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Matter an energy balances in bioprocess engineering

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Collection *Académica* http://tiny.cc/edUPV_aca

To cite this publication please use the following reference:
Fito Suñer, Pedro J.; Castelló Gómez, María Luisa; Castro Giráldez, Marta and Asensio Grau, Andrea (2023). *Matter and energy balances in bioprocess engineering.* Valencia: edUPV

ISBN: 978-84-1396-179-8
Legal deposit: V-3307-2023

Printed: Byprint Percom, S. L.

If the reader detects a mistake in the book or wishes to contact the authors, he can send an email to edicion@editorial.upv.es

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Impreso en España

Preliminary comments

This book aims to teach, in an interactive way, to pose and perform matter and energy balances combining theory in text and video format, exercises and self-assessment tests. It is recommended that students start by reading the text and follow up by viewing the video contents of each section, since the information that appears in the videos is a summary of the text and it is set as a reinforcement for comprehension.

The entire book has followed the annotations and units of the international units and measurements system published in the Green book 2007 IuPAC.

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Chapter 1
Introduction to processes engineering

1.1. Introduction

Since the beginning of the Universe, there have been changes in matter and energy caused by various phenomena, these changes have allowed the formation of all the matter that makes up the current universe. Whilst the complexity of things grew, the various phenomena that caused these changes also increased exponentially. The most complex system that exists in the Universe, the cellular system that enables life, is also the system in which most types of changes in mass and energy occur.

Humanity, since ancient times, has used these changes in mass and energy to transform things, from utensils and food in prehistoric times, to the testing that led to the discovery of the Higgs boson in 2012 in the CERN particle accelerator. Leucippus of Miletus (fifth century BC) described the atom for the first time, as the smallest indivisible particle that forms matter and Aristotle (fourth century BC) defined energy for the first time as "living force" (Asimov, 1999), this term was then used twenty-three centuries later by Gottfreid Leibniz to define kinetic energy (Nelson, 2005).

The scientific foundations required to quantify changes in matter and energy took time to consolidate. In the eighteenth century Lavoiser established the Law of Conservation of Matter, this law unified contributions of Descartes, Leibniz and Lomonosov as it was defined as "matter cannot be created nor destroyed, it is only transformed" (Estevan, 2010). This allowed Mayer, in the nineteenth century, to establish the Law of Conservation of Energy, with contributions from Joule or Helmhotz, defined in the same way as matter (Logunov, 1998). Years later the merge of both these laws led to the first principal of thermodynamics, that initially, was only defined through energy and later on adopted matter aswell, enunciated as "Matter and energy cannot be created nor destroyed, they can only be transformed". In 1905 Einstein proved that the law was not strictly true as he displayed in his relativity theory that mass and energy are interchangeable. Einstein and subsequent theories of quantum mechanics have shown that under certain conditions this might not be fulfilled, although in most cases it is still valid.

Parallel to the quest to discover how to quantify changes in matter and energy, in the seventeenth century, Isaac Newton opened a new chapter for science by presenting an equation that described the motion of fluids, which led to the birth of transport phenomena. In the nineteenth century Fick developed an equation to predict the transport of chemical species, based on the kinetic theory of ideal gases of Boltzmann and Maxwell (Bird et al., 2006). In this same century Fourier, a distinguished mathematician, developed a model that predicted the thermal energy transmitted through a system. These equations were then established as laws due to various discoveries throughout the nineteenth and twentieth centuries, by Reynolds, Prandtl or Colburn, but also showed vast exceptions in which these equations were not fulfilled. Alternative fluid models emerged from these exceptions such as Ostwald's or Maxwell's models, as did other models of matter and energy with the reciprocal relations of Onsager (Demirel, 2007). In 1968 Lars Onsager would receive a Nobel prize in chemistry for this work.

In the first half of the twentieth century, in the Massachusetts Institute of Technology (MIT), several researchers in the department of chemistry, compiled the knowledge acquired in the last two centuries to assemble a new department and to establish the foundation of what later on would be known as Process Engineering. They realized that, if they were to design an industrial process, they would have to implement this knowledge in conjunction.

Process Engineering: branch of knowledge that studies how to quantify and predict changes when transformation activities are applied to a constricted system. The macroscopic transformations in a system can be relative to its matter or its energy. This allows us to determine and quantify the transformation steps in several raw materials that are brought in contact, applying specific changes in its environment, in order to obtain a number of end products.

Process Engineering, originally chemical engineering, kicked off as of great importance to the industry, as it was the foundation for industrial manufacturing processes design in various areas. As a result, new areas of engineering emerged such as Food and Agricultural Engineering, Biotechnology Engineering, Chemical and Nuclear Engineering, etc…

1.1.1. Basic principles of process engineering

The tools assembled in Process Engineering allow us to quantify matter and energy transformations, as well as the speed at which they occur, in a conversion process of several raw materials in a product. Initially, we can define The Process as a sequence of changes, both physical and chemical, that a number of raw materials go through until they become a product or several products.

This process will take place in sequenced stages, so that each stage entails a transformation of matter and/or energy forming intermediate products. Each transformation stage will be referred to as a Unit Operation (Ibarz, 2005).

Unit operation: it has traditionally been considered as an operation for each team of an industrial plant. However, it actually refers to a specific volume in which product streams flow in and out with one or more components, producing some form of internal transformation, whether it be caused by; an exchange of components between streams; by a chemical or biochemical transformation of its component; or by the accumulation of streams of entry or exit inside the volume.

Process: set of unit operations that aim to produce some form of transformation in a series of raw materials to obtain a specific product or products.

Traditionally, the concept of unit operation has been associated to an industrial team, with a clearly defined transformation. Figure 1.1 shows how the process to obtain oil and meal from sunflower seeds is carried out in 5 unit operations that correspond to the industrial teams used in the process.

Once the unit operations are defined, and to ease the understanding of the process, each unit operation is represented with a block, with a name that describes the transformation that occurs inside, using arrows to indicate the streams that enter and exit each unit operation.

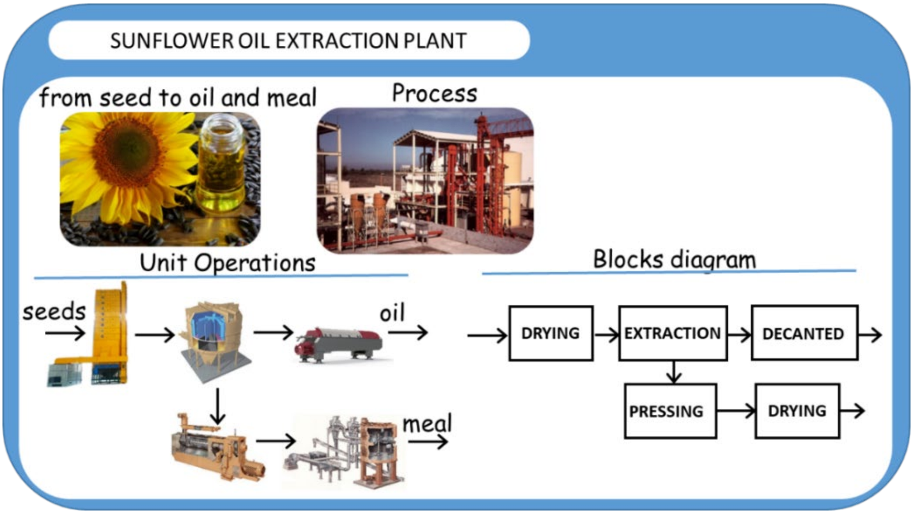

Figure 1.1 Process to obtain oil and protein meal from sunflower seeds.

However, the scope of process studying is not limited to industrial processes, any transformation process in the universe can be depicted and quantified in the same way. From galaxies and planets to cellular systems and atoms, we can perform an analysis of their transformation processes. For example, the analysis of the process of digestion of ethanol that is shown in figure 1.2.

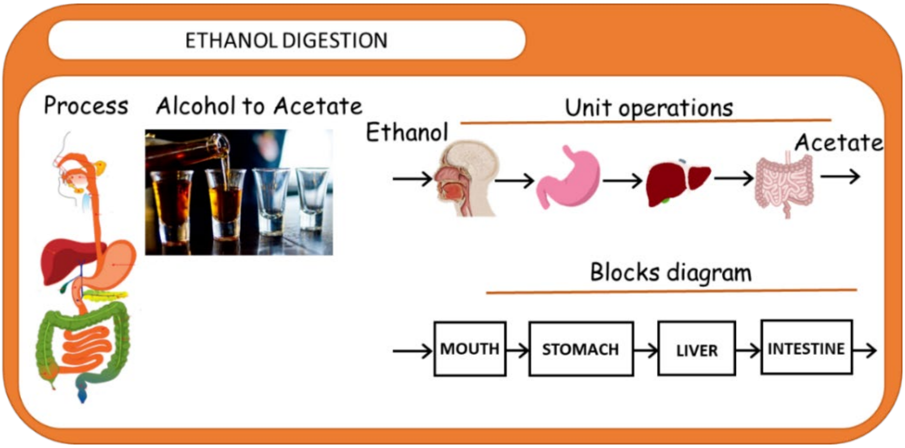

Figure 1.2. Process of digestion of ethanol.

Moreover, when analysing a process, it is not required to subdivide it into unit operations, we can analyse it by subdividing the process in groups of several unit operations or even in minor parts smaller than a unit operation.

In modern processes engineering there are no limits on process analysis. We define the delimitation of parts in which we divide our study into. In order to define freely the delimitations of a subsystem in a process, the concept of **control volume** was born.

Control volume: Delimitation of a specific region of a process in order to be studied. The control volume intended to be studied is also referred to as a system. When the control volume includes the whole process it is known as **global volume**. The control volume can be differential volumes in a unit operation, one or several unit operations, or even the whole process.

There are two types of processes, processes formed by unit operations that constantly transform, that require input of raw materials and output of products where the system is non-stop, known as **continuous** processes. If a unit operation in the process requires us to stop the inflows and outflows to achieve the transformation the process is known as **intermittent** or **batch process** (Felder y Rousseau, 1999).

There is a third type for industrial processes called **semicontinuous** processes. These processes include a batch operation, it differs from the intermittent process in the fact that the required transformation time for this operation is counterbalanced by increasing the capacity of the batch operations in the rest of the production line. In other words, if the line processes 1 t/h and the operation requires 4 transformation hours, the batch operation is adapted so that it transforms 4 t.

Intermittent process: any process that includes a unit operation that requires the product movement to stop, thus stopping the whole process.

Continuos process: process composed by operations that produce the necessary product changes without stopping its movement, maintaining the same mass from the beginning to the end of the operation. Thus, the production does not vary over time as the process is always running.

Semicontinuos process: process that contains a batch unit operation that manages to maintain a constant production throughout the process, increasing the production of the batch operation to a level capable of supplying the end of the production line during the periods of stoppage of said operation.

1.1.2. General balance

The transformation processes in each process are governed by the first principle of thermodynamics, that is, **"matter and energy cannot be created or destroyed, they can only be transformed".** This implies that both for matter and for energy the transformation possibilities within a system are limited.

Let us analyse a unit operation made by a plant (see figure 1.3). This plant interacts with the soil, the air, and the sun, exchanging matter and energy.

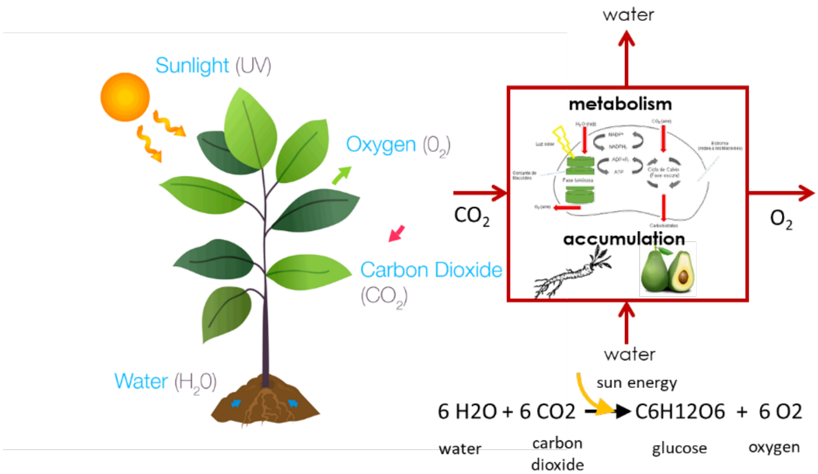

Figure 1.3. General Balance applied to a plant.

Let us view the possibilities for matter and energy in this unit operation:

Looking at the exchanges in matter, we can see that the air provides an **input** of carbon dioxide and an **output** of water and oxygen, and the soil provides an input of salts and water. A portion of the water and the carbon dioxide **react** to form glucose and oxygen. Another portion of the water, glucose and salts are **stored** in the roots and fruits. Thus, the chemical species can be an **input or output** for the plant, they can **react** to be consumed or produced and, lastly, they can be **accumulated**.

As for the energy, we find that from the sun; the plant receives radiant energy, absorbing a portion of it to transform it into chemical energy for photosynthesis; and receives thermal energy to heat the plant. The other part of the radiant energy is reflected, displaying its colours to any observer. From the air and soil, we either gain or lose heat depending on the temperature of its environment. For this reason, as would occur with matter, energy can be an **input** or **output** for the plant, it can be **transformed** into other types of energy or it can be **accumulated**.

Thus, we can define the general balance as:

INPUT + GENERATION = OUTPUT + ACCUMULATION *(ec. 1.1)*

Where the terms **input and output** are the sum of matter and energy flows that cross the boundaries of the unit operation analysed, and the terms **generation and accumulation** represent the transformations that occur within the unit operation. The term **generation** represents the chemical species that react or the energy that is transformed, being negative if it is consumed or positive if it is produced. The term **accumulation** represents the matter or energy that increases or decreases within the unit operation without transforming.

1.1.3. Steady state and Unsteady state

As described previously, a process can be continuous or intermittent; this implies that each unit operation can, in turn, work continuously or in batch. The differentiation in the work system of these two types of unit operations is directly corelated with the type of transformation that is produced. If an operation works continuously, this means that matter or energy is constantly going in or out without undergoing a transformation within. Therefore, a continuous unit operation should be able to function for an infinite amount of time. On the other hand, a batch unit operation requires the process to stop during the transformation period, and therefore, it will function depending on the time variable.

If the transformation in a unit operation does not depend on time, the matter will constantly keep moving forward, and the transformation time will be the same as the time that the matter will be kept inside the unit operation. This means that if we position a sensor that measures chemical or physical properties of a specific point in the unit operation, the measures received must be steady irrespective of the time. When the unit operation functions irrespective of the time the system is in a **steady state**.

Conversely, when a unit operation functions in batch, the transformations produced in the system will be time dependent. In this case, the system is in a **transient state** (Bird, et al. 2006).

Regarding the general balance, the time dependency affects the matter or the energy accumulation of the system, since the system cannot be time dependent when the unit operation is in a steady state; consequently, the accumulation must be zero. Conversely, a unit operation in a transient state does have accumulation.

Steady state: a system is in a steady state when all the chemical and physical properties, at a specific point in the system, remain stable and invariable over time, and points may differ from one another.

Unsteady state: A system is in a transient state when all the physical and chemical properties, at any point in the system, varies over time.

The processes that function in a steady state, at the starting or stopping points, have a transient behaviour and take a certain amount of time until they reach a steady state.

Use the QR code if you are unable to view the videos correctly or if you would like to access the self-assessment test.

http://tiny.cc/6715_intro_eng

QR Code 1.1 Video and self-assessment test of this chapter's contents.

Chapter 2
Matter Balance

2.1. Introduction

As explained in the previous chapter, the changes in matter that can occur in a specific system or control volume, chosen by us, are ruled by the first principle of thermodynamics. In other words, the chemical species that enter our control volume can transform into other chemical species, they can be stored inside, or they can exit. If we observe figure 2.1 we can see an example of the analysis described previously of a cell. A number of chemical species penetrate the membrane through the protein channels; and some react in the various cellular metabolisms, like the respiratory metabolism; others, are stored in the cells reservoir; and lastly, other chemical species are excreted outside the cell.

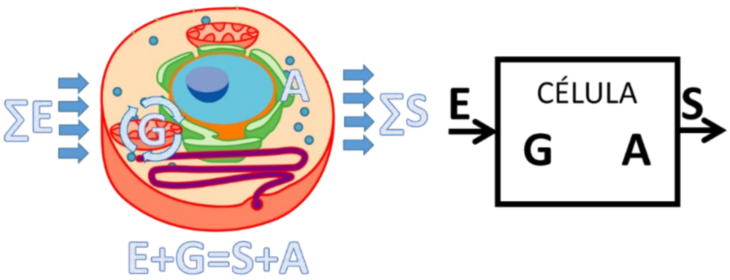

Figure 2.1. Control volume of a cell and the application of the general balance. Where E represents the input of chemical species, S represents the output of the same, G represents the chemical (biochemical or microbiological) transformation and A would be the accumulation.

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