evidences of this phenomenon could be observed: First, in 2005, the average American passenger vehicle (including SUVs) consumed about forty per cent less fuel per kilometer

Considering these effects, any fuel being used in a MGT will be depleted faster as the MGT efficiency is improved. In any case, if the MGT burns sustainable obtained biogas, the faster depletion of the fuel as a consequence of improvements in the MGT efficiency is not an issue, since the biogas is also renewable. This holds true for any bio-fuel and motivates the improvement of flexible fuel micro gas turbines.

We proceed with a discussion on the basics of anaerobic digestion, the process that yields biogas from nutrient rich biomass.

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than in 1960, but more widespread ownership of automobiles (two people per vehicle in 2005, compared to nearly three in 1970) and the higher annual average distance driven (roughly 20000 km, compared to 15000 km in 1960) resulted in an average per caput consumption some thirty per cent higher. Second, during the twentieth century, the efficiency of British public street lighting rose about twenty-fold, but the intensity of this illumination (MWh per km of road) rose about twenty-five times, again more than eliminating all efficiency gains.[51] These observations gave rise to the Jevon's Paradox.

Part II

Chemistry

Chapter 2

Anaerobic Digestion - Biogas production

Biogas is associated with higher conversion efficiency if compared to syngas originated from gasification of biomass. Furthermore conversion equipment requires less skilled operators and are less expensive. Therefore, focus in this chapter will be given to Anaerobic Digestion process and the supply of biogas to a MGT.

Firstly we present the relevant substrates indicating the respective possible methane content (biogas quality) and yields of biogas. Most of them have relevance in Brazil, specially coming from agriculture and food industry, some others are relevant in beer producing countries (such as Spain, UK, Germany and Denmark) and others in olive-oil producing countries (such as Spain and Italy). Some of these substrates including sewage and the organic fraction of municipal solid waste can be treated anaerobically in any country with the benefit of biogas production, this seems to be currently done in Denmark.

Afterwards, we discuss the reactor technologies usually applied to digest the substrates. In the last sections we present the biogas general characteristics that make it suitable for use in a gas turbine and the common treatments to which the raw biogas is subjected prior to the utilization in a MGT.

We note that an economical viability analysis could consider heat and electricity demand of the overall anaerobic digestion process. Henceforth, the biogas produced in some of these treatments could be utilized in a flexible fuel MGT for co-generation of electricity and heat with economical gains.

2.1 Substrates

We review some basic anaerobic digestion concepts and present the residues and effluents commonly treated via anaerobic digestion in four economic sectors in Brazil (agriculture, food industry, Municipal Solid Waste disposal and sewage treatment).

The methane content in the biogas (a.k.a. the biogas quality) is the single parameter that will be used directly in the design of the combustor for the MGT, it is therefore of utmost importance [1]. The biogas yield for each substrate is shown in convenient units that could provide a basis for an eventual economic viability study.

2.1.1 Basics of Anaerobic Digestion

Given that a proper set of microorganisms and nutrients (carbohydrates, proteins, lipids) are well mixed and that proper conditions (oxygen concentration, pH, temperature, humidity, etc.) are provided, the nutrients will be converted into biogas, a gaseous fuel containing substantially methane (the fuel) and carbon dioxide (an inert gas).

Recall that the process is divided in four consecutive *phases* (Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis) where the products of a set of microorganisms is the substrate for the next group of microbes. Figure 2.1 shows these phases, the types of microorganisms participating, the subtrates used, intermediate and final products. It also shows that two methane formation inhibitor can be formed: hydrogen sulfide (H_2S) and ammonia (NH_3).

The various molecules that can be present in the substrate have different oxidation numbers. Figure 2.2 indicates the methane content expected in the biogas based on different substrate molecules. Fats usually have the lowest oxidation number if compared to proteins and carbohydrates that have the highest oxidation number among the three. This explains why biomass rich in fats produce biogas with the highest methane content and carbohydrate rich matter the lowest biogas quality.

The gas yield is generally higher for fats, followed by carbohydrates and proteins. Common substrates treated with AD are a mixture of these types of nutrients' molecules [2].

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[1] Methane content can be experimentally determined using chromatography in gaseous phase using nitrogen gas (N_2) as the mobile phase.

[2] The knowledge of substrate composition in terms of proteins, fats and carbohydrates becomes important when the gas composition needs to be corrected. Too much proteins may cause excessive ammonia or hydrogen sulfide formation and fats can cause the formation of too much fatty acids, all these components have inhibitory effects. Other relationships are given more precisely in literature. These considerations must be done when the substrate is being corrected with nutrients or when co-substrates are being selected for improving the digestion of the substrate.
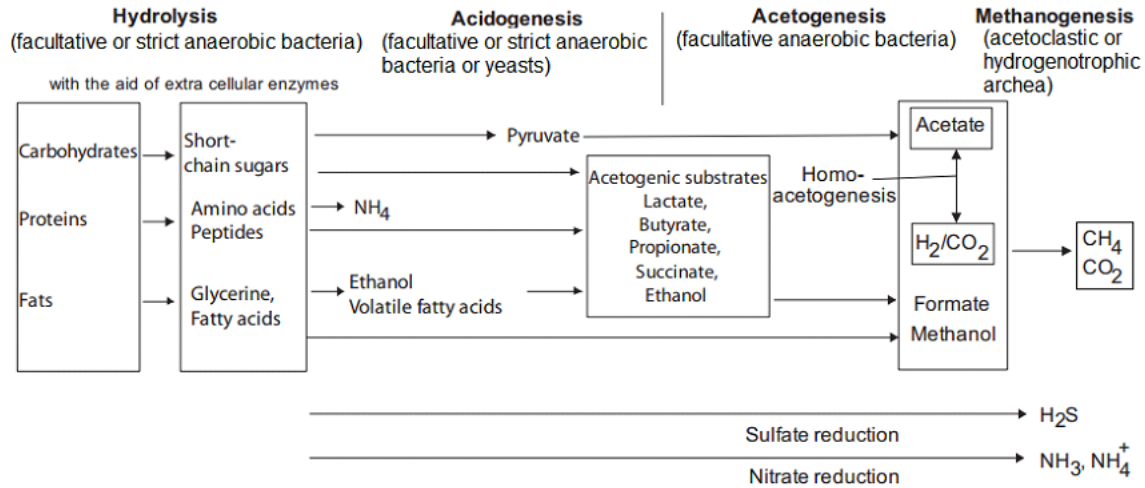
Figure 2.1: Anaerobic digestion steps, substrates, intermediate and final products (Source: Adapted from [49])
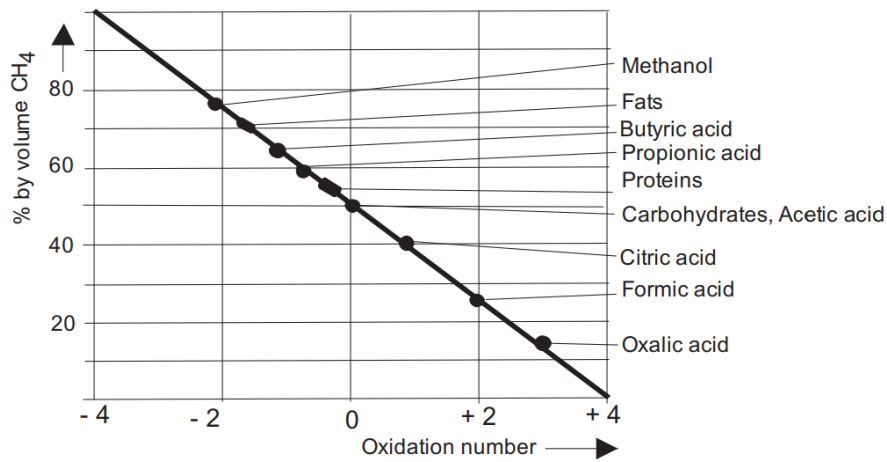
Figure 2.2: Correlation between methane content in biogas and oxidation number of molecules eventually in the substrate (Source: [49])

The solid by-product of AD is called digestate and can be dried, have the pathogens killed and the nutrients eventually corrected for posterior utilization as biofertilizer.

2.1.2 Proper units for comparison of residues

Humid residues   If the residue has a concentration of suspended or dissolved solids higher than $0.3 \, \text{g l}^{-1}$, it is designated as a humid residue. It's common practice in the field of anaerobic digestion to characterize a humid residue containing suspended or dissolved solids based on total solids fraction (TS) and on volatile solids fraction (VS) instead on proteins, fat or carbohydrates content[3][4]. The knowledge of TS of a particular substrate is the prime parameter in the choice of reactor type for anaerobic digestion (see Section 2.2). In addition, the biogas production potential is directly proportional to the VS content of the substrate and thus commonly used in the denominator of yield expression (Nm^3/t_{VS}), while biogas quality depends on substrate chemical composition (Figure 2.2).

It is important to note that the microorganisms acting during AD will degrade only part of the volatile solid fraction (BS, Biodegradable solid fraction), the fraction of volatile solids that does not decompose is called recalcitrant fraction (RS) which is large or small depending on the amount of recalcitrant substances present, for example lignin, the main constituent of woody matter. This recalcitrant fraction can be determined only through experiments. The fraction that remained in the total solid sample after the 550 °C heating is called fixed solid fraction (FS) and is composed mainly by mineral and inert substances. Figure 2.3 illustrates the subdivision of the humid residue.

Too humid residues (Effluents)   If the residue has a concentration of suspended or dissolved solids lower than $0.3 \, \text{g L}^{-1}$, it is designated as an effluent and it is usual to consider that the biogas yield potential is proportional to the Chemical Oxygen Demand of the effluent instead of the VS content[5]. The main objective of a sewage or waster water treatment plant (be it a municipal or industrial plant) is to decrease the COD to acceptable legal levels. Most sewage treatment plants use anaerobic digestion systems to accomplish part of this task. Biogas has always been produced in the process but just in the last years attention was given to its economic utilization. The

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[3]TS is determined after drying the sample at 103 °C to 105 °C for at least 12 hours.

[4]VS is determined when the total solid sample has been heated at 550 °C for 2 hours, after this procedure the VS fraction has be volatilized.

[5]The COD is defined by the U.S. Environmental Protection Agency (EPA) as a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant, usually reported as mg_{O_2}/L.
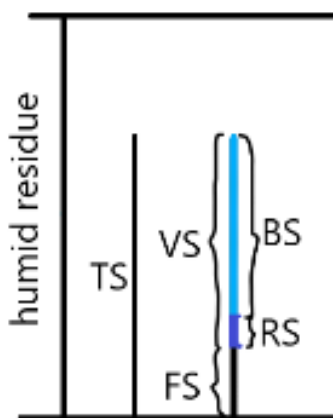
Figure 2.3: Humid residue and its fractions

food industry sector produces part of its residues as effluents and the vast majority of sewage produced in the world is sent to treatment plants as effluents. Similarly to the degradation of volatile solids, not all the organic matter in the effluent can be converted into biogas, and a measure of the yield of biogas is usually given on the basis of COD actually removed from the effluent ($Nm^3/t_{CODremoved}$).

The objective of this Section is to gain insight on the biogas yield and quality deriving from common substrates treated anaerobically in different relevant economic sectors in Brazil. For this reason, the biogas yields are indicated as $Nm^3/t_{substrate}$ for all humid residues and as $Nm^3/hab \cdot day$ for effluents[6].

2.1.3 Co-digestion

Some examples illustrate the interconnection between the substrate, microorganisms present (hardly controllable) and biogas composition. Formation of H_2S depends on two factors: presence of sulfur rich organic matter such as proteins and presence of Sulfate - reducing bacteria[7]. Excreta from poultry can provide the substrates for the excessive formation of ammonia NH_3. As a rule of thumb, substrates with a too

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[6]The yield given as Nm^3/t_{VS} or $Nm^3/t_{CODremoved}$ could be useful from a process point of view. It can be determined knowing the biogas yield in $Nm^3/t_{substrate}$, the total solids content (TS [%]) with respect to the mass of the humid residue (the remaining part being water) and the ratio of volatile solids to total solids (VS/TS [%]).

[7]Hydrogen sulfide, or sulphuric acid formed during combustion can cause corrosion in downstream equipment in a biogas utilization plant.

low C:N ratio lead to increased ammonia production. Despite the inhibitor effect, whenever sulfate or nitrogen is reduced, less hydrogen is available for methanogens to produce methane.

Co-digestion is the digestion of a co-substrate together with the main substrate in the same reactor. One of the functions of co-digestion is regulating the formation of the inhibitors mentioned above. The advantages of co-digestion include:

- Toxic effects of some substrates (e.g.: from pharmaceutical industry, or antibiotics used in cattle creation) can be eliminated [9];

- Buffering capacity (neutralization in case of over acidification) increases [9];

- The viscosity of the residue may reduce, which decreases pumping and mixing costs;

- Some substrates are seasonal, by using co-substrates (e.g.: silage or manure) found nearby and with biochemical affinity, the biogas production can be performed continuously [9];

- Increase biogas yield and reduce lag phase time [31];

- Nutrients content (specially C:N ratio) are corrected, avoiding formation of inhibitors such as H_2S and NH_3, as said before [49].

2.1.4 Biogas data

Agriculture

The residues coming from agriculture are divided in crop residues and animal manure, they contain high energy content, specially based on carbohydrates (Table 2.1).

Table 2.1: Agricultural residues and respective biogas yield and quality

Substrate	TS [%]	VS/TS [%]	Gas yield $[Nm^3/t_{substrate}]$	Quality $[\%CH_4]$	Ref.
Agriculture residues					
Wheat straw	86	92	292	50.8	[41]
Corn - green leftovers	35	92	157.6	51.5	[41]
Potatoes harvest residues	22	94	150.1	51.5	[41]
Corn silage¹	33	96	185.3	52.2	[41]
Grass silage¹	40	90	208.3	54.1	[41]
Banana stalk	8	81	49	65	[13]
Banana peels	12	89	87	65	[13]
Sugar-beet	23	91.9	147	50.8	[41]
Sugar-beet leaves	16	83	85.1	53.7	[41]
Forb plants²	17.3	89	90.4	60	[31]
Grass inocula³	3.1	77.4	5.2	57.5	[31]
Soy bean hulls	90	95.1	516.7	52.7	[41]
Animal residues					
Dairy cattle manure (with fodder residues)	8.5	85	25.3	55	[41]
Cattle manure	10	85	34	55	"
Pig manure	6	85	20.4	60	"
	22.5	82.5	74.3	60	"
Poultry manure	15	75	53.6	65	"

1 Silage is fermented, high-moisture stored fodder which can be fed to cattle, sheep and other ruminants or used as a biofuel feedstock for anaerobic digesters.

2 Co-digestion of a mixture containing 30% rye grass 30% white clover 20% chicory and 20% plantain with grass inocula.

3 Inocula are necessary to supply the substrate with active microorganisms. Its biogas yield is relatively low because of the advanced stage of biodegradation.

4 In $Nm^3/m^3_{substrate}$.

Food industry

Residues coming from food industry are divided according to their humidity in humid residues and effluents.

Humid residues An industrial residue can be considered humid if its TS content is higher than $0.3\,\mathrm{g\,L^{-1}}$ and effluent on the contrary. Table 2.2 shows food industry residues with their respective biogas yield and quality.

Table 2.2: Food industry residues and respective biogas yield and quality

Substrate	TS [%]	VS/TS [%]	Gas yield $[Nm^3/t_{substrate}]$	Quality $[\%CH_4]$	Ref.
Vegetable origin					
Brewery used grains	24	95.5	122.2	59.3	[41]
Potato pulp pressed	25	94	143.3	50	"
Palm kernel residues from oil extraction	88.6	95.7	499.1	54.2	"
Coconut residues from oil extraction	89.4	92.5	542.2	55.4	"
Soybean residues from oil extraction	87	93.1	546.6	60	"
Sunflower cake (residues from oil extraction)	89.4	91.9	488.2	61.3	"
Olive pomace (residues from oil extraction)	10	83	5.11[1]	79.5	[15]
Animal origin					
Rumen content	15	84	60.5	55	[41]

1 In $Nm^3/m^3_{substrate}$.

Effluents Among the industrial effluents, special attention is given here to sugar cane vinasse and brewery wastewater. Vinasse is the wastewater from ethanol production it is produced in large amounts in Brazil and is usually used directly as fertilizer, without energetic recovery, this is associated with a series of environmental impacts on the soil, water bodies and on the sugarcane crop itself.

Sugar cane vinasse can be treated anaerobically by the use of up-flow anaerobic sludge blanket (UASB) reactors in a single stage or in two stage operation (with two reactors) for better conversion efficiency. It was showed that a two-stage opera-

tion was able to remove 63% of COD in the vinasse and produce biogas with yield $3.66 Nm^3/m^3_{vinasse}$ with 75.9% of methane [5].

An example of large scale treatment of brewery waste water in South-Africa shows that 77.2% of COD can be removed from the effluent. In the processes, biogas is produced with 65.9% of methane and yields range from $0.37 Nm^3/m^3_{effluent}$ to $2.04 Nm^3/m^3_{effluent}$ depending on a series of operational factors including the hydraulic retention time (HRT) [6]. Such parameter will be explained in Section 2.2.

Municipal waste management

The next sector of interest is the Municipal Solid Waste (MSW) disposal. Such residues are ideally separated in recyclable fraction (which may be sent to the beginning of production chain), organic fraction which should be recycled energetically and undifferentiated fraction[8]. Only the undifferentiated fraction should end up in landfills. The energetic recycling of organic residues and material recycling of recyclable residues helps to increase the life-time of landfills and keep their number as low as possible. However, in many locations part of the waste sent to landfills still contains recyclable materials or organic waste. The landfill gas naturally produced through AD is a diffuse source and requires some adaptation in the landfill for its collection. In any case, the landfill gas represent a shrinking market and since their local requirements for heat is minimal, the co-generative solutions, such as MGT, should seek to associate with dedicated AD plants of municipal solid waste (MSW) treatment, heat may be used in these cases for drying the digestate, maintaining the AD reactor in mesophilic or thermophilic conditions or supplying hot water to local neighbourhoods [9].

The MSW (Table 2.3) can be classified in four types that will determine the type of technology used in AD treatment. The first type is the mixed residue without separation of recyclable components such as glass or plastics, this residue usually comes from households and is sent directly to the AD treatment. The second type is the organic fraction of the municipal solid waste (OFMSW) and it has been separated from recyclabe and undifferentiated components at households or at external separation units. The third type of MSW is the organic waste collected from big producers such as restaurants or supermarkets; this type is very similar to the residues coming from food industry and it will be shown in Section 2.2 that the AD technol-

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[8]Energetic recycling involves anaerobic digestion that is relatively more simple and efficient or, depending on the substrate (for example lignin rich material), through gasification or if the substrate is organic but cannot be anaerobically digested or gasified via incineration, for example bio-hazard waste from hospitals.

[9]In Section 2.2.2 the distinction between mesophilic and thermophilic conditions is done.

ogy employed is essentially the same, among the MSW this residue has the highest nutrient content and thus the highest biogas potential. The fourth type is the fat and grease that is usually separated from the effluents originated by big producers (such as a food industry or restaurants) or at the first steps in a effluent treatment station (sewage treatment plant); the fat and grease are collected in boxes and have notable characteristics as co-substrates for the AD of the residues from food industry or from municipal origin.

Table 2.3: Municipal solid wastes and respective biogas yield and quality

Substrate	TS [%]	VS/TS [%]	Gas yield $[Nm^3/t_{substrate}]$	Quality $[\%\mathrm{CH}_4]$	Ref.
Mixed residue	30 - 40	50 - 60	450 - 600	60 - 65	[9]
OFMSW[1]	30 - 40	70 - 80	350	60 - 65	"
Organic fraction from big producers	15 - 20	85 - 95	850	55 - 60	"
Fat and grease[2]	25 - 45	90 - 95	1300	50 - 60	"

1 Organic Fraction of Municipal Solid Waste
2 From collection boxes

UASB - Sewage treatment

The fourth and last sector of interest is the sewage treatment. Sewage is sent to the treatment plant usually in a very humid condition. One of the common treatments of sewage adopted in Brazil is the use of up-flow anaerobic sludge blanket (UASB) reactors [9].UASB reactors are essentially anaerobic and produce biogas continuously (see Section 2.2).

Tipically, sewage sent to UASB has TS content of $1.1\,\mathrm{g\,L^{-1}}$, ratio VS/TS equal to 30%, methane content in the biogas ranges from 60 % to 85 % and approximate yield is $0.21 \times 10^{-3} Nm^3/L_{sewage}$, assuming that each person produces 163.6 L of effluent as sewage per day, the biogas yield in a UASB is approximately equal to $34.3 \times 10^{-3} Nm^3/hab \cdot day$. The methane yield per COD removed is tipically $0.35 Nm^3/t_{CODremoved}$. UASB reactors can remove from 60 % to 70 % of the COD [9].

2.2   Reactors

The choice among the different reactors used for biogas production through anaerobic digestion depends on the substrate, on its loading rate and on capital and technical

expertise available to operate it. The most important substrate characteristic that guides through the choice of reactor is the total solid content (TS). The VS/TS ratio or COD may also influence the decision.

Eventually, before the substrate is disposed or pumped into the reactor, the water content might be corrected to the level accepted by the reactor, as do the nutrient content because sometimes the substrate needs addition of macro-nutrients such as Nitrogen, Phosphorous or Potassium for the microorganisms to develop. In addition, fibrous material can be reduced by shredding or other mechanical procedure and certain co-substrates can be added in order to reduce inert formation and increase gas quality, yield and reduce lag phase time. These requirements may be facilitated by using upstream buffer and preparation tanks[10].

Downstream the reactor, the gas is collected and treated (see Section 2.5), and the digestate (solid and liquid by products of AD) is collected and sent to dehumidification and eventually drying. The drying process can receive heat from the combined heat and power (CHP) plant.

Before describing the reactors it's important to discuss the role of temperature and mixing since both are intrinsically related to biogas yield.

2.2.1   Effective mixing

For optimal biogas yield, microorganisms must be supplied evenly with nutrients and their metabolites, including biogas bubbles, must be also removed. In addition, the temperature in the reactor must be uniform for stability of the reactions. A good mixing that doesn't damage physically the microbes is then advised [49].

2.2.2   Thermophilic and mesophilic conditions

Thermophilic and mesophilic conditions refer to the temperature range to which acidogenesis and methanogenesis microorganisms are subjected. If the temperature ranges from $32\,°C$ to $42\,°C$ the condition is considered to be mesophilic if it ranges from $50\,°C$ to $58\,°C$ the condition is considered to be thermophilic [49].

Most species of methanogens are mesophilic. Only a few are thermophilic. Thermophilic methanogens are more temperature-sensitive than mesophiles. Even small variations in temperature cause a substantial decrease in activity. Therefore, the temperature should be kept exactly within a range of $\pm 2\,°C$. The energy requirement for maintaining temperature in thermophilic range is higher, and overall conversion

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[10]Buffer tanks store the substrate and co-substrate in order to guarantee desired yields and process stability.
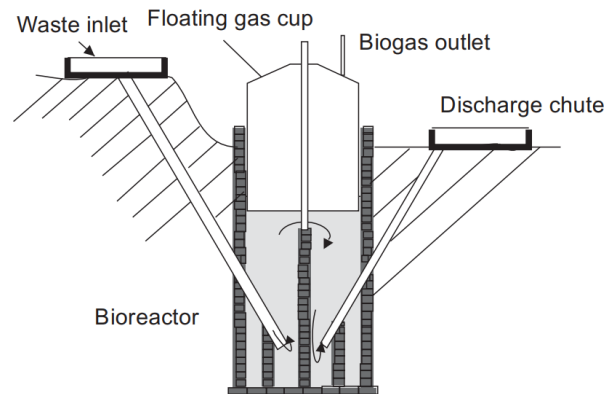
Figure 2.4: Constant pressure batch reactor - Floating cup (Source: Adapted from [49])

efficiency might result lower. On the other hand, the thermophilic operation mode results in about 50% higher rate of biodegradability and the biogas yield is provided in a shorter time [49]. Thermophilic conditions also favor a faster killing of pathogens.

Thus, if thermophilic conditions are desired, the reactor must be better insulated and a source of external heat might be required. This heat can come from CHP plant located nearby the biogas plant. These considerations apply to all types of reactors, either batch or continuous flow reactors. In some cases, given the environmental conditions (temperature and wind) and the temperature of the substrate the insulation and external heat supply may be required even to maintain mesophilic conditions.

The most common reactors for anaerobic digestion will be described below. The reactors can be divided in two types: batch reactors and continuous flow reactors.

2.2.3 Batch reactors

Batchwise operation means that the substrate is added and digestate is removed discontinuously. The batch reactor can be of constant volume type or constant pressure type. The former type is most commonly found, two examples are anaerobic ponds and sealed compartments. Constant pressure type are less common and produce gas at a constant pressure slightly higher than atmospheric. They are employed in small scale agricultural contexts and are referred to as floating cup reactors (Figure 2.4).

The operation in batch reactors is relatively simple which is associated with low

costs and low skill requirements from the operators: there is an initial inoculation with a substrate with similar physic-chemical characteristics and in the final stage of degradation (methanogenesis), then the already homogenized substrate is added, the reactor is sealed and the reactions take place in a closed system. In batch reactors the gas composition and yields are functions of time. Pressure can vary or be constant depending on the type of reactor. In constant volume reactors, pressure increases as the solid biomass is converted into gaseous products, literature describes that when pressure reaches an operating level gas is withdrawn, this pressure can be around 2 atm [49].

Figure 2.5 shows the results of an experiment carried out in batch mode at constant volume lab-scale reactor for the co-digestion of the organic fraction of municipal solid waste (OFMSW) and pomace oil (co-substrate)."Control reactor" refers to the digestion of pure OFMSW while "Run 1" represents a mixture of 70% OFMSW and 30% Pomace Oil and "Run 2" to a mixture of 30% OFMSW and 70% Pomace Oil. It's possible to see from the cumulative yield (Figure 2.5a) that biogas production tends to zero (the system goes to chemical equilibrium) and that the biogas with highest methane content is collected at the half of reaction time which lasts 170 days for the example shown or can last last around 21 to 42 days for digestion of mixed MSW [9]. Degradation is asymptotically exponential and these periods usually refer to a certain acceptable conversion of the biomass. This acceptable conversion is chosen depending on the biodegradability of the substrate, it can be as low as 70% or as high as 95% of the TS.

The simplest batch reactors with constant volume used in agriculture are called anaerobic ponds or fixed dome reactors, these reactors usually have no mixing system, impairing biogas yield. In the urban context, dry (TS ranging from 35% to 45%) and mixed municipal solid Waste is also usually treated in constant volume sealed compartments with no mixing in batchwise mode (Figure 2.6). In this case, the produced leachate is used for the initial inoculation, the leachate tank is insulated and receives heat from a CHP unit in order to keep the metabolism of inocula for the next batch. In addition, the CHP unit provides heat to the reactor, to compensate heat losses to the environment (anaerobic digestion is slightly exothermic) and keep the mesophilic or thermophilic conditions. Biogas quality and yield follow similar trends to those shown in Figure 2.5.

An example of anaerobic pond applied in an agriculture integrated context is shown in Figure 2.7. The fertilizer (digestate) needs to be removed and stabilized for further utilization.
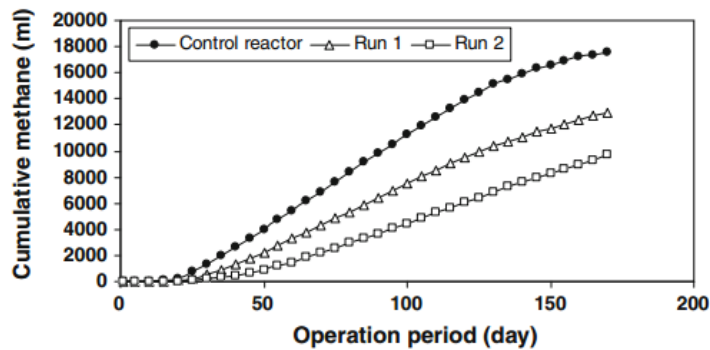
(a) Cumulative yield
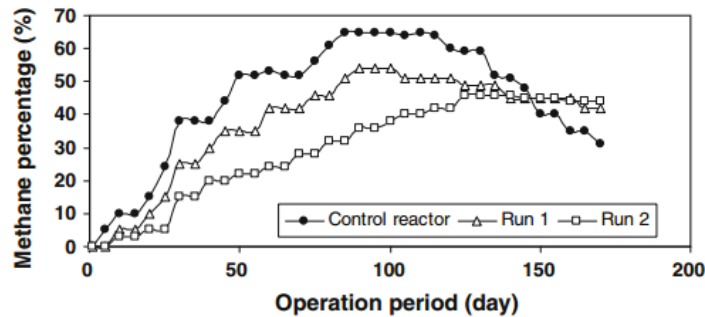
(b) Quality

Figure 2.5: Biogas results of anaerobic digestion in batch mode at constant volume reactor of OFMSW ("Control reactor") and mixtures with pomace oil (Runs 1 and 2) (Source: [2])

2.2.4 Continuous flow reactors

Most of the residues produced in agriculture and food industry and sewage in treatment plants are produced continuously, or in semi-continuous manner. Operating in ideal continuous manner, biogas is continuously produced with constant quality and yield. If the load is intermittent the quality may vary slightly, this effect can be counteracted by building larger reactors. The three most common types of continuous operation reactors are described below: Continuous Stirred Tank Reactor - CSTR, Plug Flow reactor and Up-flow Anaerobic Sludge Blanket (UASB) reactor.

Continuous Stirred Tank Reactor - CSTR

The operation of the CSTR follows these steps:
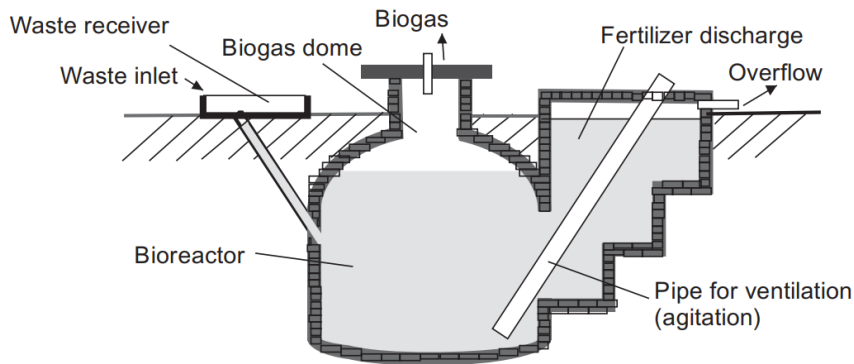
(a) Anaerobic pond (fixed dome). (Source: Adapted from [49])
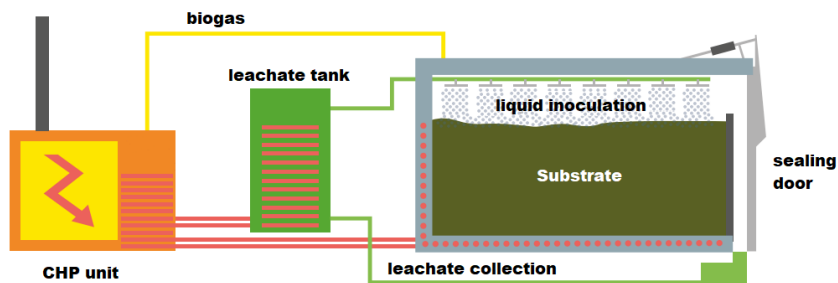
(b) Sealed compartment for MSW. (Source: Adapted from [9])

Figure 2.6: Constant volume batch reactors
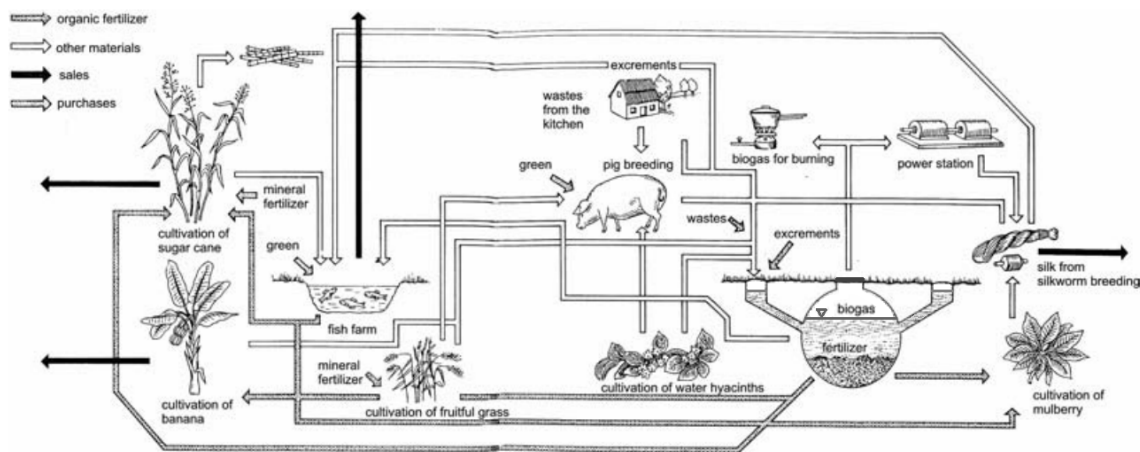
Figure 2.7: Production of biogas in a rural context using anaerobic pond with electricity production and black water treatment (Source: Adapted from [49])

- The reactor is initially loaded with inocula;

- after a period of initial digestion it is loaded with the substrate and proper mixing is started in order to have maximum homogeneity inside the reactor;

- substrate is constantly or intermittently added at inlet and residual mass is removed from outlet at the same rate;

- after a certain transient period the composition of organic matter inside the reactor remains unchanged and uniform (due to the mixing process);

- biogas is withdrawn in the top and digestate in the bottom of the reactor.

The key parameter for designing a CSTR, or any other continuous flow reactor, is the hydraulic residence time (HRT), defined as the mean time of residence of fluid particles inside the reactor. The level of degradability of the substrate, measured for example by the the fraction of VS or COD that were actually reduced in a lab-scale anaerobic digester (reactor) after a certain time, helps to chose the HRT that need to be adopted in the design phase of a continuous flow reactor[11]. Usually longer HRT are allowed, 20% or 50% higher than the values observed in laboratory. This creates a safe margin for eventual needs to operate with lower degradability substrates or to operate in unusual cold winters.

Then, give a process flow rate (Q), the reactor volume can be calculated simply multiplying it to the HRT. The reactor is constructed large enough to guarantee that the substrate particles remain inside it for time enough to reach a higher degradation. Liquid digestate leaves the outlet located at the opposite side of the inlet (Figure 2.8).

Two-stage reactors Optimum environmental conditions for all microorganisms involved in the degradation can only be set in a two-stage plant with one CSTR stage for hydrolysis/acidification and one CSTR stage for acetogenesis/methanation (Figure 2.9). Usually methanation is the slowest step, and the first stage CSTR may result smaller than the second stage. Actually, an advantage of operating CSTR in two or more stages is to obtain the same yield as in a single stage but reduce the total volume of the reactors. Table 2.4 summarizes the set conditions for two stage operation. The easiest controllable condition is the temperature of both reactors, other conditions could be controlled also in order to maximize conversion of biomass into methane.

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[11]Values observed in literature range from 10 to 50 days depending on substrate.
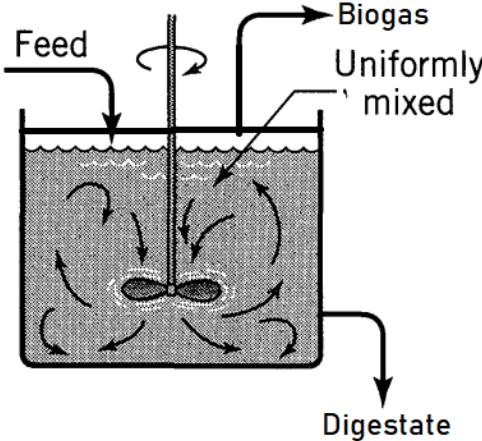
Figure 2.8: Continuous Stirred Tank Reactor (CSTR) applied to anaerobic digestion (Source: Adapted from [42])
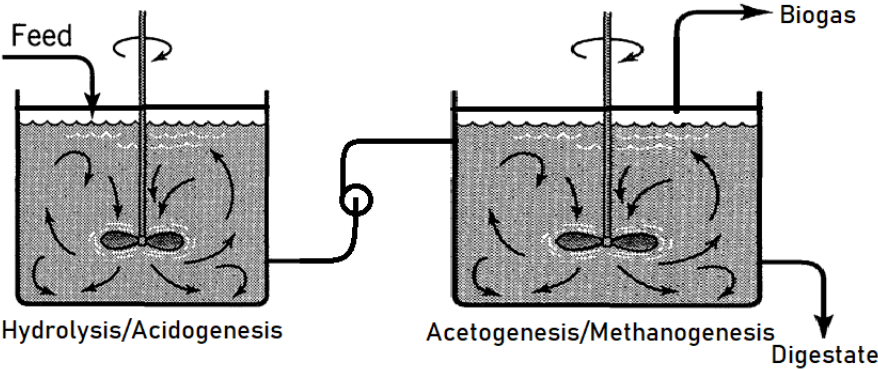
Figure 2.9: Anaerobic digestion with 2-stage CSTR (Source: Adapted from [42])

Plug flow reactor

A second type of continuous flow reactor usually applied to anaerobic digestion of substrates with low humidity (a condition typically found in separated municipal waste) is the plug flow reactor (Figure 2.10). This type of reactor was originally conceived to increase yield to a maximum with same reactor volume (or alternatively, reduce reactor volume to a minimum with the same yield). Its concept can be seen as infinite small CSTR put in series. In each transverse section of the reactor there will be homogeneity and an infinitesimal conversion takes place, such that by the end of the reactor only the equilibrium mixture of reactants and products are theoretically

Table 2.4: Set conditions for anaerobic digestion in two-stage operation. (Data source:[49])

Parameter	hydrolysis/acidogenesis	acetogenesis/methanogenesis
Temperature	$25 - 35°C$	Mesophilic: $32 - 42°C$
		Thermophilic: $50 - 58°C$
pH value	$5.2 - 6.3$	$6.7 - 7.5$
C:N ratio	$10 - 45$	$20 - 30$
DM content	$< 40\%$	$< 30\%$
Redox potential	-300 to $+400mV$	$< -250mV$
Required C:N:P:S ratio	500:15:5:3	600:15:5:3
Trace elements	No special requirements	Essential: Ni, Co, Mo, Se
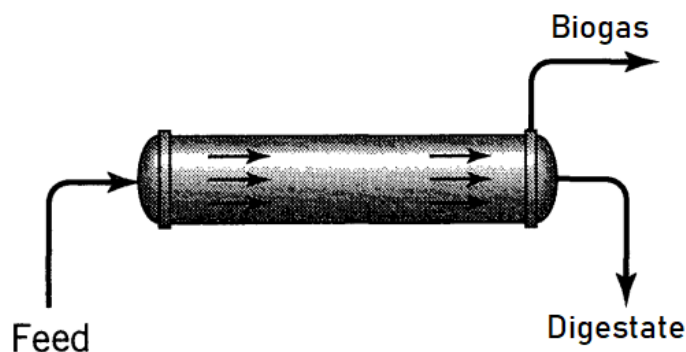
Figure 2.10: Plug flow reactor applied to anaerobic digestion (Source: Adapted from [42])

extracted. In the case of anaerobic digestion, this means that at the end extremity we extract the digestate with negligible amounts of fresh substrate and biogas only. For enhancing the treatment of organic fraction of municipal solid waste (OFMSW), the plug flow reactor usually has mixing paddles disposed locally along the reactor extent and recirculates the water rich in inocula extracted from the digestate (Figure 2.11).

Up-flow Anaerobic Sludge Blanket (UASB) reactor

The next type of anaerobic digester is actually a sub-type of plug flow reactors and is called Up flow Anaerobic Sludge Blanket reactor. It is commonly used for treating effluents, in sewage treatment plants or industrial waste water treatment facilities.

The relationship with plug flow reactors lies in the fact that the effluent properties
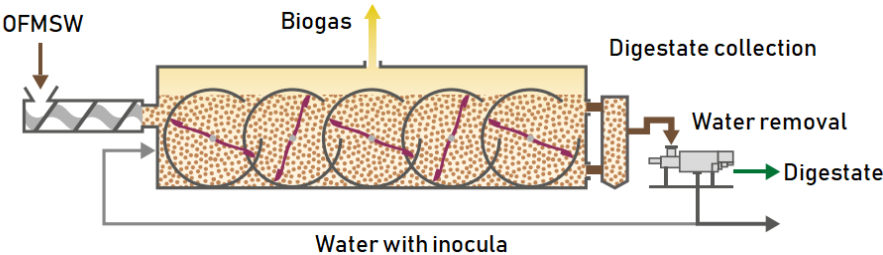
Figure 2.11: Plug flow reactor with mixing and water recirculation applied to anaerobic digestion of OFMSW (Source: Adapted from [9])
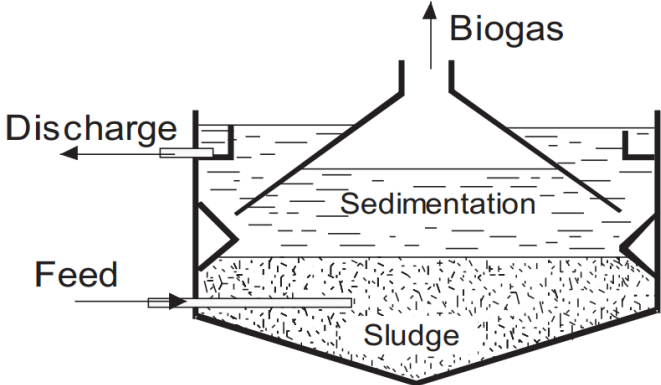
Figure 2.12: Up-flow Anaerobic Sludge Blanket (UASB) reactor applied to anaerobic digestion (Source: [49])

are not uniform inside the whole reactor as in the case of CSTR but are somewhat uniform in transverse cross sections of the reactor (Figure 2.12).

Initially active sludge (inocula) is loaded in the bottom of the UASB reactor, very humid substrate (effluent) is fed from the bottom and the reactor is fulfilled. Anaerobic digestion of the effluent takes place as it passes through the pores of the sludge and ascends. To avoid clogging the sludge pores, the effluent must be almost free from solid particles and grease. The remaining suspended particles in the ascending effluent have enough space and time to sediment in the sedimentation zone and integrate the sludge. The reactor is composed by an external cylinder, an inner protuberance, and an inverted cone; the biogas bubbles formed which form mainly in the sludge zone ascend and are guided by the protuberance and the inverted cone to a biogas zone in the top. Therefore, the liquid digestate that occupies the discharge zone is free from biogas and can be sent to posterior stabilization, i.e. the

process in which the digestate becomes eligible for environmental disposal or for use as biofertilizant.

This type of reactor is suitable for effluents with high organic load ($COD > 3000\,\mathrm{mg\,L^{-1}}$).

Applicability of different reactors

The information was collected from a series of white papers published in 2015 by the Brazilian Ministry of Cities aimed at the diffusion of biogas technologies and promotion of markets in Brazil (see [9]).

Reactors for agriculture   Residues generated in agriculture are usually treated with anaerobic ponds or CSTR noting the following aspects:

- Anaerobic pond

  - TS % inside reactor: $< 15\%$;
  - Plant capacity: range from 50 to 1000 $Nm^3_{\mathrm{CH_4}}/h$;
  - There are approximately less than 100 plants worldwide.

- CSTR

  - TS % inside reactor: $< 20\%$;
  - Plant capacity: range from 50 to 2500 $Nm^3_{\mathrm{CH_4}}/h$;
  - There are approximately less than 10000 plants worldwide.

Reactors for food industry   Generally, residues generated in food industry are treated with CSTR and effluents with UASB noting the following aspects:

- CSTR

  - TS % inside reactor: $< 20\%$;
  - Plant capacity: range from 50 to 10000 $Nm^3_{\mathrm{CH_4}}/h$.

- UASB

  - TS % inside reactor: $< 6\%$;
  - Plant capacity: range from 50 to 10000 $Nm^3_{\mathrm{CH_4}}/h$;
  - There are approximately from 800 to 1200 plants worldwide (from which 263 are in Germany);

– Suspended solids: $< 0.3 \, \mathrm{g \, L^{-1}}$;
– Relatively high flow rate ($> 500 m^3/day$);
– Relatively high organic load ($> 1500 kg_{BOD_5}/day$)[12].

Reactors for MSW   Municipal Solid Waste is usually treated with sealed compartments, CSTR or plug flow reactors with mixing noting the following aspects:

- Sealed compartment

  – TS % in the residue: $< 35\%$;
  – TS % inside reactor: $35\% to 45\%$;
  – Plastic or glass contaminants acceptable;
  – Plant capacity: range from 25 to 1250 $Nm^3_{\mathrm{CH_4}}/h$.

- CSTR

  – TS % in the residue: $< 15\%$;
  – TS % inside reactor: $10\% to 15\%$;
  – Plastic or glass contaminants NOT acceptable;
  – Plant capacity: range from 25 to 750 $Nm^3_{\mathrm{CH_4}}/h$;
  – There are approximately from 500 to 1000 plants worldwide.

- Plug flow reactor

  – TS % in the residue: $< 25\%$;
  – TS % inside reactor: $25\% to 30\%$;
  – Plastic or glass contaminants are partly acceptable;
  – Plant capacity: range from 100 to 1850 $Nm^3_{\mathrm{CH_4}}/h$;
  – There are approximately from 500 to 750 plants worldwide.

Reactors for Sewage treatment   Specially in Brazil and other tropical countries, sewage is in most of the cases treated using UASB reactors noting that the ratio of total solid content (TS %) of the effluent and the TS % of the sludge inside the reactor must not exceed 6%.

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[12]The BOD_5 is defined by the U.S. Environmental Protection Agency (EPA) as the amount of oxygen taken up by microorganisms that decompose organic waste matter in water during 5 days in the dark. It is usually interpreted with the COD in water treatment analysis.

Chemical kinetic models

Anaerobic digestion involves complex biochemistry and reactions taking place in heterogeneous media. An analytic approach to the dynamic of reactor, similar to what can be done with biodiesel production through (transesterification), is considerably difficult. Notwithstanding, simplified analytical approaches have already been applied such as the Michaelis-Menten kinetics model for predicting AD reactor dynamics where the inocula is probably taken as the enzyme [10][42]. In this chapter, we have skipped the details regarding this discussion.

2.3 Biogas contaminants

Biogas is not absolutely pure, but may contain droplets, dust, mud, and or trace gases. These contaminants have to be removed, depending on the further utilization of the biogas.

Physical contaminants in the biogas may also cause corrosion and can include larger or small particles, either liquid or solid.

For the removal of trace gases (e.g., H_2S and NH_3), techniques such as scrubbing, adsorption, absorption, and drying are applied, among others. See Sections 2.5.2 and 2.5.3 for a detailed explanation of rough and fine removal of ($H2S$).

Siloxanes when burned can originate silica, which is very hard and can cause hot corrosion in turbine blades and accumulate in them. Digesting waste which contain cosmetics made in part of silicon compounds can lead to the formation of siloxanes.

2.4 Required syngas/biogas characteristics for MGT utilization

The required biogas characteristics for application in a gas turbine were taken from [49]:

- CH_4 : higher than $40\%v/v$ according to a MGT producer [18] and higher to $60\%v/v$ according to a text book [49];

- H_2S : between 100 and $500mg/Nm^3$ according to Reference [49]. Short peak loads above these limits can occasionally be accepted. Indeed, a manufacturer of micro gas turbines establishes the H_2S upper limit of $2280mg/Nm^3h$ [18];

- Siloxanes : lower than $150mg/Nm^3h$ [18].

Particularly, water vapor is not a concern when burning biogas in a gas turbine. However, it must have a relative humidity of less than 60% to prevent the formation of condensate in the transporting pipelines. Such condensate, particularly in combination with other impurities, could corrode the pipe walls.

A MGT manufacturer requires that the CH_4 concentration be higher than 40% and establishes that the biogas consumption range will lie between 34 and $85 Nm^3/h$ depending on: Lower Heating Value, concentration of CH_4 and biogas composition. Therefore, it's possible to infer that the heating value isn't in fact too restrictive. In fact, if the heating value is relatively low, more biogas need to be burned to provide the same amount of heat capable of heating the flow entering the combustion chamber at the compressor outlet temperature and exiting it at the turbine inlet temperature. Chapter 7 presents this discussion with more details.

Flammability range

For combustion to take place three things must be present in right amounts:

- Combustible;

- Oxidizing agent;

- Ignition energy (e.g., a spark or a heat source).

Supposing that the source of ignition energy is available, we can focus on the composition of air and gas mixture.

If the gas produced (biogas or syngas) can be burned then it can release heat and thence be eligible for use in a combustion chamber of a gas turbine. The flammability range is presented in the following diagram, Figure 2.13.

The flammability range of gases produced from biomass (biogas or syngas) is different from flammability of methane due to the presence or inert gasses (mainly CO_2 and N_2). In the abscissa, the effective inert gases are given by the sum of CO_2 concentration (which will come from the fuel, since the air contains exiguous amounts of CO_2) and two thirds the excess concentration of N_2 relative to the normally found concentration in the air introduced in the mixture which is usually 79%. In the ordinate, the effective combustible gases are given by the sum of CH_4 concentration, H_2 concentration multiplied by a factor equal to 1.25 to compensate for increased flammability of hydrogen gas and CO concentration multiplied by a factor equal to 0.4 to compensate for decreased flammability of carbon monoxide. In addition, a parameter "R" is used to delimit the flammability regions, it is given by the ratio of CH_4 concentration and the sum of CH_4, H_2 and CO concentrations.
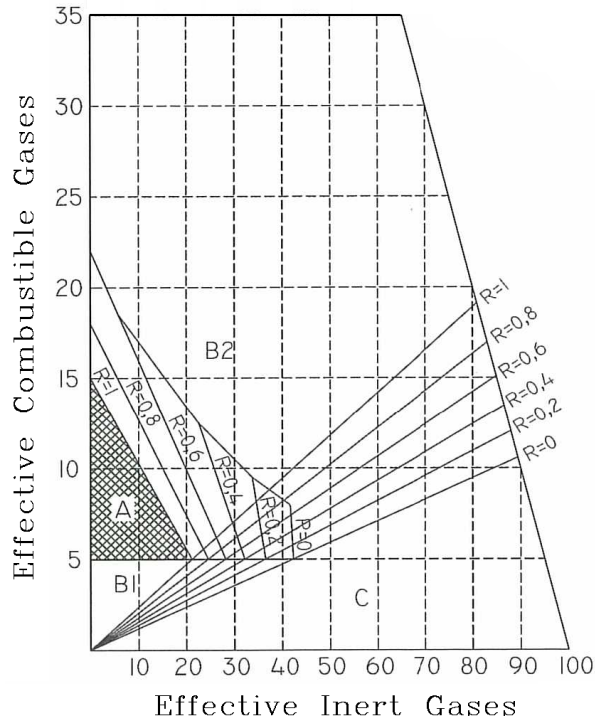
Figure 2.13: Flammability range of biogas and syngas. For biogas with only methane as combustible gas we have $R = 1$; for pure syngas, i.e. with no methane, $R = 0$ (Source: [34])

- Effective Inert Gases : $\frac{[CO_2]+2/3[N_2]_{in\,excess}}{N}$;

- Effective Combustible Gases : $\frac{[CH_4]+1.25[H_2]+0.4[CO]}{N}$;

- R parameter : $\frac{[CH_4]}{[CH_4]+[H_2]+[CO]}$

Where N is the total number of mols in the mixture.

Any biogas or syngas mixture can be located in one of the four different zones in the diagram 2.13.

- Zone A : Autonomously flammable mixture in case of presence of proper ignition energy;

- Zone B1 : not flammable mixture due to absence of combustible;

- Zone B2 : not flammable mixture due to absence of oxidant;

- Zone C : not flammable mixture due to excess of inert gases.

Combustion of mixtures in Zones B1 and C are compromised but a mixture in Zone B2 can be mixed with more oxidant and enter Zone A, becoming flammable.

For biogas, $[H_2]/N$ and $[CO]/N$ are usually limited and R is about unity. For syngas, these concentrations are considerably higher and R may result much lower than unity. R is zero for a syngas with no methane.

2.5 Biogas purification for MGT utilization

Recall the biogas composition from Section 2.4 required for utilization in a MGT:

- CH_4 : higher than $40\% v/v$ according to a MGT producer (see [18]) and higher to $60\% v/v$ according to a text book [49];

- H_2S : between 100 and $500 mg/Nm^3$ [49]. Short peak loads above these limits can occasionally be accepted. A manufacturer of MGT establishes the H_2S upper limit of $2280 mg/Nm^3 h$ [18];

- Siloxanes : lower than $150 mg/Nm^3 h$ [18].

- Water vapor : not a concern.

The choice of methane content is actually arbitrary, however it dictates the behavior of the MGT and discernment must be used based on available biogas (Section 2.1) and purification techniques. In the Chapter 7, we discuss the implications of this choice.

Water vapor is not a concern when burning biogas in a gas turbine, nonetheless it is recommended that it has relative humidity of less than 60% to prevent the formation of condensate in the transporting pipelines.

Hydrogen sulfide (H_2S) needs to be removed to protect downstream components since it can react with water and form sulfurous acid, which is a strong acid. Desulfurisation is done in two steps, a rough and a fine desulfurisation. The processes involved can be of biological, chemical or physical nature. The german norm DWA M361 can be used as a basis to provide desulfurisation criteria.

The most commonly indicated *steps* for purifying the biogas prior to the utilization in a MGT are the following:

1. Filtering out solid particles (dust or scum);

2. Rough separation of hydrogen sulfide (H_2S);

3. Removal of traces of H_2S;

4. Siloxane removal;

5. Separation of carbon dioxide and other trace gases such as ammonia;

6. Dehumidification (if the carbon dioxide removal is a dry gas process, dehumidification must be carried out before step 5).

2.5.1   Step 1 - Solid particles removal

After leaving the reactor, the first step into which the biogas is submitted is removing solid particles using cyclones or filters. Coarse particles, such as scum[13] can be removed in gravel pots which are used as pre-filters and help dehydrating the biogas.

2.5.2   Step 2 - Rough H_2S removal

Two techniques can be used to remove great part of H_2S from biogas: Air injection inside the reactor (over the free surface) or Mixture of the substrate with salts of iron hydroxides prior to injection in the reactor.

Air injection   Chemolithotrophic bacteria can oxide H_2S into sulfate and other sulfur compounds in presence of oxygen. Therefore injecting air in the region between the free surface of the reactor and its dome is a strategy to reduce H_2S. Adequate support in this region needs to be provided for these bacteria to grow, for example cloths can be hanged or plates can be fixed in such region. This technique is cheaper compared to the others but a drawback is that methanogens being very sensitive to oxygen may have their metabolism inhibited somehow and biogas yield can be sligtly reduced. The concentration of H_2S can be reduced to the range of 50 to 2000 ppmv (i.e. 75 to $3040 mg/Nm^3$)[14].

Mixing the substrate with iron salts or hydroxides   Mixing the substrate with salts of iron hydroxides prior to injection in the reactor allows the formation of insoluble sulfides in the sludge as biogas is formed, these sulfides are retained in the

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[13]The top layer which can form in the reactor if substrate is not well balanced nutritionally.

[14]The equivalence for hydrogen sulfide in biogas is $1 ppmv = 1.5214 mg/Nm^3$, were biogas is assumed an ideal gas.

digestate. The concentration of H_2S can be reduced to the range of 50 to 500 ppmv (i.e. 75 to $760 mg/Nm^3$).

2.5.3   Step 3 - Fine H_2S removal

Again, we cite two techniques that can reduce the hydrogen sulfide to trace amounts: Precipitation in biologic column and Adsorption in activated carbon.

Precipitation in biologic column   The biogas is forced to pass in a column external to the reactor containing chemolithotrophic bacteria with proper air injection, as explained in the Air injection technique of the Step 2 there is formation of sulfates and other sulfur compounds that are immobilized in the column. The concentration of H_2S can be reduced to the range of 50 to 100 ppmv (i.e. 75 to $150 mg/Nm^3$).

Adsorption of H_2S in activated carbon   If H_2S is limited up to 500 ppmv then activated carbon can be used to adsorb it. Very low concentrations can be reached, in the order of 1 ppmv. The process is usually the last process used to remove H_2S.

2.5.4   Step 4 - Siloxane removal

After removing H_2S the biogas still contains carbon dioxide and water vapour and may contain siloxanes.

Adsorption of siloxanes in special activated carbon   Special activated carbon filters are usually in pair number operating in parallel to retard saturation and remove siloxanes to low levels of $0.1 mg/Nm^3$. For the octamethylcyclotetrasiloxane, a low weight cyclic siloxane, eventually in the biogas this concentration is equivalent to 0.008 ppmv, much inferior than the limit established.

2.5.5   Step 5 - CO_2 removal

Carbon dioxide is removed to meet the required biogas quality. The techniques for such task abound, they differ in type of materials used and pressurization or heat transfer requirements. Note that for H_2S removal techniques, neither pressurization or heat transfer were required. CO_2 removal processes are described briefly below.

The following two methods use molecular level sieves to collect carbon dioxide:

Pressure Swing Adsorption - PSA A solid porous material such as zeolites, activated carbon or carbon molecular sieve is used to trap carbon dioxide when biogas pressure is raised and flow is forced to pass through it, this is the adsorption step. The reverse step, is the desorption of carbon dioxide and is done by depressurizing the vessel containing the porous material. Not only CO_2 is adsorbed in the process but also some water vapour, some H_2S still in the biogas and a small amount of methane that has not passed the sieve, for this reason the gas flow generated in the desorption is catalytic oxidized or simply burned. This process requires mechanical work for pressurization of biogas and special materials. The positive aspect is that the cleaned biogas stream will have a moderate to high pressure which reduces the work necessary in the boosting compressor prior to the combustion chamber of the MGT.

Membrane separation Polymeric membranes filter the biogas. The membrane separation allows to lower the content of CO_2 (and H_2S) by an order of magnitude if compared to the concentration leaving the ethanolamine plant which is assumed to be used upstream. This technique requires relatively low mechanical work for pressurization of biogas if compared to the PSA technique. The positive aspect is that the cleaned biogas stream will have a moderate pressure which reduces the work necessary in the boosting compressor prior to the combustion chamber of the MGT. The negative aspect is that biogas stream need to be dehumidified prior to reaching the membranes.

The following three methods take advantage of the change of carbon dioxide solubility in certain fluids due to variation in fluid pressure or temperature:

Dissolution in pressurized water Pressurized water is put in contact with the biogas stream and H_2S (which is still present in trace amounts), eventually present ammonia (NH_3) and the CO_2 are caused to dissolve in the water. The removal of these gases is done by depressurizing the water. This process requires mechanical work for pressurization of water and no special materials.

Dissolution in cold organic solvents Carbon dioxide (and also hydrogen sulfide) can dissolve into ethanolamines. The solubility is higher if temperature is lower. Therefore, this process requires heat transfer for changing the solubility of contaminants in the organic solvents which are required.

Dissolution in pressurized organic solvents Carbon dioxide (but also H_2S and H_2O) can dissolve in pressurized polyglycol. If the fluid is depressurized these con-

taminant gases are released. This process requires mechanical work for pressurization of organic solvents which are required.

2.5.6   Step 6 - Water removal

Dehumidification can be done by condensing the biogas through compression[15] or through cooling. A heat exchanger can be used with a cooling fluid, or alternatively, the biogas can pass in buried pipelines about $50m$ long having a certain slope for collecting the water that condenses. A physico-chemical means of dehydrating biogas involves adsorption of water in silica (SiO_2) or activated carbon.

2.6   Heat demands

The inherent advantage of the association between Anaerobic Digestion plants and MGT in a co-generative scheme derives from the following observations:

- Heat can be used during the obtainment of the substrate, its pre-treatment, the biogas production in the reactor, the disinfection of the digestate or during some biogas cleaning steps.

- In comparison to internal combustion engines (ICE), micro gas turbines (MGT) provide a more concentrated stream of hot gases and dissipate less heat to the environment.

2.6.1   Heat demands related to the substrates for AD

Agriculture   Heat can be used to dry grains before processing; It can be used in the thermal pre-treatment to increase biodegradability of ligneo-cellulose rich substrates. Other processes associated with the production of residues listed in Table 2.1 may require heat, for example cattle is usually maintained in an air conditioned space in order to reduce diseases and increase productivity.

Food industry   Almost all the industrial processes that produce the substrates shown in Table 2.2 require heat either as hot water or as super heated vapour.

Municipal waste management   As said before heat can be used to dry the digestate or supply hot water to local neighbourhoods.

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[15]Such compression is suitable for some CO_2 removal steps and eventually alleviates the boosting compressor.

Sewage treatment   According to the World Health Organization (WHO), in order to eliminate faecal coliforms and parasites, it is indicated that the digestate be exposed to heat over to 50 °C, for seven days [9].

2.6.2   Heat demand related to anaerobic digester operation

Heat is required to compensate reactor thermal losses and maintain mesophilic or thermophilic conditions (table 2.4).

2.6.3   Heat demand related to biogas purification

Heat may be required during CO_2 removal via dissolution in cold organic solvents.

Part III

Mechanics

Chapter 3

Compressor-Turbine matching effects due to fuel change

In this Section we discuss the compressor-turbine matching possible effects due to fuel change from Natural Gas to Biogas and vice-versa.

At first glance, in order to compensate the reduced Lower Heating Value (LHV) of the biogas, obtain the same temperature rise in the combustor and maintain net power output constant, the fuel flow rate might be increased in the combustion chamber. An energy balance in the combustor is used to indicate this new fuel flow rate, however, the actual inlet and outlet temperatures that should be used in this energy balance may differ slightly from the original values, even if net power output remains the same. That's because there is a slight alteration in the matching between compressor and turbine.

Section 3.1 shows how these accurate temperatures could be obtained by knowing the compressor and turbine characteristic maps and regenerator estimates of total pressure loss and effectiveness (all these data is available only when compressor, turbine and regenerator prototypes are tested). In the absence of these data we can use a simplified hypothesis: the inlet and outlet temperatures in the combustor remain fairly constant in the range of fuel flow variation. This means that the boundary conditions in which the flow field will be simulated can be assumed to be constant. Therefore, the combustor boundary conditions could assumed to be constant, except for the fuel flow rate (calculated in basis of the fuel LHV) and its composition.

3.1 How matching is actually affected

Consider the case of fuel shift from natural gas to biogas, i.e. from a higher to a lower LHV fuel, in a recuperated single shaft gas turbine with both compression and expansion done in sigle stages.

Since the LHV of biogas is lower than the LHV of NG, it's expected that in order to maintain the same temperature rise across the combustor and guarantee the same net power output of the MGT, the mass flow rate of fuel needs to increase. If the turbine is not yet choked[1], as most of the cases, the mass flow rate of gases across it is allowed to increase and, assuming that we keep the rotational speed of the axle constant, the pressure ratio across the turbine will also increase as a consequence. This can be observed in the typical turbine characteristic curves, or map (Figure 3.1).

When this occurs, the turbine will output more power since it is proportional to the pressure ratio (Equation (3.2) gives the turbine specific work output).

For the same net work output, the compressor will also increase its power consumption ((3.1) gives the compressor specific work input), meaning an increase in its pressure ratio. But increasing compressor pressure ratio and keeping its rotational speed constant (as assumed) brings a reduction in its flow rate (Figure 3.2). Therefore, the flow rate that enters the combustor is reduced, if the assumption of constant shaft speed is held.

$$w_{12} = c_{p,a}(T_{02} - T_{01}) = c_{p,a} \cdot \frac{T_{01}}{\eta_c}\left[\left(\frac{p_{02}}{p_{01}}\right)^{(\gamma_a - 1)/\gamma_a} - 1\right] \tag{3.1}$$

$$w_{34} = c_{p,g}(T_{03} - T_{04}) = c_{p,g} \cdot \eta_t T_{03}\left[1 - \left(\frac{1}{p_{03}/p_{04}}\right)^{(\gamma_g - 1)/\gamma_g}\right] \tag{3.2}$$

Following the reasoning presented in the last paragraphs, it is not certain if the flow rate across the turbine will actually increase. The assumption of constant rotational speed is questionable and actual case scenarios could give the basis for a thorough investigation.

The forementioned explanation could be reversed (quantities that increase might decrease and vice-versa), in order to describe what would happen if the gas turbine stops burning biogas (or any relatively low LHV) and starts burning a high LHV fuel as the case of natural gas.

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[1]Condition when a convergent duct reaches sonic speed in the throat and mass flow rate peak at its maximum. In this case, increasing velocity may be possible by using a divergent section downstream the throat but increasing mass flow rate is not.
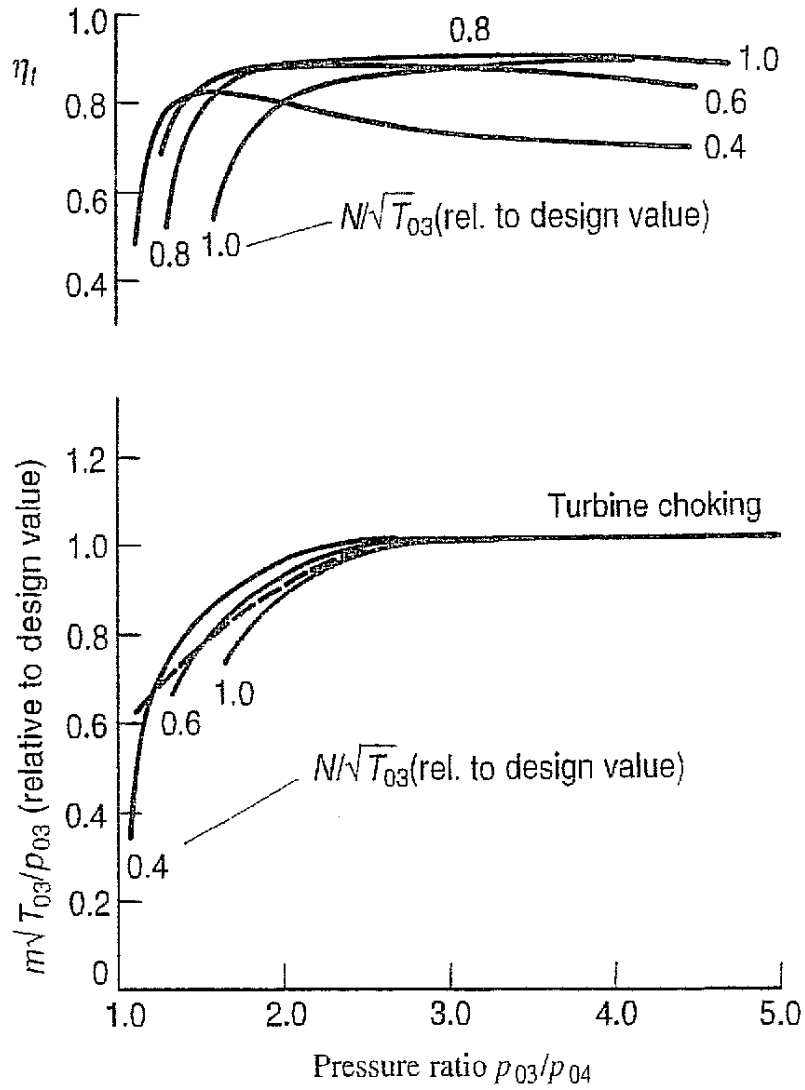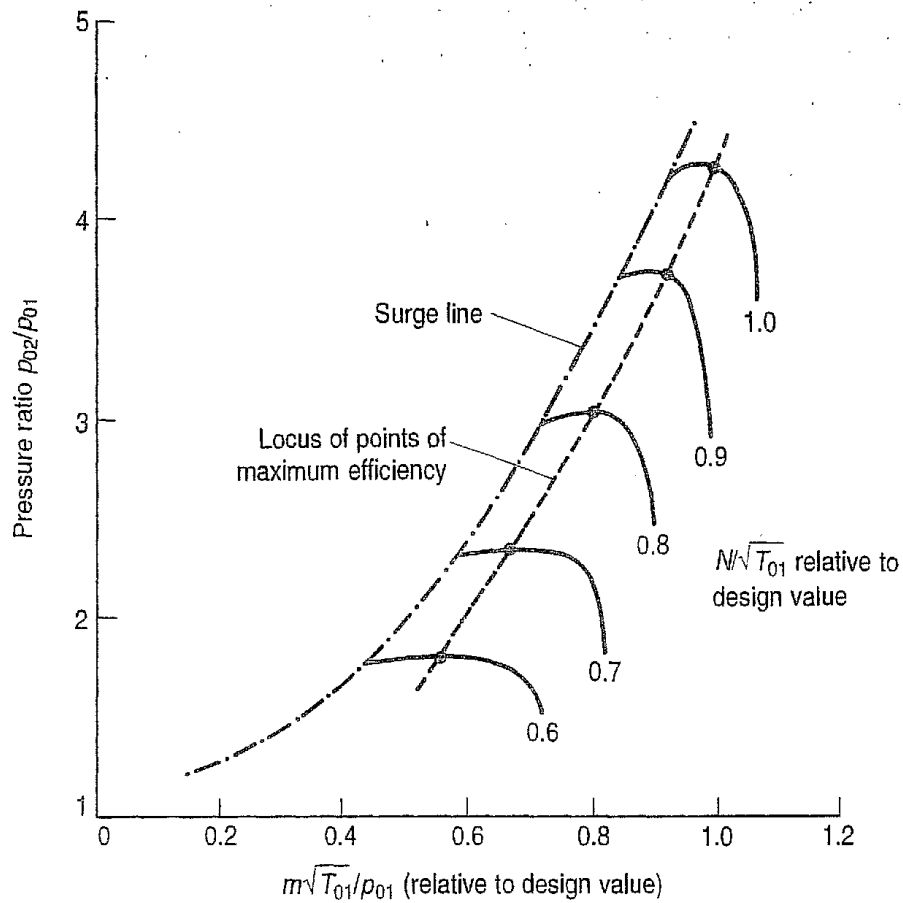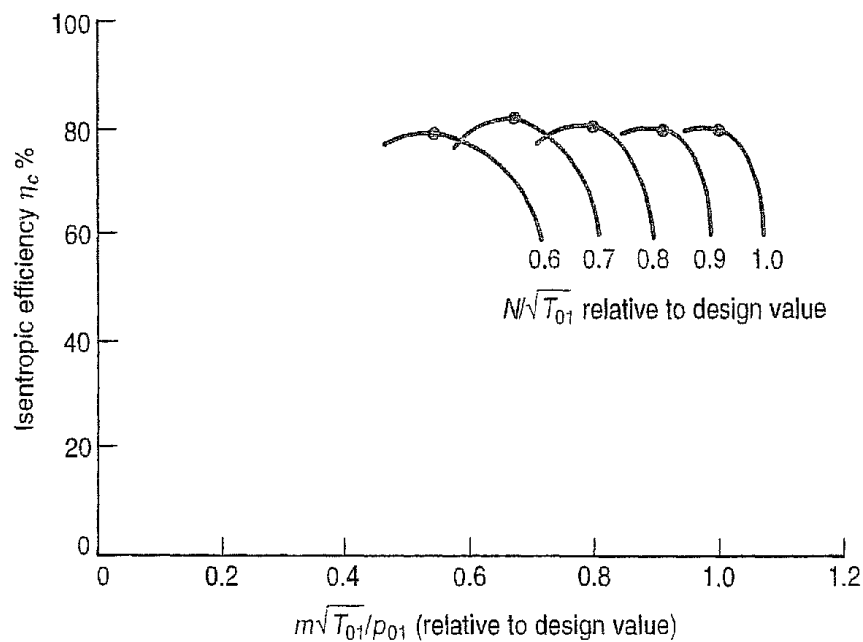
Figure 3.1: Turbine characteristic curves (Images source: [36])

Figure 3.2: Compressor characteristic curves (Images source: [36])