Universidad de Oviedo
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MASTER'S DEGREE FINAL PROJECT

MASTER IN CHEMICAL ENGINEERING

TECHNO-ECONOMIC STUDY OF THE SEPARATION OF GASES FROM IRON AND STEEL MAKING BY MEMBRANE TECHNOLOGY

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RESUMEN

El actual sistema energético se basa principalmente en el uso de los diversos combustibles fósiles existentes. A día de hoy, suplen más del 75% de la demanda energética. Esta fuerte dependencia energética ha dado lugar a un problema de carácter ambiental, el llamado cambio climático.

A fin de revertir esta situación, o de minimizarla, se están invirtiendo grandes recursos en la investigación de energías renovables y de tecnologías para la prevención de la contaminación. En este contexto se ha propuesto el concepto de captura del dióxido de carbono, basado en la posibilidad de atrapar dicho compuesto, uno de los principales gases emitidos a la atmósfera por el uso de combustibles fósiles y responsable directo de la temperatura terrestre. Esta tecnología facilitaría también el almacenamiento del dióxido de carbono, que podría emplearse posteriormente para otros fines.

A día de hoy existen varios métodos para la captura del dióxido de carbono, sin embargo, estos no están aún lo suficiente desarrollados. Entre las tecnologías en estudio se encuentran la adsorción con cambios de presión (PSA), la destilación criogénica y la separación con membranas.

Una de las ventajas que supone el uso de membranas frente a los otros dos métodos es el menor consumo energético requerido, así como la posibilidad de unas mayores cantidades de dióxido de carbono capturado. Tiene la ventaja adicional de emplear equipos de instalación y operación sencilla, y además, presenta gran flexibilidad para combinarse con otros procesos de separación.

En este Trabajo de Fin de Master (TFM) se ha evaluado el empleo de membranas poliméricas comerciales en el tratamiento corrientes gaseosas de la industria metalúrgica con presencia de dióxido de carbono. Para ello se ha creado un modelo matemático que incluye las ecuaciones de transporte y el diseño de unidades con una o varias etapas. La simulación se ha implementado en MS Excel y automatizada mediante el empleo de macros. Los pasos seguidos para ello están recogidos también en este documento, así como el proceso de validación de modelo.

Las simulaciones han permitido seleccionar la membrana más adecuada e identificar los parámetros óptimos de operación. Sobre la base del mejor diseño encontrado, se ha realizado un estudio económico de la inversión y los costes de operación asociados para una instalación a escala industrial.

EXECUTIVE SUMMARY

The current energy system is primarily based on the use of various existing fossil fuels. Today, more than 75% of the energy demand is provided by these fuels. This strong energy dependence has given rise to an environmental problem, the called climate change.

In order to reverse this situation, or to minimize it, large resources are invested in the investigation of renewable energies and technologies for the prevention of pollution. It is in this situation that the concept of carbon dioxide capture appears. This initiative is based on the possibility of trapping this compound, one of the main gases emitted into the atmosphere by the use of fossil fuels and directly responsible for the earth's temperature. This technology would also facilitate the storage of carbon dioxide, which could later be used for other purposes.

At present, there are several methods for capturing carbon dioxide, but these are not yet sufficiently developed. One of the main routes for carbon dioxide sequestration is adsorption with pressure changes (PSA) or cryogenic distillation. However, today an already existing technology that has raised interest for the capture of these gases is the called membrane technology.

One of the advantages of using membranes over these methods is the lower energy consumption required, as well as the possibility of greater quantities of captured carbon dioxide. This technology is also easy to install and can be combined with other devices.

In this Master Thesis, we will show the simulation data obtained for different polymeric membranes when treating gaseous streams of industrial origin (metallurgical industry) with the presence of carbon dioxide. For this purpose, it was required to build a program that simulates a membrane unit using the MACROS application of Microsoft Excel. The steps followed for this are also included in this document, as well as the validation process.

The simulations have made it possible to identify not only which of the membranes under study gives the best results, but also to identify optimal operating parameters in carbon dioxide permeation.

Subsequently, an economic study was carried out on the possible installation of membrane equipment to treat this type of metallurgical streams.

INDEX

INDEX OF TABLES

INDEX OF FIGURES

1. INTRODUCTION

1.1. General information

The called greenhouse effect is a phenomenon that causes an increase in the temperature of the earth's crust. The gases responsible of this effect are called greenhouse gases (GHG), and they are compounds regulated by the carbon and nitrogen cycles. These types of elements have always been found naturally, but as humans evolved and developed industrial activities, along with an increase in energy consumption, industrial emission of these gases also rose. Therefore, most GHGs have an anthropogenic origin today, as the methane present in natural gas, perfluorocarbons (PFCs) in refrigerants and carbon dioxide emitted during the combustion of fossil fuels. The latter is considered the main GHG (*Zhao et al., 2010)*.

The concentration of carbon dioxide in the atmosphere has increased more than 100 ppm in the last century, from 280 ppm at the beginning of the century to 384 ppm in 2007 *(Zhao et al., 2010).* In addition, the World Meteorological Organization (WMO) reported that in 2015 the atmospheric concentration of carbon dioxide exceeded 400 ppm for the first time. Given that the economic growth of developed countries is linked to the consumption of fossil fuels, it is logical to think that as their energy demand increases, the carbon dioxide emissions will also increase along with the Earth's temperature, if no more environmentally efficient CO_2 capture technologies or new technologies are developed.

Figure 1 shows several projections of the global Earth's temperature, as a function of the tons of carbon dioxide emitted over the next century.

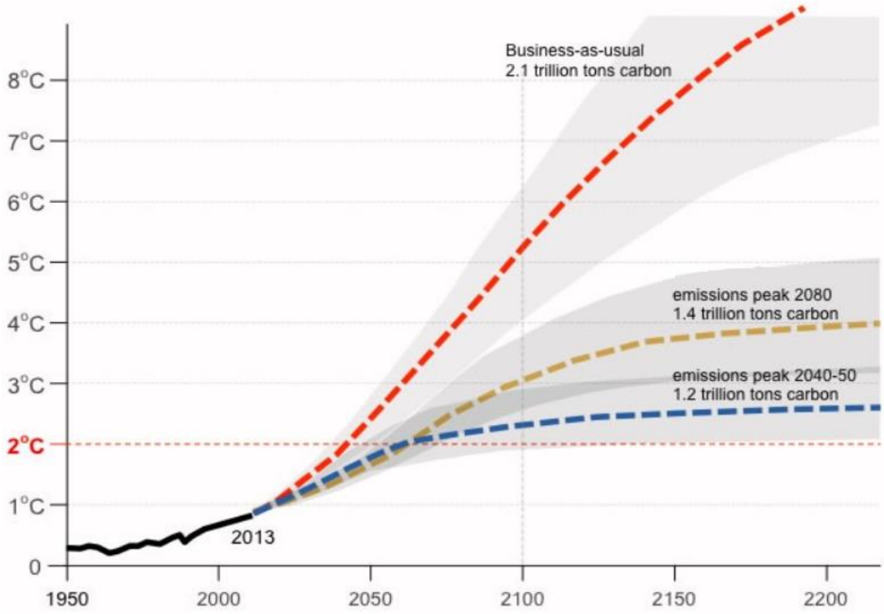


Fig 1. Projection of terrestrial temperature increase in relation of tons of carbon dioxide emitted (*Architecture200, 2013*)

The long-term climate impact is beginning to be understood and that is why it is necessary to control the emissions of these gases. In order to achieve an environmental commitment from the different sectors involved in carbon dioxide or other GHG emissions, various environmental regulations have been promoted, such as the Kyoto Protocol and the Paris Agreement, which seek to comply with the 20/20/20 commitments and stipulating that each country attached to it has the obligation to combat global warming to ensure that the temperature of the earth's surface does not increase by more than 2°C by the end of the century *(European Commission, 2010)*. To this end, the 20/20/20 includes a 20% reduction in greenhouse gases compared to 1990 levels, a minimum of 20% consumption in renewables and a 20% increase in energy efficiency. In order to achieve these objectives, various measures have been implemented, among which are permits of emission which grant the right to emit a certain quantity of compounds into the atmosphere. This forces companies that need an increase in emissions above their limit to buy bonds from other companies to satisfy their demands. Another measure that complements carbon credits were carbon taxes, an environmental tax that affects the emission of carbon dioxide released into the atmosphere. This tax sets a price for the released quantities and applies to small senders of carbon dioxide that can hardly be assigned any quota. The idea behind these measures is to discourage emissions of pollutants produced in industry, as they would lead to an increase in the price of their products, and –thus- a loss of competitiveness. For this reason, the most efficient companies should be able to reduce costs by not having to deal with invoices caused by emission permits or the trading of these rights *(Ramstein et al., 2019)*. That is why the objective is not only to contribute to a decrease in the carbon dioxide emitted, but also to achieve a lower dependence of many countries on fossil fuels and achieve progress towards a sustainable economy.

It is not surprising that the most developed countries have carried out more research with the aim of developing technologies to reduce the carbon dioxide emitted in energy production processes, the production of goods or the revaluation of waste through technologies for the capture, sequestration and storage of greenhouse gas, investing large sums of both financial and human resources.

1.2. The carbon dioxide in the steel industry

Steel is today one of the most important construction materials due to its durability, strength and cost. However, steel production is also responsible of carbon dioxide emissions because of the high energy consumption involved in the process. Carbon dioxide emissions constitute 93% of the greenhouse gas emissions of the steel industry. Figure 2 shows the evolution of these emissions over the last decade.

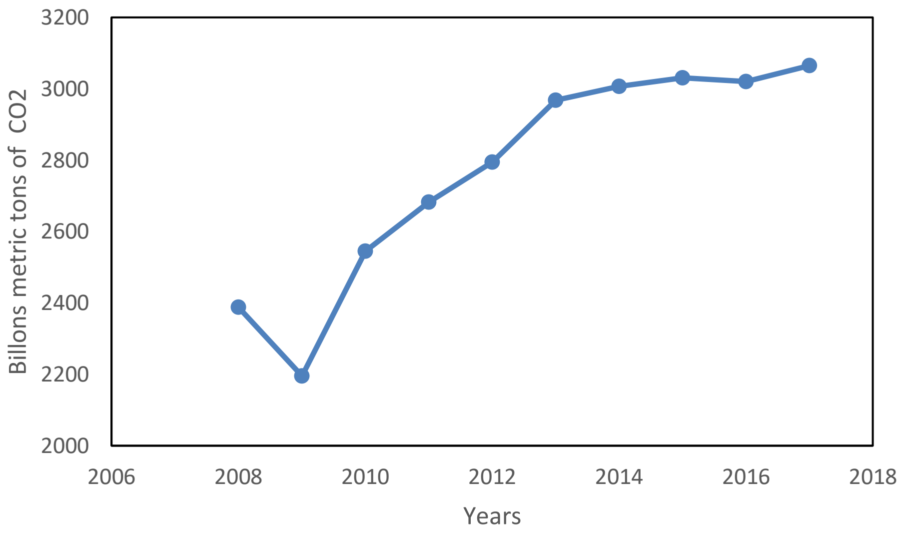


Fig 2. Evolution of CO_2 emissions in recent years (adapted from World Steel Association, 2018)

A sudden drop in emissions in 2008 can be observed, this is due to the economic crisis that began the same year.

The increases from 2015 are due to an increase in the proportion of steel produced via blast furnace (BF). Today it is estimated that the steel industry generates 6.7% of greenhouse gas emissions in the world *(Chen et al., 2014)*.

BF and electric arc furnace (EAF) processes are the dominant routes for steel production in the world and account for about 70% of energy consumption and emissions mentioned above *(Chen et al., 2014)*. Multiple studies have shown that various energy saving technologies have significantly reduced the energy consumption of the ironmaking process. *(Shen et al., 2018)*, as can be seen in Table 1 (Annex 1), however, this reduction in manufacturing costs does not take into account the rising costs of carbon dioxide emission permits and taxes explained in section 1.1, as well as the expected increase in energy demand because of the progressive industrialisation of developing countries. Therefore, innovative proposals, alike those focused on capture and recycling of carbon dioxide in order to convert it into useful products, such as fuels, derived hydrocarbons, refrigerants, solvent for supercritical extractions, as well as and in agricultural applications may play an important role.

1.3. Technologies for the reduction of carbon dioxide emitted

There are multiple technological pathways to achieve GHG emission reductions: reduced energy consumption, increased energy efficiency, use of less carbon-intensive fuels, use of renewable energy and capture and storage of carbon dioxide (CSC). The CSC is a recent alternative proposed to reduce carbon dioxide emissions into the atmosphere *(Bains et al., 2017)*. This process has three stages, in the first one the capture of the emitted carbon dioxide takes place, separating it from the rest of the compounds and compressing it at high pressures. After this, the captured carbon dioxide is transported to a storage space *(Rubin et al., 2012)*. This carbon dioxide can be used as a reagent for the production of fuels, carbonates or other chemicals of interest. This results in a circular economy of carbon dioxide of anthropogenic origin, as it can be used to obtain value added products (in addition to the economic savings for the emitting industry). In this report, the use of membrane technologies for the capture of carbon dioxide in the metallurgical industry is studied. This is still an emerging technology, but promising on the long-term, compared to other gas stream capture technologies such as chemical or physical adsorption *(Bredesen et al., 2004)* .

2. OBJECTIVE

The main objective of this Master Thesis is the development of a techno-economic study of the separation of exhaust gases from steel manufacturing by means of membrane technology. The specific objectives are:

1. A detailed research on the different steel gases (origin and features) together with the correct identification of the components present in these gases in addition to carbon dioxide. A bibliographic analysis of the state of the art of the applications of membrane separation technology in steel manufacture will also be carried out.

2. Based on the data obtained, the design, simulation and optimization of the membrane separation processes will be carried out. Several steel gases, as well as different membranes will be assessed and sensitivity analyses performed to evaluate how the different operating variables (pressure, temperature, membrane area and unit configuration) affect gas separation. Single and multi-stage membrane separation processes will be studied while developing a user-friendly spreadsheet with automatic calculations based on the desired design/optimization criteria.

3. Finally, a preliminary economic evaluation of the optimized design will be carried out, taking into consideration investment and operating costs. Special emphasis will be put on membrane costs and lifetime, and energy consumption as it is anticipated they will be the most relevant contributions to the operating costs.

3. STATE OF THE ART

3.1. Sources of carbon dioxide in industry

The carbon dioxide is a gas that mostly results from combustion of organic matter (mostly from fuels in industry). However, can be obtained in other ways in industry, both directly and indirectly. Some examples are explained below.

- Combustion of carbon-based fuels:

  These fuels include methane or natural gas, oil distillates such as gasoline, wood and coal. All these processes lead to the production of carbon dioxide. An example of this type of reaction (methane combustion) can be seen below *(Simmons, 2000)*

  $$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O} \qquad \text{C.R. [1]}$$

- Iron reduction:

  Iron is reduced from its oxides with coke in a blast furnace, producing pig iron and carbon dioxide. This process is very common in the metallurgical industry and the gases produced are amongst those studied in this Master Thesis *(Spirin et al., 2016).* The main chemical reaction is:

  $$\mathrm{Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2\ O} \qquad \text{C.R. [2]}$$

- Production of alcohol beverages:

  Carbon dioxide is a by-product of the fermentation of sugars in the brewing of alcoholic beverages and in the production of bioethanol. The yeast metabolizes sugar to produce carbon dioxide and ethanol, the overall reaction is as follows *(de Matos et al., 2017):*

  $$\mathrm{C_6H_{12}O_6 \rightarrow 2\,CO_2 + 2C_2H_5OH} \qquad \text{C.R. [3]}$$

- Partial oxidation of oil fractions:

  This process is very common for the production of hydrogen and consists of the reaction of hydrocarbons with oxygen in a stoichiometric amount. This is to avoid the total combustion of the hydrocarbons and for obtaining a synthesis gas enriched in hydrogen. This process can be defined by the following reactions *(Campanari et al., 2020):*

$$\mathrm{C_nH_m + \frac{2n+m}{4} O_2 \rightarrow n\,CO + \frac{m}{2} H_2O} \qquad \text{C.R. [4]}$$

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2} \qquad \text{C.R. [5]}$$

The first reaction is partial oxidation, which is carried out at high temperatures. This reaction is exothermic and the heat released helps to maintain the necessary temperature. The second reaction is the so called the WGS (Water Gas Shift Reaction) type which is actually a water gas conversion reaction.

3.2. Current technologies to capture gas emissions

Although the ability to remove carbon dioxide from emission sources is known, there are very few large-scale implementations of these technologies. Reasons are the high costs involved and in most cases, the lack of development of some technologies at the desired level. Therefore, one current objective of the research that is being carried out worldwide is to achieve the economic optimization of the processes employed. From a technical point of view, the objective is to produce concentrated streams of carbon dioxide, easily transportable to safe storage spaces. These technologies were initially applied in coal and natural gas power plants. This has generated an increased interest in these technologies, as well as their study for possible implementation in other types of industries such as steelworks, refineries, cement and chemical plants, and in biomass processes that involve carbon dioxide emissions *(Wankat, 2004)*.

There are different methods to capture carbon dioxide or other gases; Figure 3 shows a diagram of the current state of development of them.

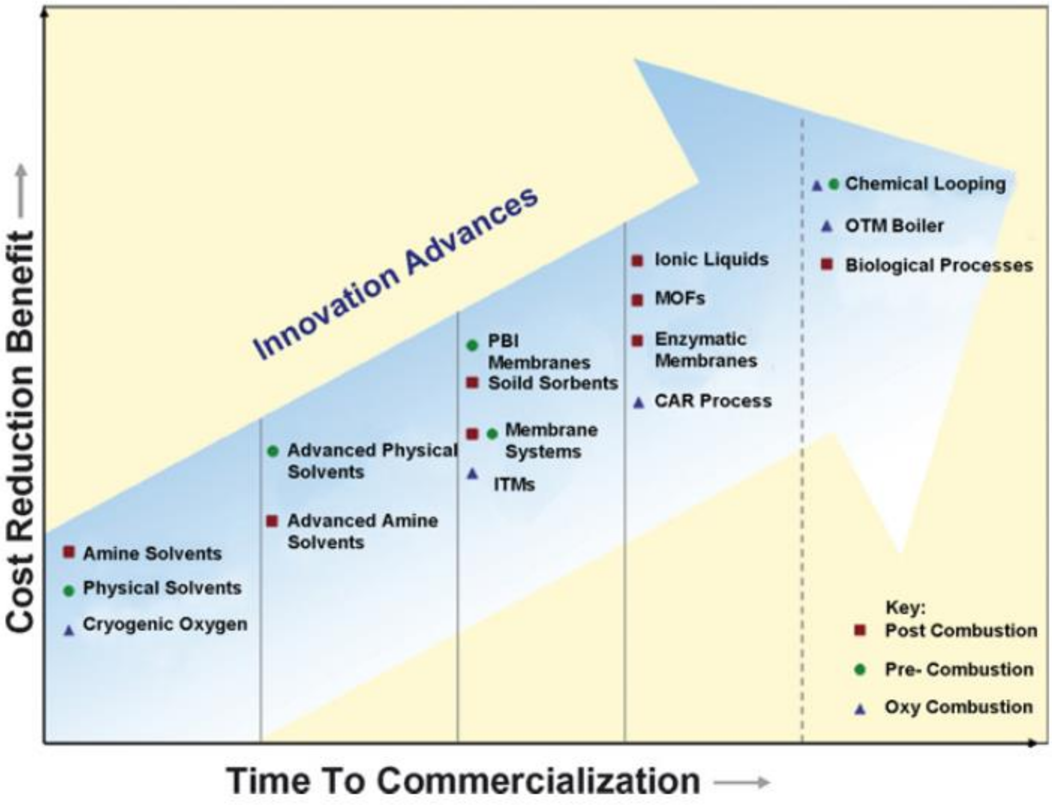


Fig 3. Innovative CO_2 capture technologies-cost reduction benefits versus time to commercialization (Figueroa et al., 2008)

Among the methods shown in Figure 3, pressure swing adsorption (PSA) systems, cryogenic separation and membrane technology are the most commonly used for separation of carbon dioxide. The first two are already used in industry but which have a high energy cost. Membrane separation is an alternative to them because it offers similar separation at a lower cost for some applications. These separation processes are explained in more detail below:

- <u>Pressure Swing Adsorption (PSA):</u>

  Chemical absorption technology is well-developed and has been used for years, particularly in chemical plants, power generation and fertilizer production. The process is usually called amine scrubbing and is the most commonly used carbon dioxide removal technology nowadays.

  The main disadvantage of this operation is its high energy costs, this affects the profitability of the process and makes it only suitable for large productions, such as those of the petrochemical industry *(Vaccarelli et al., 2014).*

- Cryogenic distillation:

  It is a process based on the physical separation of carbon dioxide from the gaseous stream, condensing it at low temperatures and obtaining liquid carbon dioxide. This is achieved through a series of compression, cooling and expansion stages.

  The main disadvantage of this process is the large amount of energy required. In addition, the need to remove some components from the streams to avoid blockages increases the overall complexity and costs. Therefore, despite it yields good performance, its presence at industry is limited *(Debnath et al., 2019)*

- Membrane separation:

  Membrane gas separation is an industrial alternative that can potentially offer comparable performances at lower costs than the two processes explained above. In addition to cost reduction, this technology stands out for its simplicity of operation and the possibility of combining it with other technologies *(Wankat, 2004).*

  This Master Thesis will address the possibilities of treating carbon dioxide-rich gases with technology.

3.3. Membrane technology

Membranes act as selective barriers that allow the separation of the components of a stream. For the current commercial membranes, the component to be separated (carbon dioxide) passes through the membrane, being separated as the permeate (or filtrate) stream. The remaining components of the feed stream produce the retentate.

The flow through the membrane is linked – in gas separation processes that use dense membranes- to the partial pressure gradient between the feed (or retentate) and permeate streams. The actual pressure gradient across the membrane, thus, affects the separation efficiency and will be evaluated. Figure 4 shows a diagram of how two gases are separated by a membrane.

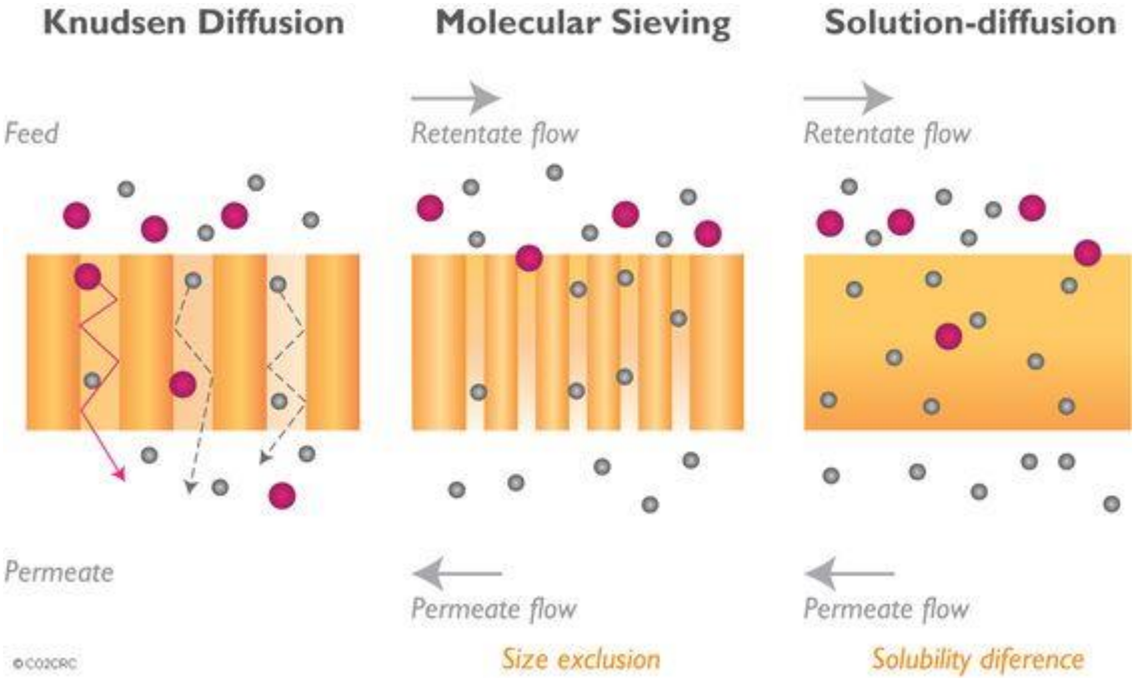


Fig 4. Diagram of the separation of different gases through a dense membrane *(Ji and Zhao, 2017)*

The main limitation of this technology is the difficulty in obtaining high purity gases. However, it has great advantages over other techniques, such as lower operating costs and greater simplicity of assembly and maintenance. Another advantage is that it is compatible with other separation technologies.

In theory, any thin-film material can act as a membrane. This includes materials as metals, crystals, polymers and ceramics. The separation will, therefore, depend on the differences in the physical-chemical properties of material forming the membrane and the substances that have to be separated. Some of these properties are density, volatility, solubility or geometry, to mention only some of them *(Wankat, 2004).*

This barrier may be homogeneous or heterogeneous in nature, symmetrical or asymmetrical in structure, solid or liquid. The correct selection of a membrane is determined by the desired objective, such as the retention of specific particles, the reduction of the hardness of a liquid or the removal of emitted gases *(Ji and Zhao, 2017)*. Membrane types and structure are described in more detail below.

3.3.1. **Types of membranes**

The way the molecules pass through the membrane is related to its structure. For this reason, it is necessary to design the membrane in such a way that it can provide high permeability and selectivity for the species to be separated. The nature of a membrane can be biological or synthetic. Membranes in turn can be differentiated into organic and inorganic.

The materials used for the preparation of (synthetic) membranes can be polymers, ceramics, glass, metals, or liquids. The materials may be neutral or carry electrical charges (fixed ions). Figure 5 illustrates the typical classification of synthetic membranes based on their material and structure.

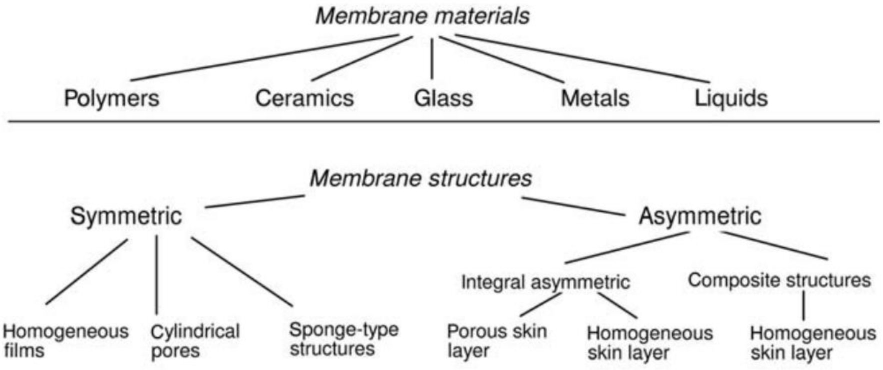


Fig 5. Possible classifications of membranes according to the chosen criteria (Strathmann, 2012)

Inorganic membranes (metallic, ceramic, glass) have the advantage of resisting harsh operating conditions, harsh chemical cleaning and high temperature. They offer wear resistance, high chemical stability, long lifetime, and can be auto washable. However, their cost is in general one order of magnitude higher than that of polymeric membranes *(Fard et al., 2018).*

Polymeric membranes are the most commonly used nowadays. Polymeric membranes can be made of different kind of polymers, with different resistance and properties. For instance, they can be hydrophobic, such as those made of polypropylene (PP), or hydrophilic, such as polyamide membranes (PA).

A variant on polymeric membranes is a carbon membrane. These membranes are constructed by heating a polymeric membrane above its decomposition temperature. These membranes can give excellent performance, but tend to have significant problems such as brittleness and cost *(Powell and Qiao, 2006)*.

The most common polymers used for membranes are thermoplastics (linear-chain polymers composed that soften with an increase in temperature and are soluble in organic solvents). They are used in industry for the separation of gases containing nitrogen or carbon monoxide. The main disadvantage of these membranes is their relatively low mechanical and thermal resistance, so their operating temperature must lie between 100-300 ºC. They are also highly sensitive to acidic compounds. For this reason, it is necessary to pre-treat the gas streams (normally carried out by physical or chemical absorption) in order to remove these compounds. These membrane materials and the cheapest and most developed.

An additional advantage is their high versatility, which can be summarized in the following points *(Seader et al., 2013)*.

- Possibility of exercising some control over the molecular configurations of the polymers, which affects the permeability and selectivity of the membranes.
- They can easily take different physical forms, which is an advantage for implementation in different equipment.
- The great variety of existing polymers, this gives multiple options to produce the desired membrane.

For all the above mentioned reasons, polymeric membranes are the most commonly found at industrial applications and will be the ones studied in this work.

3.3.2. **Membrane structure**

The synthetic membranes may have a symmetric or an asymmetric structure. In a symmetric membrane, the structure and the transport properties are identical over the entire cross section, and the thickness of the entire membrane determines the flux. Symmetric membranes are used today mainly in dialysis and electro dialysis. In asymmetric membranes structural and transport, properties vary over the membrane cross section. An asymmetric membrane consists of a ‘‘skin’’ layer on a highly porous thick substructure. The skin represents the actual selective barrier of the asymmetric membrane. Its separation characteristics are determined by the nature of the material or the size of its pores. Asymmetric membranes are used primarily in pressure-driven membrane processes such as reverse osmosis, ultrafiltration, and gas and vapour separation, since here the unique properties of asymmetric membranes, that is, high fluxes and good mechanical stability, can best be utilized *(Fard et al., 2018).*

A porous structure represents a very simple form of membrane, which closely resembles the conventional fibre filter in terms of separation mode. These membranes consist of a solid matrix with defined holes or pores with diameters ranging from less than 1 nm to more than 10 micrometres. The separation of the different components is carried out by means of a sieving mechanism in which the determining parameters are the diameters of the pores and the size of the particles. Porous membranes can be made of various materials such as ceramics, graphite, metals, metal oxides and various polymers.

Porous membranes are used to separate components that differ significantly in size or molecular weight in processes such as micro and ultrafiltration or dialysis *(Elsevier and Wiley-liss, 1996)*.

A dense membrane is a film through which a mixture of molecules is transported by a gradient of pressure, concentration or electrical potential. They can be used in symmetric membranes or as the top layer in asymmetric membranes. The separation of the different compounds of a mixture is related to their transport rates within the membrane phase, determined by their diffusions and concentrations in the membrane matrix. These membranes are mainly used to remove components of similar size but of different chemical nature in processes such as reverse osmosis, gas and vapour separation and pervaporation *(Hamad et al., 2005)*. In this study, commercial asymmetric membranes with a dense skin layer are studied.

3.4. Membrane carbon dioxide permeation mechanisms

The transport mechanism of carbon dioxide can follow several diffusion mechanisms depending on the structure of the membrane:

- Fully porous membranes:

  When the pore size is high, the molecule-molecule collision is dominant over the molecule-wall collision. That means that the free path less than the pore size.

$$\frac{\lambda}{d} \ll 1 \qquad \text{Eq. [3.1]}$$

Where λ is the free path and d the diameter of the pore.

In such situation, viscosity plays an important role in the mass transfer. Viscosity increases with temperature for gases, specifically, if the transportation is in the viscous regime, the flux is a decreasing function of temperature.

When the pore size is reduced down to the scale much smaller than mean free path, the molecular-wall collision is more dominating than intermolecular collision. This means that viscosity is not playing a role for the gas transportation. In this situation, the pore geometry and gas molecule velocity are more dominant in the mass transfer. This type of transport is called Knudsen diffusion. If he molecule-wall collision is dominant over molecule-molecule collision, the Knudsen number (K_n) must be much higher than 1 *(Ji and Zhao. 2017)*.

$$Kn = \frac{\lambda}{d} \gg 1 \qquad \text{Eq. [3.2]}$$

The permeate flux (J) can be described by the Knudsen diffusion model.

$$J = -\frac{2}{3} \cdot \frac{\varepsilon_p r_p}{\tau_T} \sqrt{\frac{8}{\pi RTM}} \cdot \frac{\Delta p}{l} \qquad \text{Eq. [3.3]}$$

Where ε_p is the porosity of the pore, τ_T is the tortuosity of the pore, R is the gas constant, T is the temperature, p is the pressure, r_p is the pore radius, M is the molecular weight and l is the membrane thickness.

For the same pore at a fixed temperature, the permeate flux can be described by the molar weight. However, due to the limited selectivity, the Knudsen diffusion is rarely used for separating real gas mixtures.

- Dense membranes:

Transport in dense films is often explained with a solution-diffusion mechanism *(Ji and Zhao, 2017)*, which for the case of carbon dioxide is as follows:

Diffusion of the carbon dioxide molecules from the feed stream through the membrane. The transport rate of a substance across a membrane can be expressed by Fick's first diffusion law:

$$J_{CO_2} = -D \frac{dC_{CO_2}}{dx} [=] \frac{mol}{m^2 s} \qquad \text{Eq. [3.4]}$$

Where D $\left(\frac{m^2}{s}\right)$ is the effective diffusion coefficient of the carbon dioxide molecule, C_{CO_2} $\left(\frac{mol}{m^3}\right)$ is the carbon dioxide concentration in the x-position and x (m) is the distance to be covered. If it is assumed that there is no interaction between the permeated molecules and the membrane (or the mixture is sufficiently diluted), the concentration of the molecules in the membrane material is proportional to its solubility:

$$C_{CO_2} = S \times P_{CO_2} \qquad \text{Eq. [3.5]}$$

Where S $\left(\frac{mol}{m^3 Pa}\right)$ is the solubility of the carbon dioxide molecule in the membrane and P_{CO_2} (Pa) is the partial pressure of carbon dioxide in the feed. Substituting eq. 3.5 in eq. 3.4:

$$J_{CO_2} = -D\frac{d(S \times P_{CO_2})}{dx} [=] \frac{mol}{m^2 s} \qquad \text{Eq. [3.6]}$$

The product of the solubility and diffusivity of the gas in the membrane is also called permeability, Q_{CO_2}

$$Q_{CO_2} = D \times S \, [=] \frac{mol \cdot m}{m^2 \cdot s \cdot Pa} \qquad \text{Eq. [3.7]}$$

If the diffusivity is independent of the carbon dioxide concentration (which is typical at low concentrations), eq. 3.6 can be integrated along the thickness of the membrane resulting in the commonly used gas transport equation:

$$J_{CO_2} = \frac{Q_{CO_2}}{L}(P_{CO_2} retentate - P_{CO_2} permeate) \qquad \text{Eq. [3.8]}$$

Where L (m) is the membrane thickness, $\mathrm{P_{CO_2} retentate\ (Pa)}$ the partial carbon dioxide pressure in the retentate, and $\mathrm{P_{CO_2} permeate\ (Pa)}$ is the partial $\mathrm{CO_2}$ pressure in the permeate. Therefore, the permeate flow of a gas compound is directly proportional to its permeability in the membrane and to the driving force (partial pressure difference), and inversely proportional to the membrane thickness. Thus, the relevance of using dense selective membrane as thin top layers on porous supports.

The ratio of permeability over membrane thickness is called permeance, and it is often used to compare performance of different membranes:

$$F = \frac{Q}{L} \, [=] \frac{mol}{m^2 \cdot s \cdot Pa} \qquad \text{Eq. [3.9]}$$

Permeability (and permeance) are strongly dependent of temperature, following Arrhenius-type equation:

$$Q = Q_0 \times e^{\frac{-Ea}{RT}} [=] \frac{mol}{m \cdot s \cdot Pa} \qquad \text{Eq. [3.10]}$$

Where $Q_0 \left(\frac{mol \cdot m}{m \cdot s \cdot Pa}\right)$ is the pre-exponential factor, $\mathrm{E_a} \left(\frac{\mathrm{kJ}}{\mathrm{mol}}\right)$ is the energy activation, $\mathrm{T}\ (\mathrm{K})$ is the temperature and $\mathrm{R} \left(\frac{\mathrm{kJ}}{\mathrm{K \cdot mol}}\right)$ is gas ideal constant. Both the pre-exponential factor and the activation energy are a function of the material that makes up the membrane.

Moreover, the efficiency of the separation process on the membrane can be defined by the separation factor:

$$\alpha_{CO_2/i} = \frac{y_{CO_2}}{yi} \Big/ \frac{x_{CO_2}}{xi} \qquad \text{Eq. [3.11]}$$

Where $\alpha_{CO_2/i}$ is the separation carbon dioxide factor with respect to another compound (i) in the gas mixture, y_{CO_2} is the molar fraction of carbon dioxide in the permeate, y_i is the molar fraction of the inert gas in the permeate, x_{CO_2} is the molar fraction of carbon dioxide in the retentate, and x_i is the molar fraction of the inert gas in the retentate. For a zero permeate pressure, the separation factor is equal to the ratio of permeabilities (or permeances). This approximation is often used even under real conditions (non-zero pressure) for membrane screening.

3.5. Parameters affecting membrane performance

Taking into account the solution-diffusion mechanisms, permeate flowrate of $\mathrm{CO_2}$ and permeate concentration (purity) are a function of the membrane (as the membrane material defines the permeability) as well as several operating variables:

- Membrane thickness
- Temperature
- Feed and permeate pressures
- Gas composition and impurities

Regarding the thickness of the membrane, it has to be taken into account how it affects the permeated carbon dioxide flow. When a membrane is very thin, is a very fast phenomenon and of mainly diffusion character, this is because in these very fine polymeric membranes (<5 µm) micropores tend to form, which leads to a reduction in selectivity.

In the case of thick membranes this phenomenon does not tend to occur and therefore its selectivity is not affected, giving rise to a separation by means of a solution-diffusion phenomenon that follows more faithfully the first law of Fick.*(Elsevier and Wiley-liss, 1996)*

With regard to temperature, CO_2 permeability and temperature are related by equation 3.9. With this it can be stated that at high temperatures the activation energy of the diffusion process (endothermic) exceeds the activation energy of the adsorption (exothermic). In summary, the higher the temperature, the more favourable is the permeation process on the membrane.*(Zhao et al., 2010).*

Feed and permeate pressure have a direct influence on the driving force. For a given feed concentration, an increase in feed pressure or a decrease in permeate pressure results in a larger driving force, thus higher permeate flow. Pressure, in practice, is limited by the compression costs and the membrane resistance.

Flue gases from combustions have a range of minor components present, typically $\mathrm{NO_x}$ (1000–5000 ppm), $\mathrm{SO_x}$ (10–500 ppm), NO (<20 ppm) and water (saturated). Hence, their presence within the polymeric membrane can lead to competition with carbon dioxide for separation, as well as chemical degradation and plasticization of the polymeric structure. All of these components can reduce the separation efficiency of the process and potentially lead to membrane failure *(Scholes et al. 2011)*. In this study, the feed stream that is sent to the membrane separation unit is considered to be free of the above impurities. In practice, this would likely require a pre-treatment of the gas mixture (which is out of the scope of this work).

3.6. Processes for the production of steel and gases produced

Carbon dioxide is present in various gaseous streams generated in steel production. The main ones are described below and their treatment using membrane technology will be the target of this work.

3.6.1. **Blast furnace gas**

Blast furnace is s a type of metallurgical furnace used for smelting to produce industrial metals, generally pig iron, but also others such as lead or copper. In a blast furnace, fuel (coke), ores, and fluxes (limestone) are continuously supplied through the top of the furnace, while a hot blast of air (sometimes with oxygen enrichment) is blown into the lower section of the furnace through a series of pipes, so that the chemical reactions take place throughout the furnace as the material falls downward. The end products are usually molten metal and slag phases tapped from the bottom, and waste gases (flue gas) exiting from the top of the furnace *(Spirin et al., 2016)*. This gas is called Blast Furnace Gas (BFG), and it consists of about 60% nitrogen and 20% carbon dioxide, which are not flammable. The rest is mostly carbon monoxide, which has a fairly low heating value already and some (2-4%) hydrogen. Due to its composition, it is a gas with very low heating value (around 3,5 MJ/m^3). It is commonly used as a fuel within the steel works, but it can be used in boilers and power plants prepared to burn it.

3.6.2. **Coke oven gas**

Coke (a grey, hard, and porous fuel with a high carbon content and few impurities) is made by heating coal or oil in the absence of air (this is a destructive distillation process). It is an important industrial product, used mainly in iron ore smelting, but also as a fuel in stoves and forges when air pollution is a concern. The industrial production of coke from coal is called coking. The coal is baked in an airless kiln, a "coke furnace" or "coking oven", at temperatures usually around 1000-1100 ºC.

This process vaporizes or decomposes organic substances in the coal, driving off volatile products, including water, in the form of coal gas. The non-volatile residue of the decomposition is mostly carbon, in the form of glassy solid that cements together the original coal particles and minerals. The gas produced in this process is called Coke Oven Gas (COG), and is a fuel gas having a medium calorific value. The main constituents are, by volume, about 50% $\mathrm{H_2}$, 30% $\mathrm{CH_2}$ and 3% higher hydrocarbons, 7% CO, 3% $\mathrm{CO_2}$ and 7% $\mathrm{N_2}$. The gas has a heating value of about 20000 kJ/m^3 *(Valia, 1994)*.

The Coke Oven Gas is normally used as a fuel, the result of this combustion (rich in $\mathrm{CO_2}$) , the so-called Burned Coke Oven Gas, is the gas which is aimed to be treated by the membrane process to recover carbon dioxide.

3.6.3. **Basic oxygen (steelmaking) gas**

Also known as, BOS, Basic Oxygen Steelmaking is a method of primary steelmaking in which carbon-rich molten pig iron is made into steel. Blowing oxygen through molten pig iron lowers the carbon content of the alloy and changes it into low-carbon steel. The process is known as basic because fluxes of burnt lime or dolomite, which are chemical bases, are added to promote the removal of impurities and protect the lining of the converter. The gas produced by this process is called Basic Oxygen Gas (BOG). The main constituents of converter gas are CO ,CO_2, O_2 and N_2. Typical composition by volume is 55-60 % CO, 12-18 % CO_2 , 0,1-0,3 % O_2 and rest is N_2 *(Kennison, 2014)*

Table 1 gives the typical compositions of these metallurgical gases *(Goyena, 2019)*.

Table 1. Typical composition of the metallurgical gases used in this work

	% N_2	% CO	% CO_2	% H_2	% O_2	% CH_4
Blast Furnace Gas (BFG)	47,36	23,23	23,90	4,79	0,72	0,00
Basic Oxygen Gas (BOG)	19,26	59,21	17,68	2,10	0,45	0,00
Coke Oven Gas (COG)	8,16	5,32	1,54	58,68	0,42	25,88
Burned COG*	15,45	8,36	55.,2	5,12	15,75	0,00

3.7. Separation processes using membrane technology

The carbon dioxide capture and storage systems are only applicable at large emission points. The objective of these systems is to separate the carbon dioxide produced until a gas stream with a sufficiently high concentration is obtained. Once this highly concentrated carbon dioxide current is available, it is compressed to transport it to the point where it will be definitively stored. Figure 6 shows a schematic representation of a common industrial combustion process versus the various gaseous component separation processes.

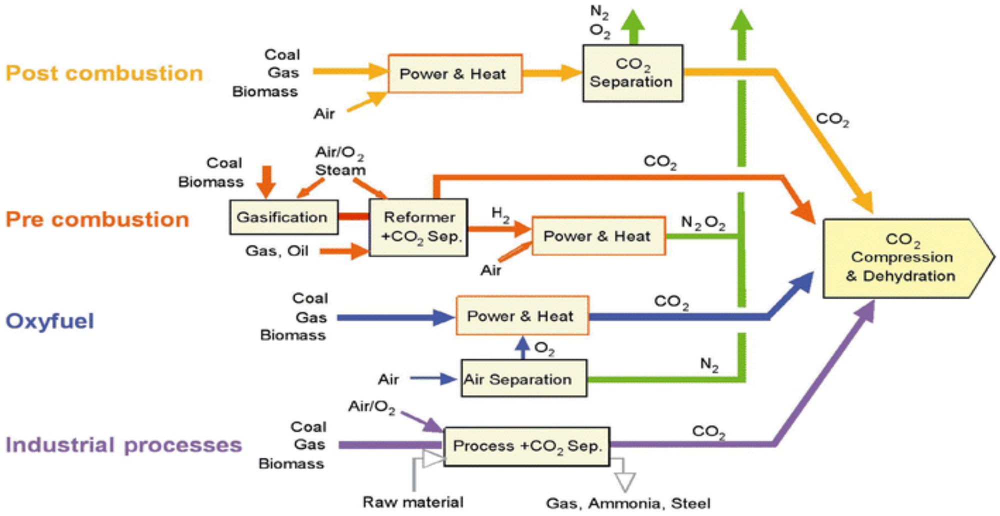


Fig 6. Industrial carbon dioxide capture systems (Benson and Orr, 2008)

The systems are Post-Combustion, Pre-Combustion and Oxy-Combustion (or Oxy-fuel) depending on the moment in which the gas separation takes place with respect to the combustion. These processes and how they affect the separation of carbon dioxide will be explained below.

3.7.1. **Post-combustion process**

A very common situation is having to separate the carbon dioxide produced by the combustion of a fuel. The post-combustion systems are used for this purpose. An example of these gases are the steelmaking gases to be treated in this work (BFG, BOG and burned COG). As already mentioned, this type of flue gases normally contains carbon dioxide, water vapour and nitrogen. The Figure 7 shows a schematic of a post-combustion system.

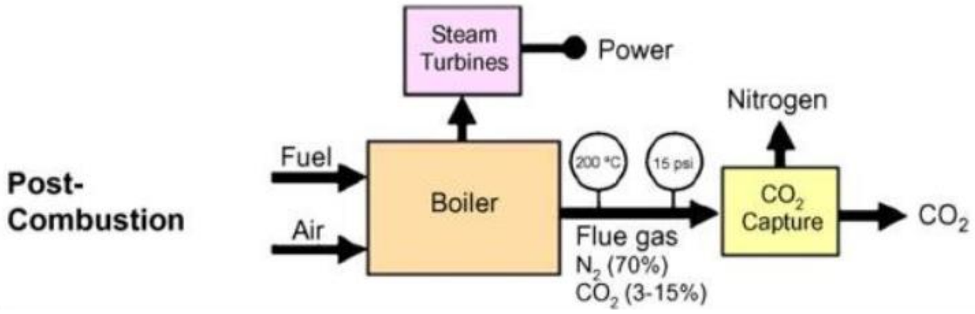


Fig 7. Schematic of a post-combustion system (Benson and Orr, 2008)

The water vapour can be easily and previously removed by a condensation system. However, the separation of CO_2/N_2 is not as straightforward. This is where the membrane process comes in. The separation of these gases is normally done at moderate temperatures and at or near to atmospheric pressure. These operating conditions allowed to compare this type of separation with other alternatives of pre-combustion and oxy-combustion.

One of the main disadvantages found in this type of capture is the commonly low fractions of carbon dioxide in the combustion gases (below 15%), which leads to a low driving force of carbon dioxide permeability.

Separation depends mostly on diffusion of the gas in the membrane and from the bulk of the gas to the membrane. Given that all membrane materials have more solubility for carbon dioxide than for nitrogen, and that carbon dioxide has a smaller diameter than nitrogen (therefore higher diffusivity) the separation takes place by the preferential CO_2 permeation. Therefore, carbon dioxide selective membranes are normally used for post-combustion capture.

In order to be able to capture carbon dioxide from the combustion gases, the membrane must have a high permeability, a high CO_2/N_2 selectivity, as well as a high chemical and thermal stability. This is why polymer membranes have been the only ones used in these systems until now *(Ji and Zhao, 2017).*

Actually, hybrid systems between membrane and absorption processes are currently being investigated, which allows the size of the equipment used to be reduced thanks to the increase in the contact surface provided by the membrane between the gas and the liquid (solvent). The operating problems related to absorption systems are also avoided. The configuration of the entire process is very similar to the chemical absorption process. Current research focuses on improving the transport capacity of the membrane. This transport capacity depends not only on the solubility of the gas and diffusion but mainly on the specific reactivity of the gas with the carrier or conductor. For carbon dioxide separations, carbonates, amines and molten salts are used as conductors *(Xu et al., 2019).*

3.7.2. **Pre-combustion system**

The pre-combustion capture is a process that separates carbon dioxide from fuel gases before the combustion. Figure 8 shows a schematic of a pre-combustion system.

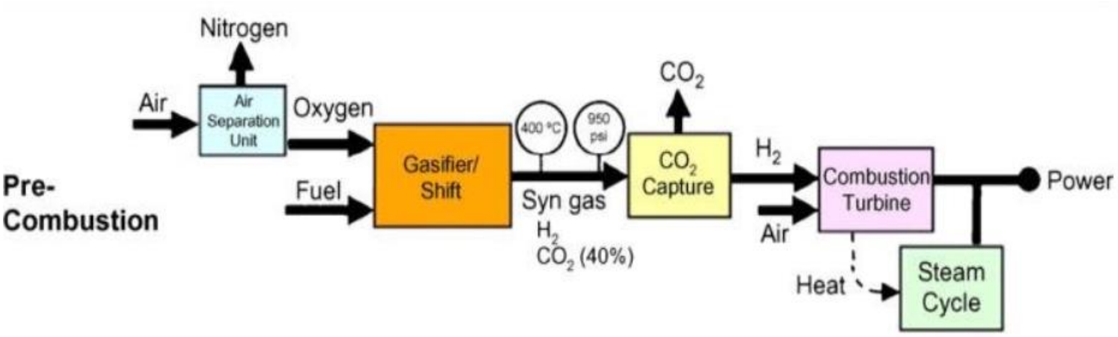


Fig 8. Schematic of a pre-combustion system (Benson and Orr, 2008)

Pre-combustion capture technologies can be applied to all fossil resources, such as natural gas, fuel oil and coal, extending also to biomass and waste *(Scholes et al., 2010)*. Three main steps can be distinguished in the use of primary fuels with pre-combustion capture.

The first step is covert the solid, liquid or gaseous fuels into a mixture of syngas (mostly hydrogen and carbon monoxide) carbon dioxide by a process of coal gasification or stream reforming.

After this, a water gas shift (WGS) reaction is conduced to reduce the presence of carbon monoxide and increasing the presence of carbon dioxide and hydrogen. The membrane separation is then used to separate these components.

The last step is a compression of the carbon dioxide rich stream and its transport to a storage o utilization site. The pure hydrogen stream is conduced to combustion chamber for power generation, this produces mainly water vapour. The feed gas of pre-combustion is hot with a temperature between 300-700 ºC. The separation is also realized at high pressures (around 80 bar) *(Ji and Zhao, 2017).*

The pre-combustion membranes are usually classified into two categories: hydrogen selective membranes and carbon dioxide selective membranes. The first type favours hydrogen permeation but retains carbon dioxide in the feed side, the other membranes does the opposite, permeates preferentially carbon dioxide.

The most used membranes for the pre-combustion separation ate the metallic membranes. These membranes are the ideal candidate for separating H_2/CO_2 due to the high selectivity. Hydrogen molecule dissociates as two atoms at the membrane surface and then the atomic hydrogen pass through the membrane to the permeate side thanks to the partial pressure drop, which is followed by the association and desorption at the permeate interface *(Ji and Zhao, 2017).*

3.7.3. **Oxy-combustion system**

In the oxy-fuel combustion, the oxygen is supplied for combustion instead of air. This prevents the presence of nitrogen in the exhaust gas, the biggest problem faced by the post-combustion carbon dioxide capture technologies. Figure 9 shows a schematic of the oxy-combustion system.

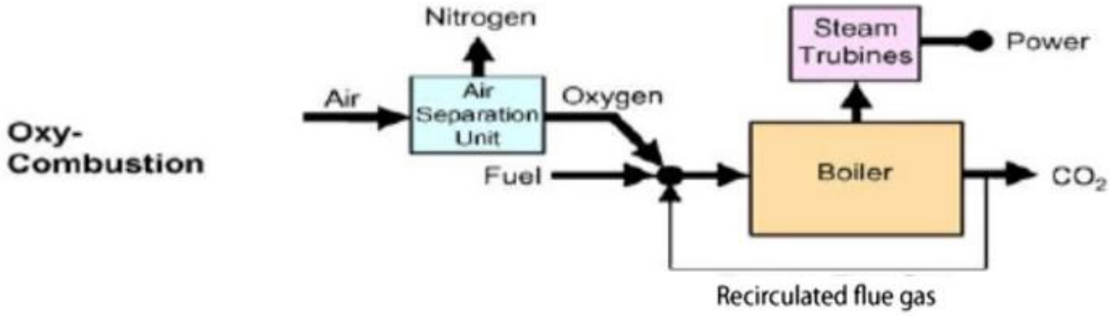


Fig 9. Schematic of an oxy-combustion system (Benson and Orr, 2008)

By using pure oxygen for the combustion, the flue gas will be composed primary by carbon dioxide, water vapour and impurities like hydrogen sulphide. The water vapour can be removed by condensation and the hydrogen sulphide by conventional desulphurization methods. The resulting CO_2 rich gas can be compressed and stored. As can be seen, this is a process in which the separation of carbon dioxide is not done by the use of a membrane, instead, the membrane performs a separation of mainly O_2/N_2. This makes it a different process from the previous ones, in which carbon dioxide selective membranes were necessary. However, it is necessary to mention this process in order to have a complete idea of all the possibilities offered by membrane technology *(Ji and Zhao, 2017).*

The O_2/N_2 separation is based on an ion transport mechanism. The oxygen molecules transforms into oxygen ions at the surface of the membrane and are transported through the membrane under an electric field. After passing the membrane, the ions change back to molecules. The air separation is done at atmospheric pressure while the permeate side it is under vacuum or continuously removed sweep gas. This process is the least developed of three systems. Moreover, compared to other traditional techniques like cryogenic air separation, the temperature and costs required are larger *(Ji and Zhao, 2017).*

4. METHODOLOGY

4.1. Basic description of the membrane separator

The permeation of carbon dioxide in the membranes under study is determined by a solution-diffusion mechanism.

The model for gas separation has been developed to be the core calculation in a spreadsheet that can be later used to simulate or design membrane separation units. Since Microsoft Excel is a commonly used, easily accessible software, and this work is actually the first step in other research or development projects, it has been chosen for this purpose.

The simple membrane separation unit, Figure 10, consists of the following equipment:

- Adiabatic compressor: provides the pressure to the feed which will have a direct impact on carbon dioxide permeation.
- Cooler: ensures the gaseous stream is at the correct temperature, which is typically lower than at the compressor output.
- Expander: (optional) sometimes it may be desired to return the retained gas to the previous pressure. Normally, expansion takes place in a turbine that allows energy recovery, favouring the economics of the process.
- Dehydrator: it can be necessary to remove possible traces of water vapour present in the feed streams.

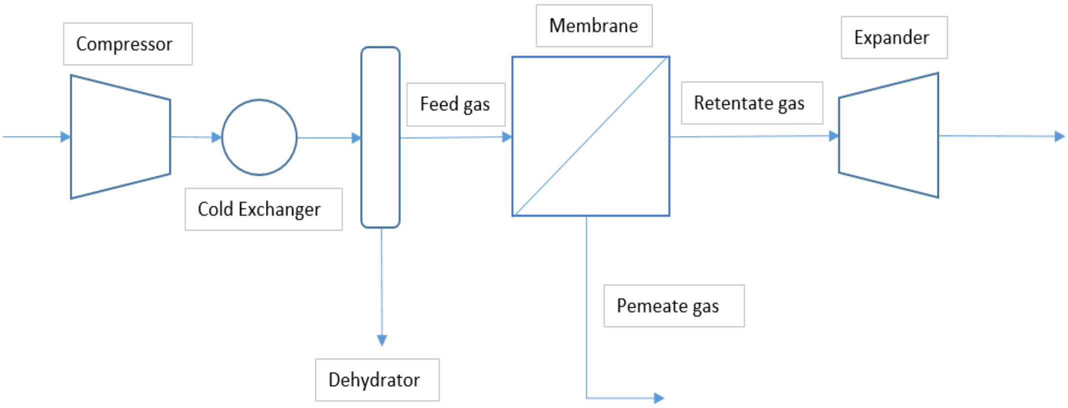


Fig 10. Diagram of a simple separation process

4.2. Membrane selection

The membranes used for gas separation (air separation, dehydrogenation or the separation of carbon dioxide from combustion) are commonly made of glassy polymers with a dominant permeability of the gas with the "smaller" molecules. It is for this reason that some of the most studied membranes present on the low free volume glassy polymers like polysulfone, polysiloxanes or polyolefins and polyimides *(Malykh et al., 2011).*

The polymeric membranes used in this Master Thesis have been selected according to their reported carbon dioxide permeability. The studies on membrane treatment of industrial gaseous streams similar to those used in this work are scarce. In addition, many reports do not include to all the components present in BFG, BOG and COG. Three commercially available membranes, made of different materials, for which it was possible to find all the required information and that had different permeabilities, have been selected (Table 2).

Table 2. Permeances $\left(\frac{L}{m^2} * h * bar\right)$of the gases in the membranes chosen for this study, *(Malykh et al., 2011)*

	H_2	CO_2	O_2	N_2	CO
Silar	440	2000	400	190	270
PVTMS	2000	1600	450	120	150
GENERON	160	45	13,6	1,8	1,6

Table 3 shows the main characteristics of the modules available on the market for these types of membrane.

Table 3. Features of the membranes modules *(Malykh et al., 2011)*

	Material	Membrane module geometry	Length (inches)	Surface area (m^2)
Silar	Siloxanerylate	Spiral	25	45
PVTMS	Poly(vinyltrimethylsilane)	Multi-tube	30	35
GENERON	Polyimide	Hollow Fiber	30	25

There are other polymeric materials that are susceptible for the separation of carbon dioxide. Some of these materials are cellulose acetate, tetrabrompolycarbonate, polyvinyltrimethilsilane or polyisoprene. However, the information available is still limited and does not go beyond certain experimental data under laboratory operating conditions.

4.3. Model development

As previously mentioned, one of the main objectives of this Master Thesis is the development of a simulation and design models based on the principles governing the theoretical behaviour of carbon dioxide in polymeric membranes. The use of a process simulation model allows to obtain a global vision of the separation process. These models provide the material or energy balances, equipment and plant design, as well as an estimation of the optimum operating conditions.

Prior to the programming of the permeation models, a review and bibliographic analysis of the existing models was carried out to determine which of them would be applicable in this case of study, the separation of carbon dioxide in the steel gas flows. From this bibliographic analysis, two possible lines of action for membrane permeation simulations have been determined:

- Use of a subroutine already included in Aspen Plus.
- Use of a subroutine in Microsoft Excel and its subsequent implementation in Aspen Plus.

Today, there are multiple process simulators widely used in the industry. Among them are tools such as Aspen software. This program has the possibility of working with ideal operation units. However, and at the request of the company where the project was carried out, programming will be done with Visual Basic through the Macros package of the Microsoft Excel software. The following sections explain the development of the model.

4.3.1. Model equations

The design of the equipment required to achieve gas separation and its simulation wer performed considering the following assumptions *(Wankat, 2004):*

- Permeabilities of all gases are concentration-independent.
- There is no temperature gradient on the membrane.
- Permeation is governed by a solution-diffusion mechanism
- The pressure of the retentate and that in the feed are equal and constant.
- The flow of the feed gas follows a vertical component, i.e. it has no possible axial dispersion.

In this section, the operating conditions, balances and equations used in the program are briefly described, following the procedure published by *Wankat (2017).*

Mass balances

The overall mole balance is:

$$\widehat{F_{in}} = \widehat{F_p} + \widehat{F_r} \qquad \text{Eq. [4.1]}$$

Where $\widehat{F}$ is the molar feed flow rate (mol/s) and the indexes refer to the feed (in), permeate (p) and retentate (r), respectively

The balance for any i component in the mixture can be written as follows:

$$\widehat{F_{in}} y_{i,in} = \widehat{F_p} y_{ip} + \widehat{F_r} y_{ir} \qquad \text{Eq. [4.2]}$$

Where $y_{i,in}$ is its molar fraction in the feed, and y_{ip} and y_{ir} are the molar fractions in the permeate and retentate streams, respectively.

These equations can be combined and solved for any given y_r or y_p

$$y_{ir} = \frac{\theta}{1-\theta} y_{ip} + \frac{y_{i,in}}{1-\theta} \qquad \text{Eq. [4.3]}$$

where the ratio θ (known as the “stage cut”, or simply "cut", is an important operating parameter):

$$\theta = \widehat{F_p} / \widehat{F_r} \qquad \text{Eq. [4.4]}$$

Transport equation and membrane area

Taking into account the transport eq. 3.7:

$$J_{CO_2} = \frac{Q_{CO_2}}{L}(p_{r,CO_2} - p_{p,CO_2}) \qquad \text{Eq. [4.5]}$$

The membrane area can be obtained from the ratio of the permeate flowrate of any given component and its flux. Equation 4.5 shows this relationship.

$$\frac{Fp}{A} = \left[\frac{P_{key}}{t_{ms} \cdot y_{p,key}}\right]\left(p_r \cdot y_{r,key} - p_p \cdot y_{p,key}\right) \qquad \text{Eq. [4.6]}$$

Where A is the membrane area (m^2), t_{ms} is the membrane thickness (m), P_{key} in the permeability of the component “key” in the membrane $\left(\frac{mol}{m \cdot s \cdot Pa}\right)$, p_r and p_p are respectively the pressures in the retentate and permeate outs.

Multicomponent permeation in perfectly mixed gases

For multicomponent flash distillation the y-x equilibrium curve is replaced by equilibrium expressions of the form of:

$$y_i = K_{mi} x_i \qquad \text{Eq. [4.7]}$$

Since the operating equations for well-mixed permeations are similar to the operating equations for flash distillation (Hoffman, 2003), if we can write the rate expression in the form:

$$y_{pi} = K_{mi} y_{r,i} \qquad \text{Eq. [4.8]}$$

Then, the mathematics to solve the permeation problem will be very similar to that used for flash distillation. Of course, K_{mi} has a totally different meaning than K_{mi} in flash distillation

Later on equation 4.9 is developed thanks to the equation 4.6.

$$K_{m,i} = \frac{p_r \cdot (P_i/t_{ms})}{\frac{F_p}{A} + p_p \cdot (P_i/t_{ms})} \qquad \text{Eq. [4.9]}$$

Composition of the gases

The K_m obtained allows us to obtain the mole fraction of each component in the retentate ($y_{r,i}$) by means of equation 4.8.

$$y_{r,i} = \frac{y_{in,i}}{1+(K_{m,i}-1)\theta} \qquad \text{Eq. [4.10]}$$

Area of the membrane

Finally, the membrane area is obtained from the feed flowrate, the stage cut and the permeate flux:

$$A = \frac{F_p}{\left(\frac{F_p}{A}\right)} = \frac{[\theta(F_{in})]}{\left(\frac{F_p}{A}\right)} \qquad \text{Eq. [4.11]}$$

4.3.2. Design and simulation

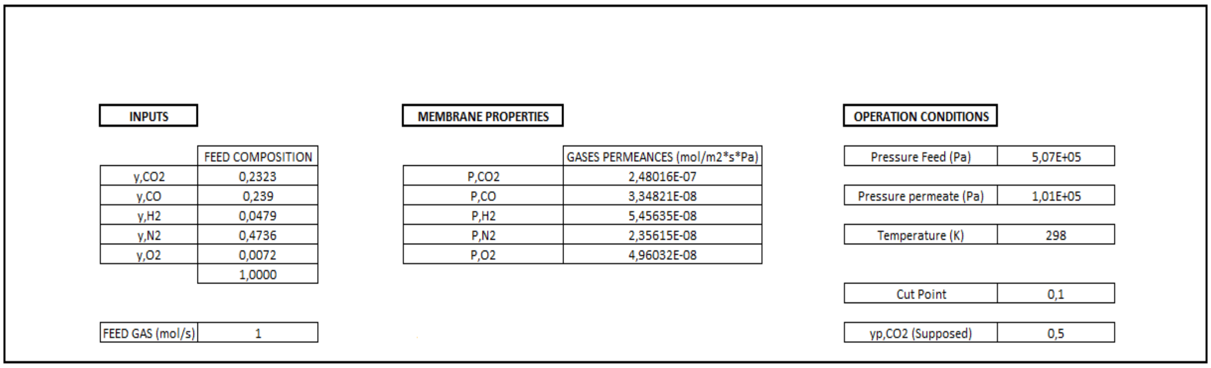
Depending on the type of calculation to be performed: the design of a separation unit for a given separation or the evaluation of the performance (simulation) of a given unit, two checklists were prepared with the required inputs and the results (Table 4).

Table 4. Checklist with the input data and the results for each type of case study:

Design	Simulation
Inputs	
Feed stream	**Feed stream:**
Feed gas (mol/s)	Molar flowrate (mol/s)
Composition (volume fraction)	Composition (volume fraction)
Membrane properties	**Membrane properties**
Gas permeances (mol/Pa·s·m^2)	Gas permeances (mol/Pa·s·m^2)
Operating conditions	**Operating conditions**
Feed side pressure (Pa)	Feed side pressure (Pa)
Permeate side pressure (Pa)	Permeate side pressure (Pa)
Temperature (K)	Temperature (K)
Iteration variables	**Iteration variables**
Cut point (recovery)	Estimated cut point (recovery)
Estimated or known y_{p,CO_2}	Membrane area (m^2)
Outputs	
Retentate flowrate (mol/s and m^3/s)	Retentate flowrate (mol/s and m^3/s)
Retentate composition (volume fraction)	Retentate composition (volume fraction)
Permeate flowrate (mol/s and m^3/s)	Permeate flowrate (mol/s and m^3/s)
Permeate composition (volume fraction)	Permeate composition (volume fraction)
Area needed (m^2)	Recovery o Cut point $(\widehat{F_p}/\widehat{F_r})$

To link these input variables with the MACROS code, a previous script is created using the Visual Basic package (also included as part of Excel). This code is shown in the annexed document together with the MACROS code itself that allows the simulation and design, in the annex of this document we can also see the decision tree that provides information on how the different equations are used in order to obtain the results.

The first step of this code is the creation of the data entry screen using the basic visual command, an example of this data already introduced can be seen in figure 11.



INPUTS

	FEED COMPOSITION
y,CO2	0,2323
y,CO	0,239
y,H2	0,0479
y,N2	0,4736
y,O2	0,0072
	1,0000

FEED GAS (mol/s)	1

MEMBRANE PROPERTIES

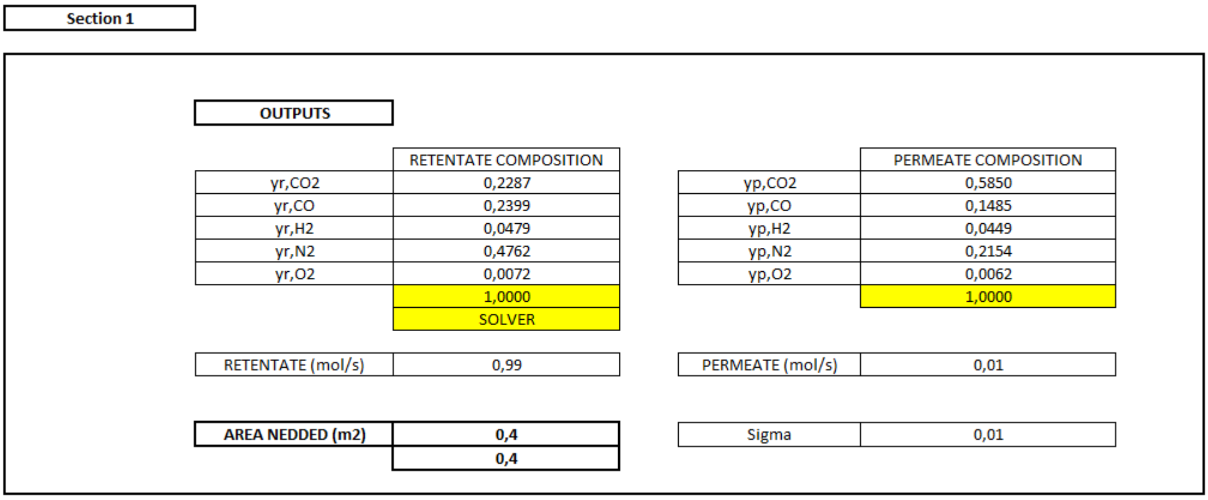
	GASES PERMEANCES (mol/m2*s*Pa)
P,CO2	2,48016E-07
P,CO	3,34821E-08
P,H2	5,45635E-08
P,N2	2,35615E-08
P,O2	4,96032E-08

OPERATION CONDITIONS

Pressure Feed (Pa)	5,07E+05
Pressure permeate (Pa)	1,01E+05
Temperature (K)	298
Cut Point	0,1
yp,CO2 (Supposed)	0,5

Fig 11. Data input in the built program

This input and operation data is passed on to the next screen, which shows one of the sub-stages into which the separation process is divided.



Section 1

OUTPUTS

	RETENTATE COMPOSITION
yr,CO2	0,2287
yr,CO	0,2399
yr,H2	0,0479
yr,N2	0,4762
yr,O2	0,0072
	1,0000
	SOLVER

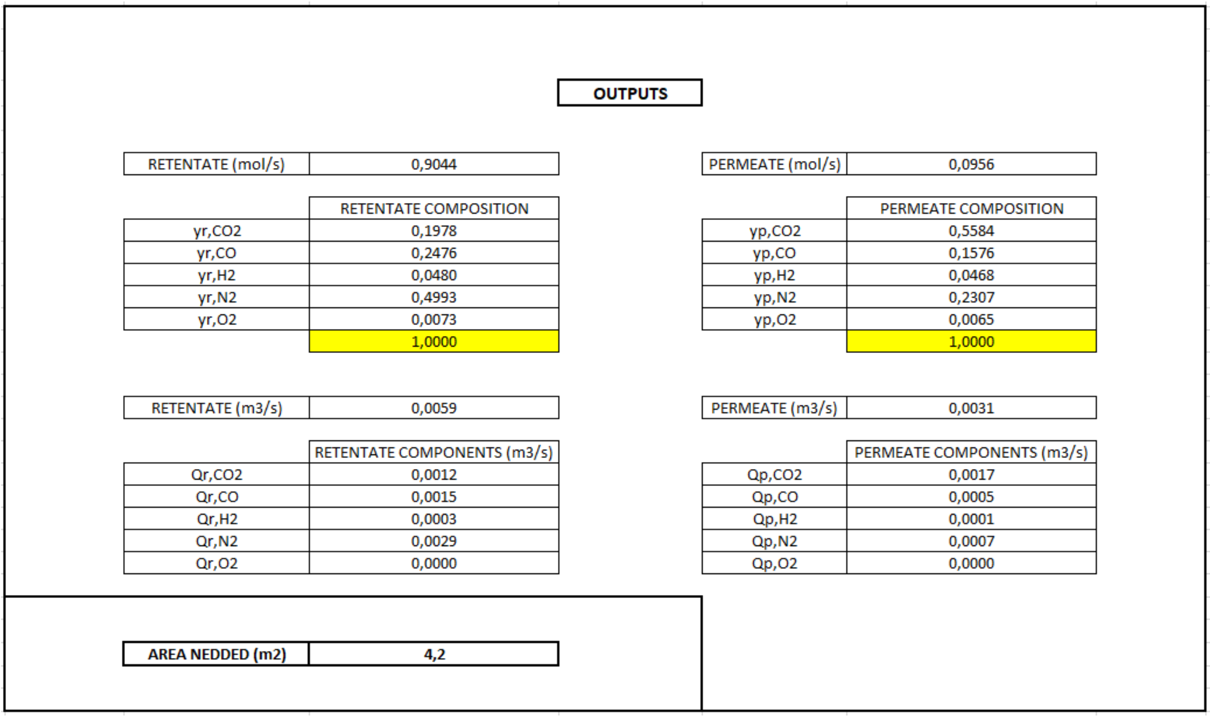
	PERMEATE COMPOSITION
yp,CO2	0,5850
yp,CO	0,1485
yp,H2	0,0449
yp,N2	0,2154
yp,O2	0,0062
	1,0000

RETENTATE (mol/s)	0,99
PERMEATE (mol/s)	0,01
AREA NEDDED (m2)	**0,4**
	0,4
Sigma	0,01

Fig 12. Capture of the sub-stage data

It is worth mentioning that the use of Microsoft Excel will require a series of iterative steps that will be introduced within the programming code itself.

Finally, with all the data obtained in each of the sub-stages, the final permeation and retention currents are obtained. Figure 13 shows a capture after a separation.



OUTPUTS

RETENTATE (mol/s)	0,9044
PERMEATE (mol/s)	0,0956

	RETENTATE COMPOSITION
yr,CO2	0,1978
yr,CO	0,2476
yr,H2	0,0480
yr,N2	0,4993
yr,O2	0,0073
	1,0000

	PERMEATE COMPOSITION
yp,CO2	0,5584
yp,CO	0,1576
yp,H2	0,0468
yp,N2	0,2307
yp,O2	0,0065
	1,0000

RETENTATE (m3/s)	0,0059
PERMEATE (m3/s)	0,0031

	RETENTATE COMPONENTS (m3/s)
Qr,CO2	0,0012
Qr,CO	0,0015
Qr,H2	0,0003
Qr,N2	0,0029
Qr,O2	0,0000

	PERMEATE COMPONENTS (m3/s)
Qp,CO2	0,0017
Qp,CO	0,0005
Qp,H2	0,0001
Qp,N2	0,0007
Qp,O2	0,0000

AREA NEDDED (m2)	**4,2**

Fig 13. Capture of the output data

With all these variables defined, it will be possible to achieve the one of the main objectives, which is to determine the permeate and permeated flows, the required area in case of designing as well the composition of the resulting permeate and retentate streams.

A sensitivity analysis will also be performed to establish the effect of the main operating parameters as a first step in the optimization of the process presented in section 4.3.4.

4.3.3. Discretization of the membrane module

The equations presented above consider the gaseous mixtures on either side of the membrane to be perfectly mixed. However, in reality, as the feed gets in contact with the membrane, and permeation takes place, feed composition changes. Taking into account the size of industrial-sized modules, this effect is not negligible. Therefore, in order for the model to better represent the actual behaviour, it will be discretized, i.e., divided in sub-sections and the (alike a plug-flow reactor being modelled as a series of continuous stirred tank reactors). This also provides a more realistic area estimation Figure 14 shows a diagram of the discretized membrane module.

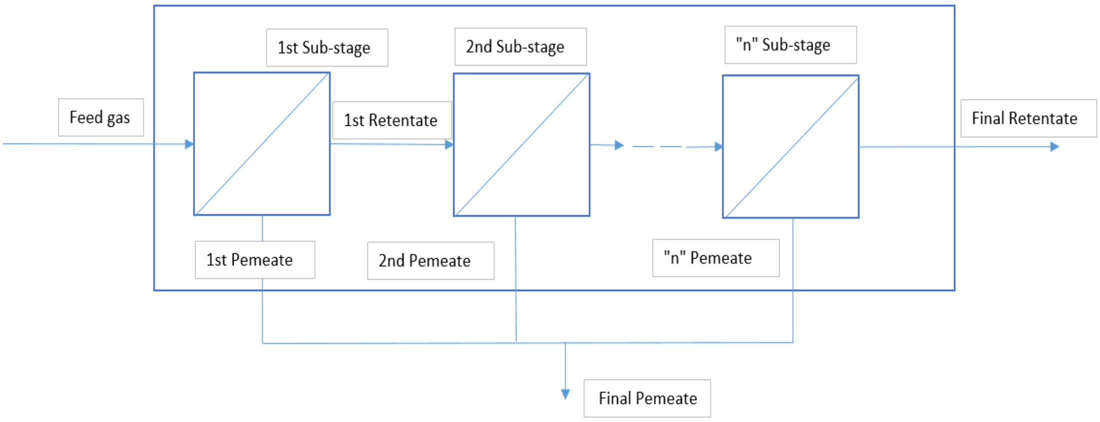


Fig 14. Membrane module discretization used in this work

In order to establish the correct number of sub-stages to consider, several cases were solved in which the total membrane needed for a given separation is calculated as a function of the number of sub- stages. Figure 15 shows the results.

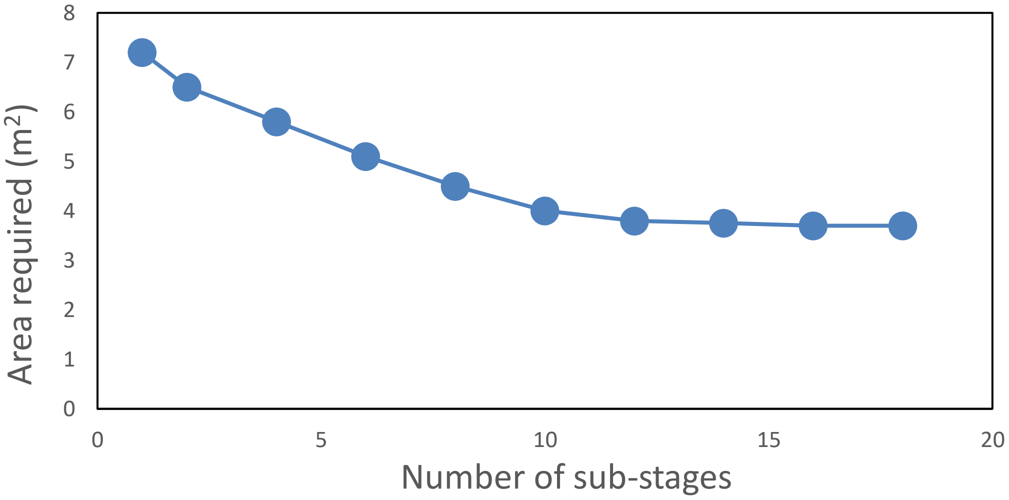


Fig 15. Total membrane area required as function of the number of divisions considered in the module.

As can be seen in Figure 15, as the number of assumed sub-stages increases, the required membrane area decreases. However, there comes a point (from 10 assumed sub-stages) where the required area does not decrease any more. This is because the actual area has been reached and no further steps are necessary. For this reason, both programs (design and simulation) considered the modules divided in ten sub-stages.

4.3.4. **Model validation**

In order to check the model, a validation procedure was set up in which the model results were compared with previously published results. Once the model is tested and proven to work correctly, it is applicable for other membranes with similar characteristics.

Experimental data obtained for a polymeric membrane called Matrimid 5218 were used. (Table 5 and Fig. 16).

Table 5. Experimental data obtained by (Falbo et al., 2014).

Temperature (K)	373
Pressure Variation (kPa)	500-400-300
H_2 Permeance (nmol/m^{2}*s*Pa)	14,9
N_2 Permeance (nmol/m^{2}*s*Pa))	0,22
O_2 Permeance (nmol/m^{2}*s*Pa)	0,97
CO Permeance (nmol/m^{2}*s*Pa)	0,21
CO_2 Permeance (nmol/m^{2}*s*Pa)	6,92
Feed (m^{3}/s)	0,4

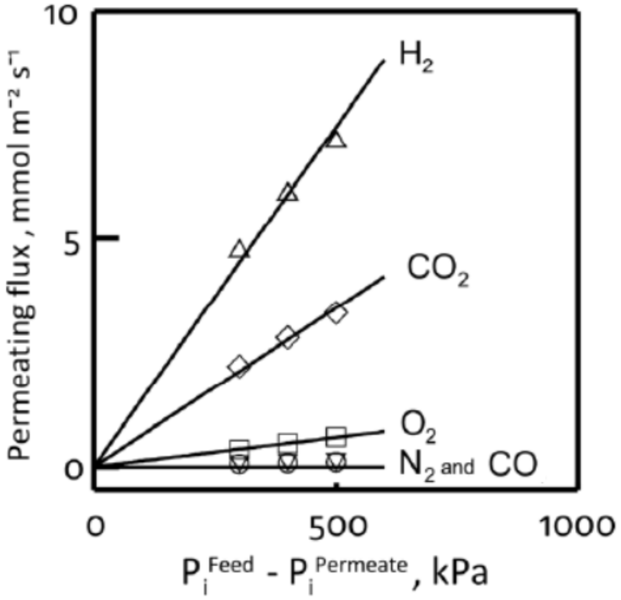


Fig 16. Experimental results obtained by *Falbo et al. (2014).*

To achieve the validation of the model, the experimental permeances (Table 5) are introduced in the model. Then the obtained permeation values are represented and compared with the those shown in Fig 16. The results from this validation procedure are given in Fig 17.

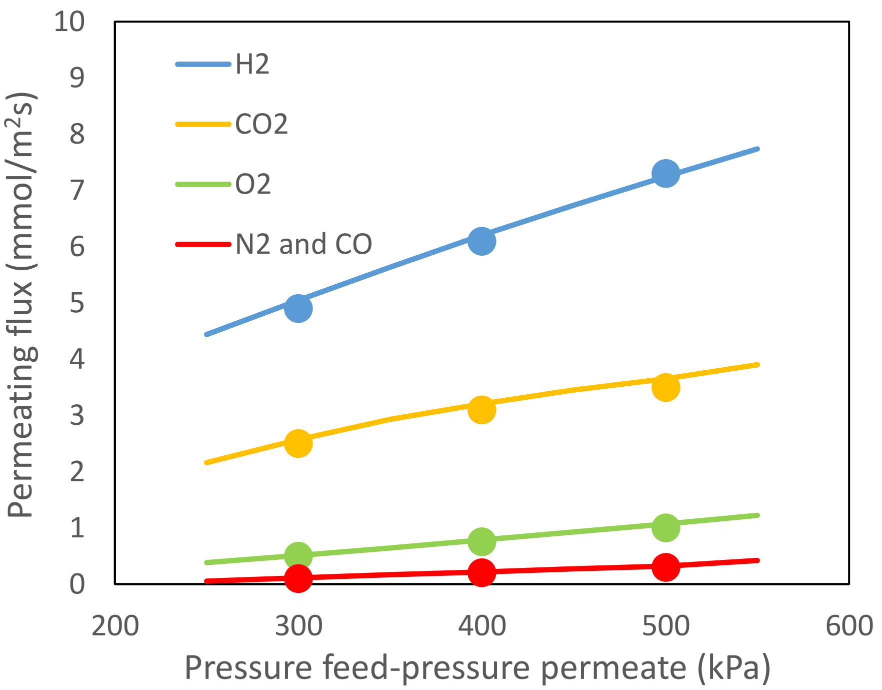


Fig 17. Comparison of permeate flows values obtained by the simulation model (lines) and the experimental values obtained by Falbo (circles)

Estimating the relative errors, in permeate fluxes in the range simulated, values of 4.7 %, 3.3%, 1% and 2.4% were obtained for $\mathrm{H_2}$, $\mathrm{CO_2}$, $\mathrm{O_2}$ and $\mathrm{N_2 - CO}$, respectively. Therefore the model implemented provides valid results, with deviations of less than 5% from the experimental data.

4.4. Economic evaluation

In the last section of this Master Thesis, after establishing which of the membranes is the best option for treating the gases under study, an economic evaluation of the best design for gas separation will be carried out.

4.4.1. Energy consumption of membrane process

Usually the compressor leads to the main energy consumption in the membrane separation process. As reported by *(Xu et al. 2019),* the membrane area requirement with vacuum pumps is several times higher than that of compressors with the same membrane perm selectivity.

Therefore, only the feed side compression process is considered in the proposal to reduce the membrane area requirement and the cost of CO_2 capture. The energy consumption (Ecp) of the compressor is defined as:

$$E_{cp} = \frac{F}{\eta_{cp}} \frac{\gamma RT}{\gamma - 1}[(\varphi)^{\frac{\gamma-1}{\gamma}} - 1] \qquad \text{Eq. [4.12]}$$

η_{cp} is the compressor efficiency (%) which is assumed to be 85%; γ is the adiabatic expansion factor which is estimated to be 1.4; T is the operating temperature (K); and φ is the pressure ratio, which equals to p_f/p_p.

The high pressure in the residue gas could be utilized to recover energy with an expander. This energy recovered (E_{ex}) from the retentate gas is displayed as shown below:

$$E_{ex} = \eta_{ex} F \frac{\gamma RT}{\gamma - 1}[1 - (1/\varphi)^{\frac{\gamma-1}{\gamma}}] \qquad \text{Eq. [4.13]}$$

η_{ex} is the expander efficiency (%) which is assumed to be 85%. For any multiple-stage membrane process, the CO_2 capture energy consumption is estimated by specific energy consumption (SEC) (MJ kg^{-1} CO_2) which is could be defined as:

$$SEC = \frac{3{,}6 \cdot 10^{-3} (\sum Ei - E_{ex})}{x_{f,CO_2} F_f r_{,CO_2}}] \qquad \text{Eq. [4.14]}$$

E_i is the energy consumption of any compressor, E_{ex} is the energy recovered from the expander, $x_{f,CO_2}F_f$ is the feed gas CO_2 molar flow rate, and $r_{,CO_2}$ is product CO_2 recovery.

4.4.2. Cost assessment methodology

Average direct and indirect cost factors such as maintenance costs are used to assess the investment cost of the carbon dioxide capture system. The technical characteristics and associated costs (such as the required membrane modules) are modelled by means of the constructed program.

The total specific capture cost or CC ($€/\mathrm{tCO_2}$) for n separation stages can be calculated from the stage capture costs and the stage capture ratios (CR):

$$\mathrm{CC_{total}} = \frac{\mathrm{CC}^{1}_{\mathrm{stage}}}{\mathrm{CCR}^{1}_{\mathrm{stage}}} + \cdots + \frac{\mathrm{CC}^{n-1}_{\mathrm{stage}}}{\mathrm{CCR}^{n-1}_{\mathrm{stage}}} + \mathrm{CC}^{n}_{\mathrm{stage}} \qquad \text{Eq. [4.15]}$$

The $\mathrm{CO_2}$ avoided cost ($€/\mathrm{tCO_2}$) has to be taken into consideration, this cost can be defined how:

$$\mathrm{CO_2\ avoided\ cost}\ \left[\frac{€}{\mathrm{tCO_2}}\right] = \frac{\text{annualized investment+annual operational expenditures}}{\text{annual amount of } \mathrm{CO_2} \text{ captured}-\text{annual direct emission}} \qquad \text{Eq. [4.16]}$$

This $\mathrm{CO_2}$ avoided cost is used as a key indicator of efficiency to determine the unit cost of carbon dioxide capture in the plant. This cost per tonne of carbon dioxide avoided has to be taken into account as it also allows a comparison with the carbon dioxide emission tax.

5.RESULTS AND DISCUSSION

5.1. Influence of the module length on separation performance

Each membrane module was simulated as a set of 10 sub-modules in series, as explained in section 4.3.3. The reason behind the discretization was to have a more realistic model that takes into account that flowrates and composition are not constant. In order to show the actual variations, for a Silar membrane module with 45 m^2 of active membrane area, the profiles for permeate flowrate and the composition of carbon dioxide in the permeate and retentate streams were calculated as a function of module length (expressed as accumulated membrane area (Figs. 18 and 19). The feed was BFG (1 mol/s), the feed/permeate pressure ratio was set at p_f/p_p =5 and the temperature 298 K. All other tests will be carried out under these standard conditions, this is because in other past projects (such as the one carried out by Malykh) it has already been said that the polymeric membranes show identical behaviour in temperature ranges of 298-423 K.

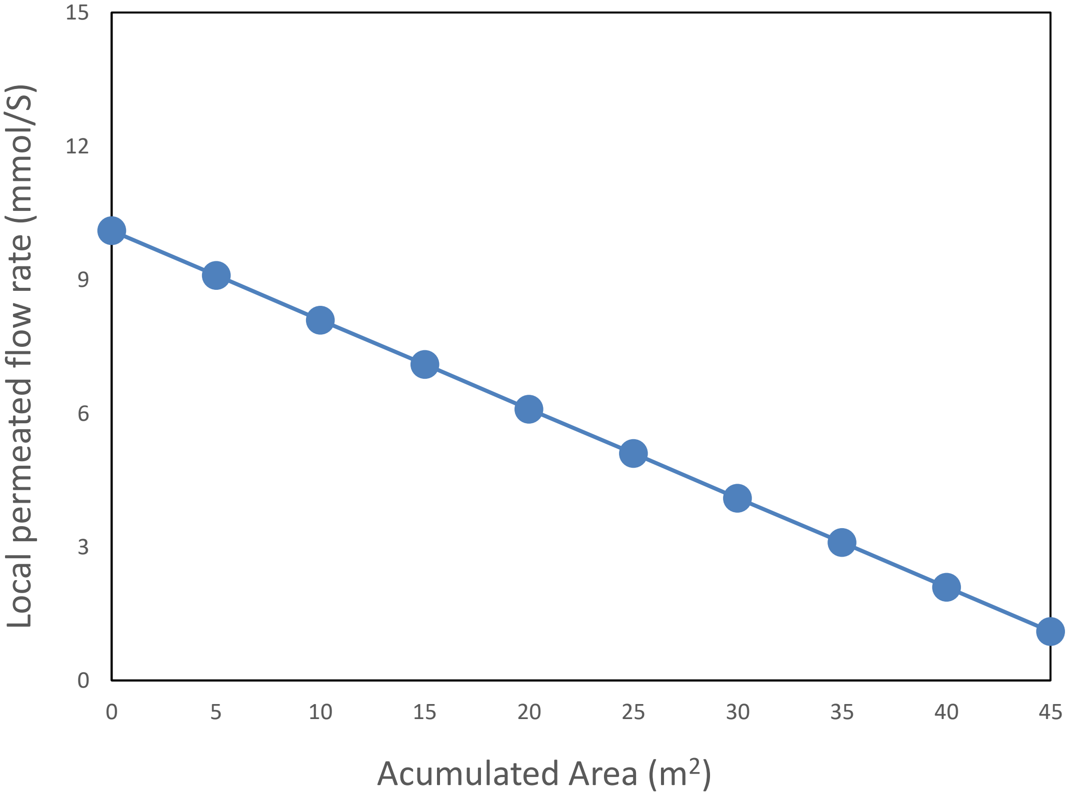


Fig 18. Variation of the permeate flowrate along a membrane module. Simulation conditions: Membrane: Silar. Feed: 1 mol/s BFG. Pressure ratio (p_f/p_p) =5. T=298 K

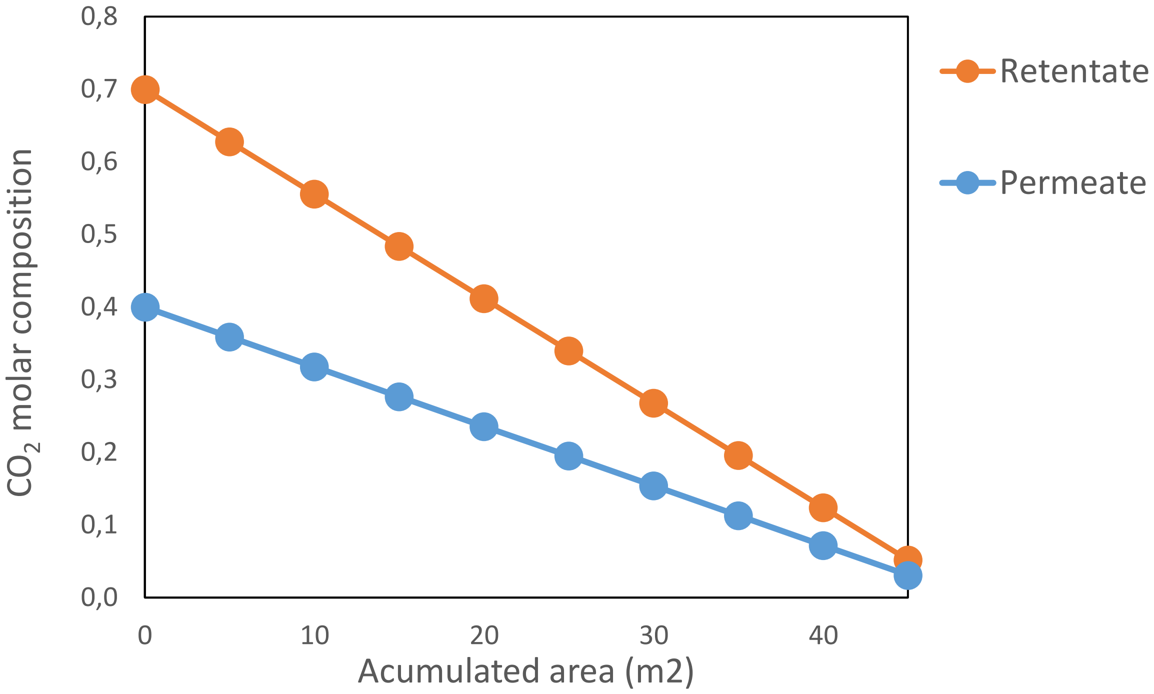


Fig 19. Variation of the local composition (mole fraction of carbon dioxide) in the permeate and retentate streams along a membrane module. Simulation conditions: Membrane: Silar. Feed: 1 mol/s BFG. Pressure ratio (p_f/p_p) =5. T=298K

5.2. Optimization of operating conditions

Given that the composition of the gaseous streams to be treated is fixed, the main operating variable that can affect the separation, once a membrane is chosen, is the pressure ratio. The pressure ratio affects the permeation of each component and –since not all permeate at the same rate- it also affects the selectivity, often expressed as enrichment factor (eq. 3.11).

Multiple simulations of the SILAR, PVTMS and GENERON membranes were run using at pressure ratios ranging from 1 to 40. For this purpose, the permeate pressure was kept constant at 1 atm (100 kPa) and 298 K while the feed pressure was increased. Figs. 20-22 show how the results obtained for the three gases under study (only values up to pressure ratios of 40 are graphed).

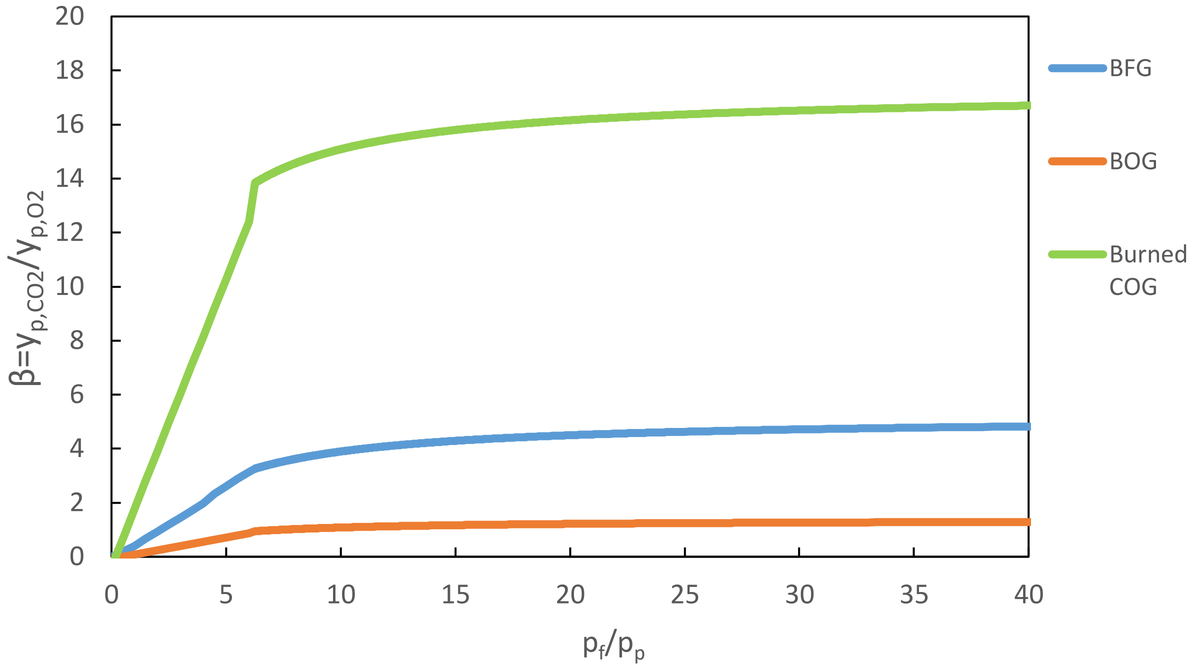


Fig 20. Representation of the relative permeate purity (β) in function of the pressure range (Membrane Silar)

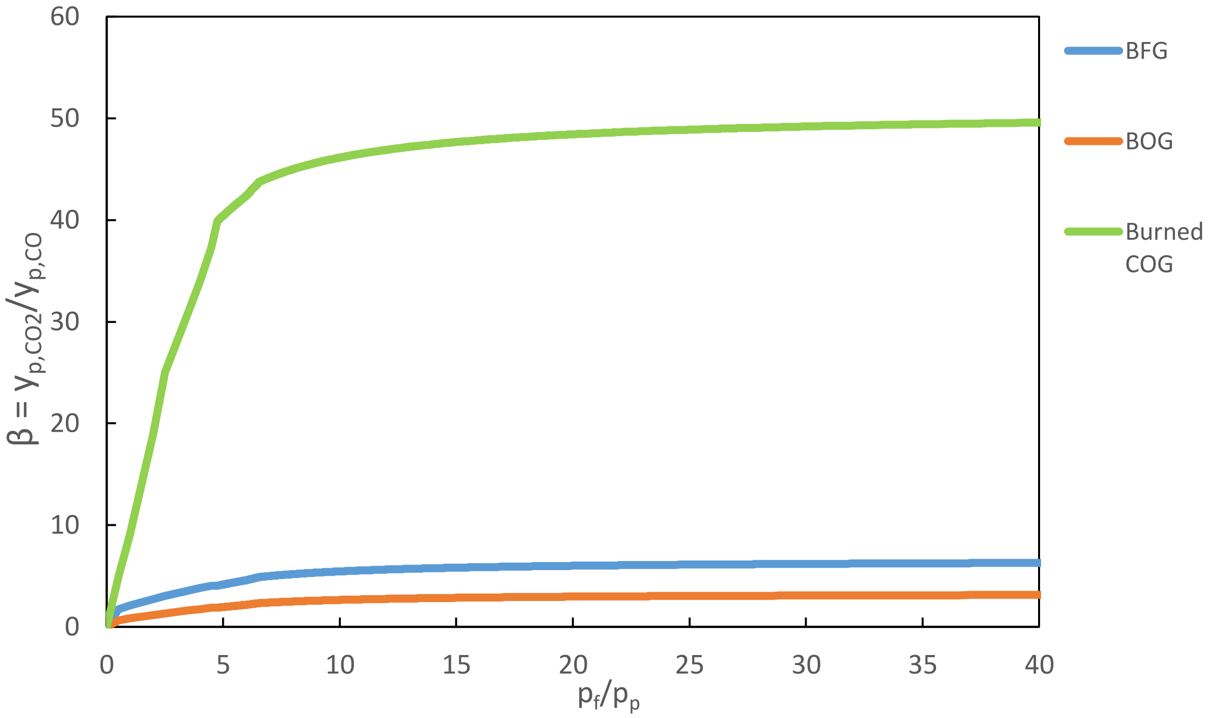


Fig 21. Representation of the relative permeate purity (β) depending on the pressure range (Membrane PVTMS)

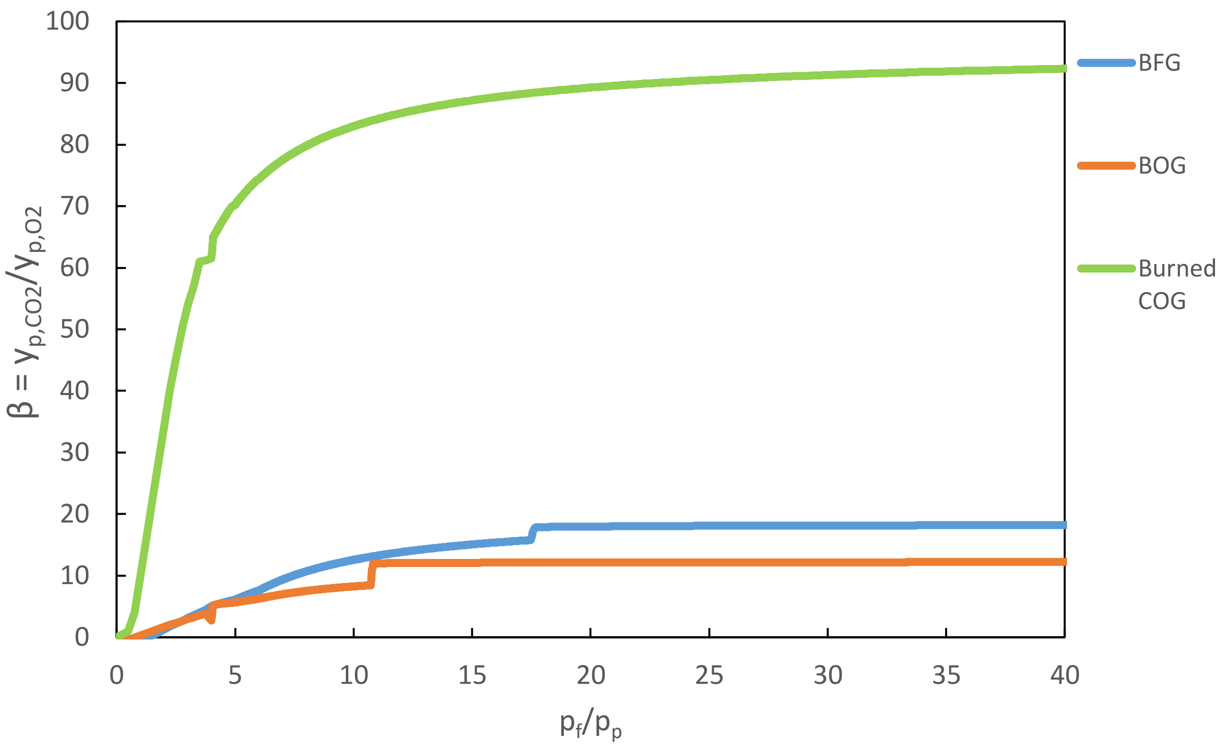


Fig 22. Representation of the relative permeate purity (β) depending on the pressure range (Membrane GENERATOR)

Initially, an increase in pressure ratio yields better separation. However, the trends are asymptotic. Higher pressure ratios also imply high feed compression costs (which will be a key factor in the economic feasibility of this application). Therefore, an optimum ratio can be set, at 90-95% of the maximum enrichment factor, while higher pressures would incur in higher energy costs while having little effect on separation. The optimum values (rounded to the nearest multiple of 5) are given in Table 6.

Table 6. Optimal p_f/p_p ratio for each membrane-feed gas under study

$\mathbf{p_f/p_p}$	SILAR	PVTMS	GENERON
BFG	15	10	15
BOG	15	10	15
Burned COG	15	10	15

5.3. Evaluation of membrane performance for the separation of carbon dioxide in steelmaking flue gases

Once the optimum pressure ratio is chosen, the next step is to evaluate the performance of the selected membranes in separating carbon dioxide from the three gases under study (BFG, BOG and burned COG). This was done by performing simulations under comparable conditions: feed flowrate was 0,02 m^3/s, permeate pressure was set at 100 kPa and 298 K, the feed pressure was at the optimum value for each case, as indicated in Table 6. Feed gas compositions were those indicated in Table 1 and the permeance of each compound are given in Table 2.

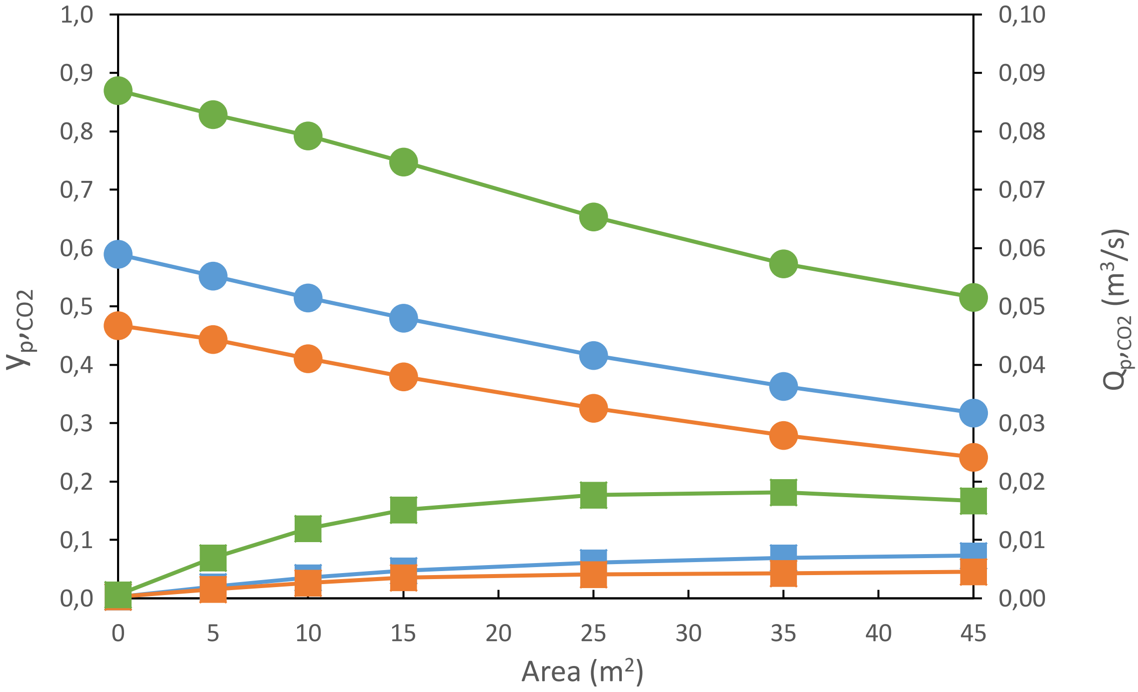


Fig 23. Evolution of the molar fraction of CO_2 in the permeate (circles) and permeate flux of CO_2 (squares) with SILAR membrane area when treating BFG (blue), BOG (orange) and Burned COG (green) gasses.

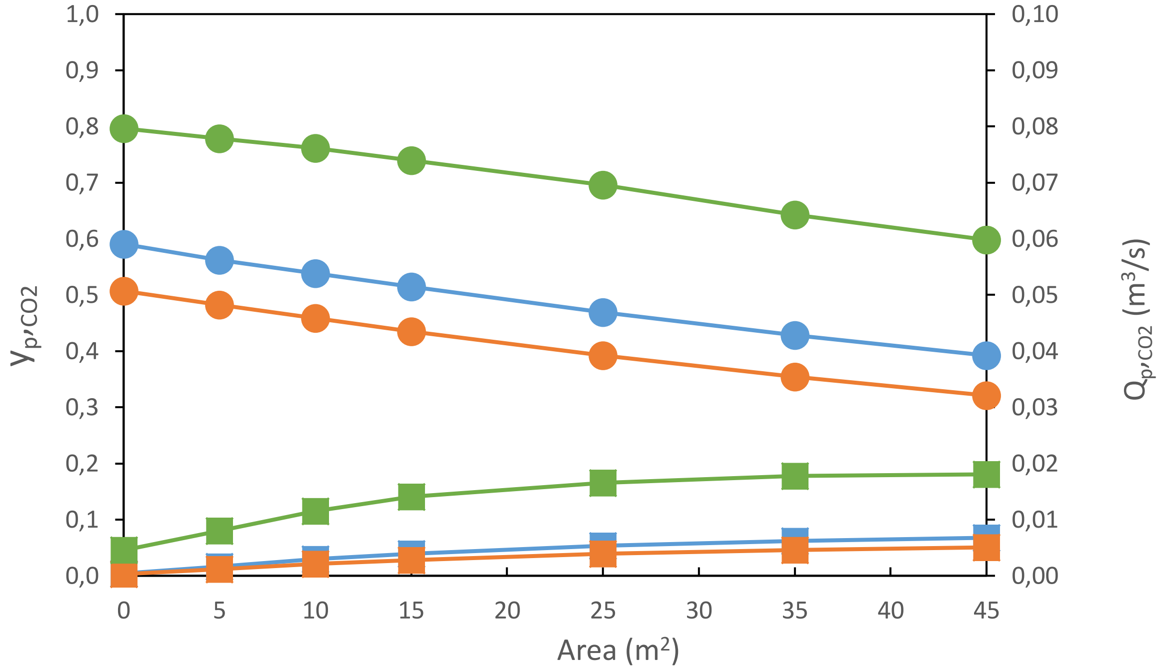


Fig 24. Evolution of the molar fraction of CO_2 in the permeate (circles) and permeate flux of CO_2 (squares) with PVTMS membrane area when treating BFG (blue), BOG (orange) and Burned COG (green) gasses.

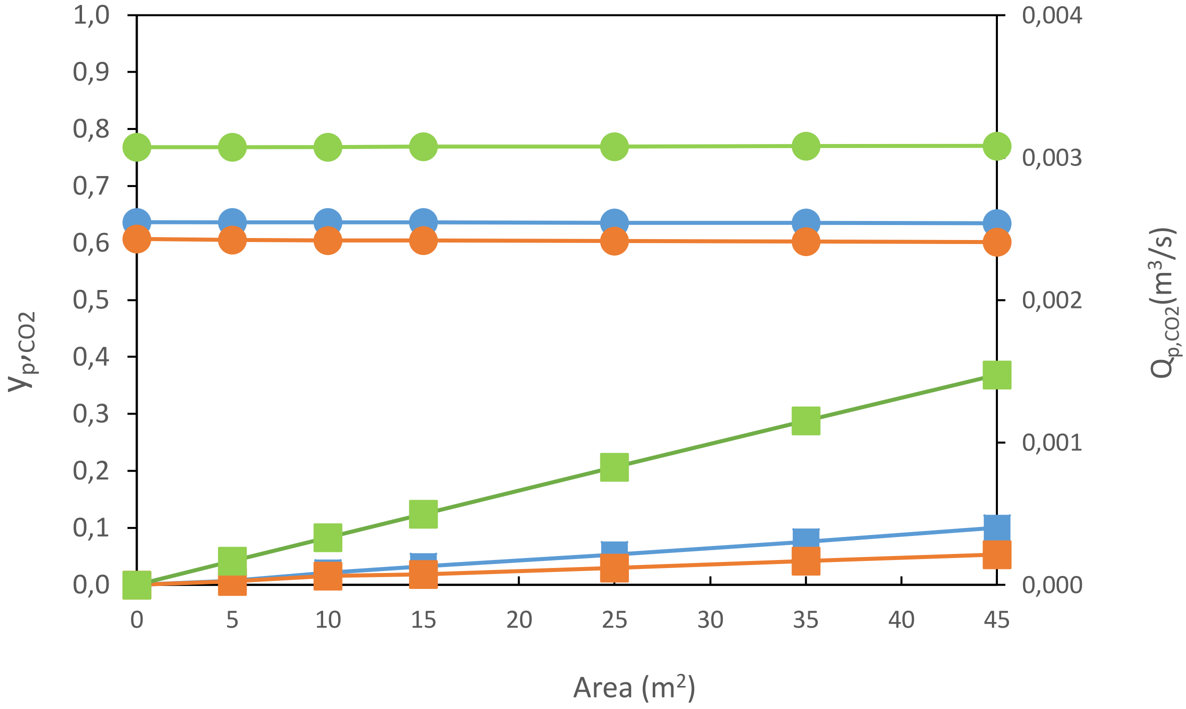


Fig 25. Evolution of the molar fraction of CO_2 in the permeate (circles) and permeate flux of CO_2 (squares) with GENERON membrane area when treating BFG (blue), BOG (orange) and Burned COG (green) gasses.

Table 7. Evolution of the component molar fractions (y_i) and fluxes (Q_i) in retentate and permeate with SILAR membrane at 298K with a feed of 1 mol/s, a pressure ratio p_f/p_p =15 and an area of 45 m^2

BFG

	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,23	0,23	0,22	0,32	0,01	0,03
CO	0,24	0,24	0,16	0,23	0,08	0,25
H_2	0,05	0,05	0,04	0,05	0,01	0,03
N_2	0,47	0,47	0,27	0,39	0,20	0,68
O_2	0,01	0,01	0,01	0,01	0,00	0,01
TOTAL	1,00	1,00	0,71	1,00	0,29	1,00

BOG

	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,18	0,18	0,17	0,24	0,01	0,02
CO	0,60	0,60	0,41	0,57	0,18	0,67
H_2	0,02	0,02	0,02	0,03	0,01	0,02
N_2	0,18	0,18	0,10	0,15	0,07	0,28
O_2	0,01	0,01	0,01	0,01	0,01	0,01
TOTAL	1,00	1,00	0,72	1,00	0,28	1,00

Burned COG

	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,56	0,56	0,44	0,52	0,01	0,01
CO	0,09	0,09	0,08	0,10	0,02	0,13
H_2	0,05	0,05	0,04	0,05	0,01	0,01
N_2	0,15	0,15	0,14	0,17	0,10	0,78
O_2	0,16	0,16	0,14	0,17	0,01	0,07
TOTAL	1,00	1,00	0,85	1,00	0,15	1,00

Table 8. Evolution of the component molar fractions (y_i) and fluxes (Q_i) in retentate and permeate with PVTMS membrane at 298K with a feed of 1 mol/s, a pressure ratio p_f/p_p =10 and an area of 45 m^2

BFG

	Feed		Permeate		Retentate	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,23	0,23	0,21	0,39	0,03	0,05
CO	0,24	0,24	0,10	0,19	0,14	0,29
H_2	0,05	0,05	0,04	0,08	0,00	0,01
N_2	0,47	0,47	0,17	0,33	0,30	0,64
O_2	0,01	0,01	0,01	0,01	0,00	0,00
TOTAL	1,00	1,00	0,53	1,00	0,47	1,00

BOG

	Feed		Permeate		Retentate	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,18	0,18	0,12	0,24	0,02	0,02
CO	0,60	0,60	0,27	0,56	0,34	0,66
H_2	0,02	0,02	0,01	0,03	0,01	0,02
N_2	0,18	0,18	0,08	0,16	0,13	0,29
O_2	0,01	0,01	0,01	0,01	0,01	0,01
TOTAL	1,00	1,00	0,49	1,00	0,51	1,00

Burned COG

	Feed		Permeate		Retentate	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,56	0,56	0,56	0,52	0,00	0,00
CO	0,09	0,09	0,08	0,10	0,01	0,14
H_2	0,05	0,05	0,05	0,05	0,00	0,01
N_2	0,15	0,15	0,12	0,17	0,03	0,78
O_2	0,16	0,16	0,16	0,17	0,00	0,07
TOTAL	1,00	1,00	0,96	1,00	0,04	1,00

Table 9. Evolution of the component molar fractions (y_i) and fluxes (Q_i) in retentate and permeate with GENERON membrane at 298K with a feed of 1 mol/s, a pressure ratio p_f/p_p =15 and an area of 45 m^2

			BFG			
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,23	0,23	0,01	0,63	0,22	0,22
CO	0,24	0,24	0,00	0,05	0,24	0,24
H_2	0,05	0,05	0,00	0,19	0,04	0,05
N_2	0,47	0,47	0,00	0,11	0,47	0,48
O_2	0,01	0,01	0,00	0,01	0,01	0,01
TOTAL	1,00	1,00	0,02	1,00	0,98	1,00
			BOG			
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,18	0,18	0,01	0,60	0,17	0,17
CO	0,60	0,60	0,00	0,21	0,60	0,60
H_2	0,02	0,02	0,00	0,10	0,02	0,02
N_2	0,18	0,18	0,00	0,08	0,19	0,20
O_2	0,01	0,01	0,00	0,01	0,00	0,00
TOTAL	1,00	1,00	0,01	1,00	0,99	1,00
			Burned COG			
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	0,56	0,56	0,05	0,77	0,51	0,54
CO	0,09	0,09	0,00	0,01	0,09	0,10
H_2	0,05	0,05	0,01	0,12	0,04	0,04
N_2	0,15	0,15	0,00	0,01	0,15	0,16
O_2	0,16	0,16	0,01	0,09	0,16	0,17
TOTAL	1,00	1,00	0,06	1,00	0,94	1,00

The results show that the carbon dioxide composition in the feed has a significant influence on both permeation rate, which was expected. As more membrane area is used, more permeate is obtained, but its concentration in carbon dioxide decreases. The SILAR membrane gives –for the same feed composition- better purity in the permeate and similar permeate flowrates than the PVTMS membrane.

The results for the GENERON membrane are very different. Carbon dioxide purity is constant because the permeate fluxes (and, thus, the cumulative permeate flowrate) is one order or magnitude lower than that of the other two membranes. This is a significant disadvantage for an industrial application, because the required membrane area would need to be one order or magnitude larger.

Based on the simulation results, the SILAR membrane is selected for the rest of the study.

5.4. Sensitivity analysis

Once the membrane has been selected, and in order to double check the operating conditions are indeed the most suitable ones, additional simulations were carried out with the SILAR membrane, feed with a BFG current of 0,02 m^3/s, and a permeate pressure of 1 atm (100 kPa) at 298 K, and with variable pressure intervals (p_f/p_p = 16,15, 14 and 12). The results of these simulations are shown in figure 26.

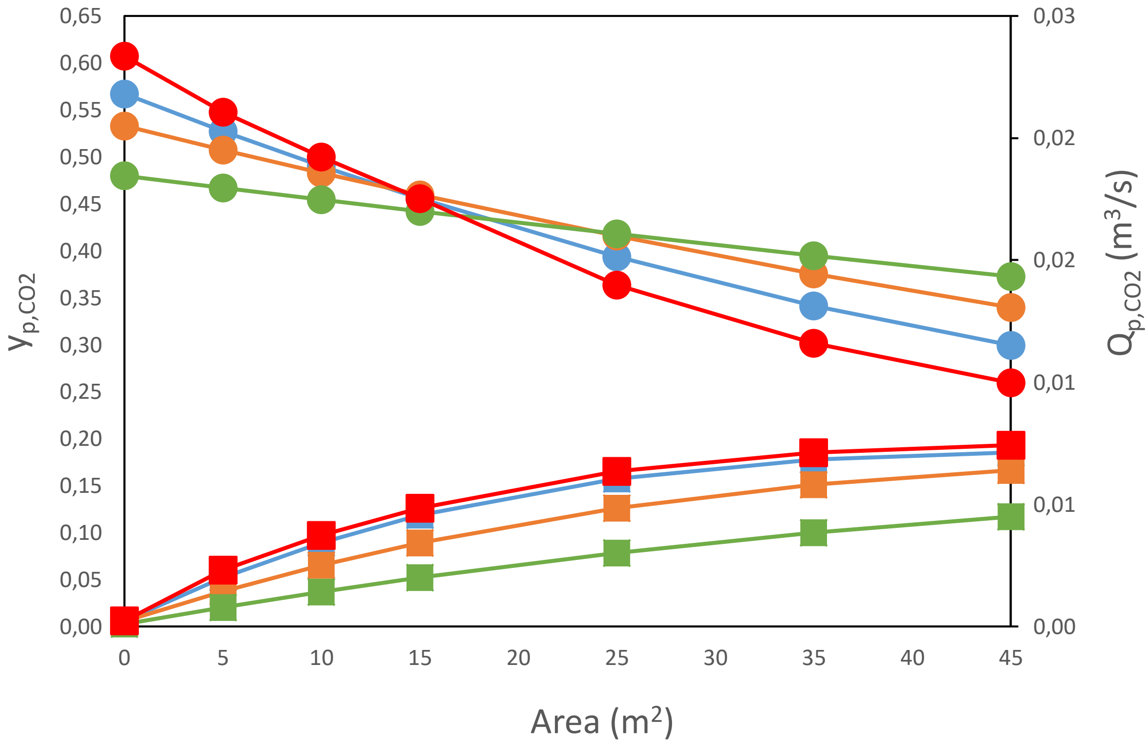


Fig 26. Evolution of the molar fraction of CO_2 (circles) and permeate flux of CO_2 (squares) with SILAR membrane area when treating BFG with a pressure ratio of 16 (red), 15 (blue), 14 (orange) and 12 (green)

It can be seen how a p_f/p_P ratio of 15 produces better results than the lower ratios because as the available area increases so does the amount of carbon dioxide permeated, and when this ratio increases does not shows better CO_2 recoveries. This means that the option chosen is the best possible one. With this we can move on to the last objective of this work, the study of the economic costs for the treatment of these gases.

5.5. Membrane separation criteria

Many works in literature is related to sensitivity analysis of single stage membrane units as inputs to process design. Some aspects like the permeate purity or the capture ratio can be expanded by varying the operation conditions (pressure ratios, membrane area, permeances). The single stage membrane separation is however, unable to provide high capture ratios and carbon dioxide purity, (around 80-85% capture and 85-95% purity). Previous works on multi-stage process design for post-combustion capture involves establishing "good" process configurations based on insights from single-stage unit sensitivities for the case at hand. Some authors has establish optimal membrane properties and synthesize processes for post-combustion capture from coal power plants and natural gas combined cycle gas *(Anantharaman et al., 2014).*

(Kundu et al., 2010), investigated the use of the dual stage membrane systems for post-combustion capture from cement plant. This membrane configuration has been stabilised as a good option to treat the metallurgical gases.

5.6. Process design: selection of the number of stages

All previous results were obtained with a single step process. However, as mentioned in section 5.5, building a two or more stage separation model is usually the only way to achieve 80-85% carbon dioxide recoveries along with 85-95% purities (considered good criteria for post-combustion separations *(Anantharaman et al., 2014).* The number of stages and their configuration depend on feed concentration, membrane selectivity and operating conditions. In this work, feed concentration is set by the steelmaking process conditions (however, the three gases under study have different composition), and in the previous sections the best membrane and optimum operating conditions were chosen.

In a two-stage system (Fig 27), in order to increase the recovery, more gas is allowed to permeate (which reduces its purity), and that permeate is treated again in a second membrane unit. The permeate from the second stage meets the purity requirement. The retentate from the second stage is recycled at the entrance of the capture system, and has the same CO_2 concentration as the feed gas. The retentate of the first stage (depleted in CO_2) is emitted to the atmosphere. A three-stage system follows the same principle

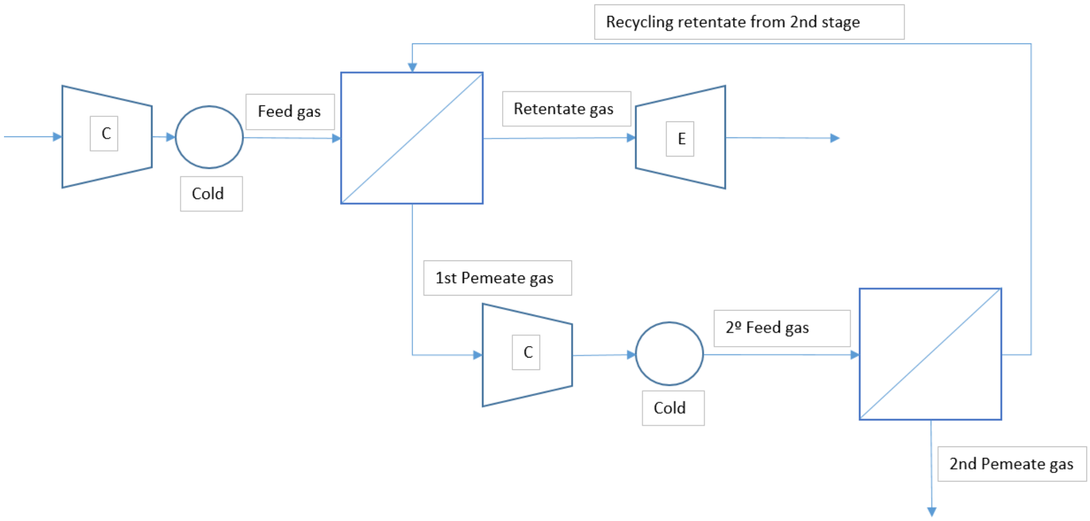


Fig 27. Schematic of a two-stage membrane system

The next figure 28 presents schematic of a three-stage membrane carbon dioxide capture.

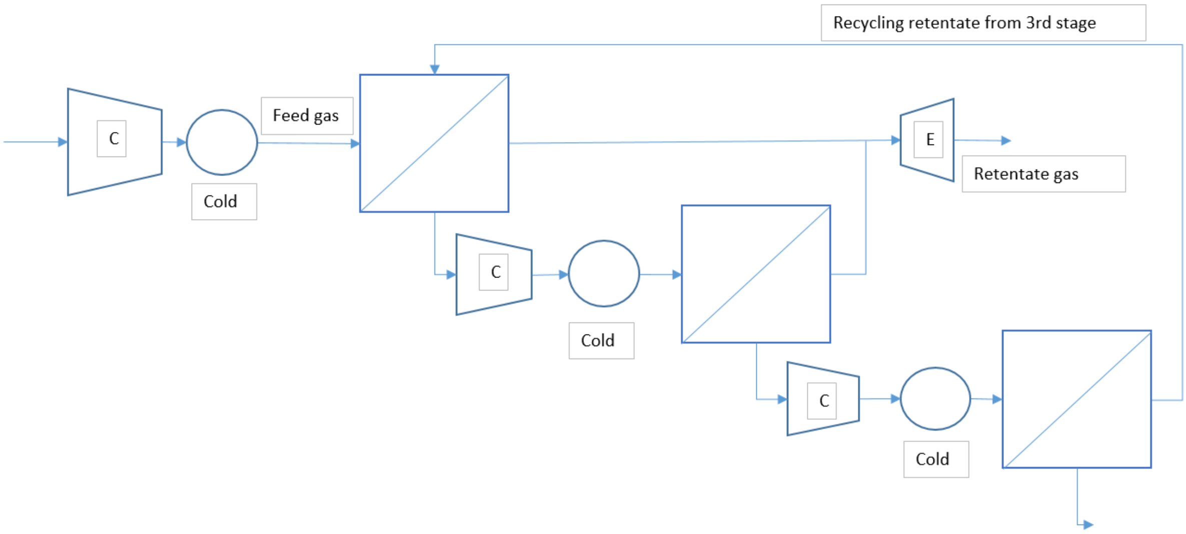


Fig 28. Schematic of a three-stage membrane system

Therefore, the next step in the study is to simulate a two-stage and a three-stage process and evaluate their performance in comparison with that of a single process.

For one stage (circles) 85% purities are achieved at a maximum of 45-47 % recovery when BFG or BOG are treated. For a two-stage process, the same 70-75 % is possible, and with a three-stage process, over 85 % recovery is possible.

Figures 29-31 show how carbon dioxide purity varies depending on the desired recovery of the flow produced, al this results were obtained working at normal conditions and with the optimal pressure ratios indicated in the table 6.

It is important to mention that when working with multiple stages the optimum pressure ratio p_f/p_p may vary, for that reason they were recalculated for each case.

It was possible to verify that this ratio varies when working with BFG in a three-stage process, with the ratio p_f/p_p going from 15 to 13.

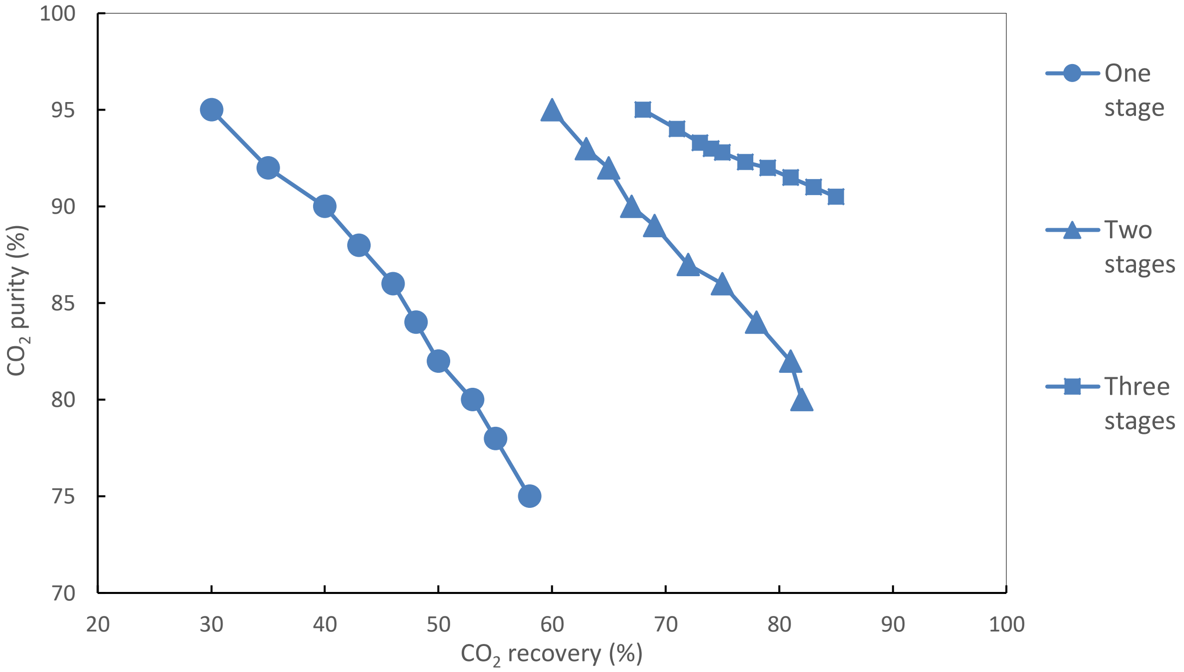


Fig 29. Variation of the carbon dioxide purity from BFG in function of the recovery obtained. (T=298K, p_f/p_p=15 for the one and two-stages, pf/pp=13 for the three stages option)

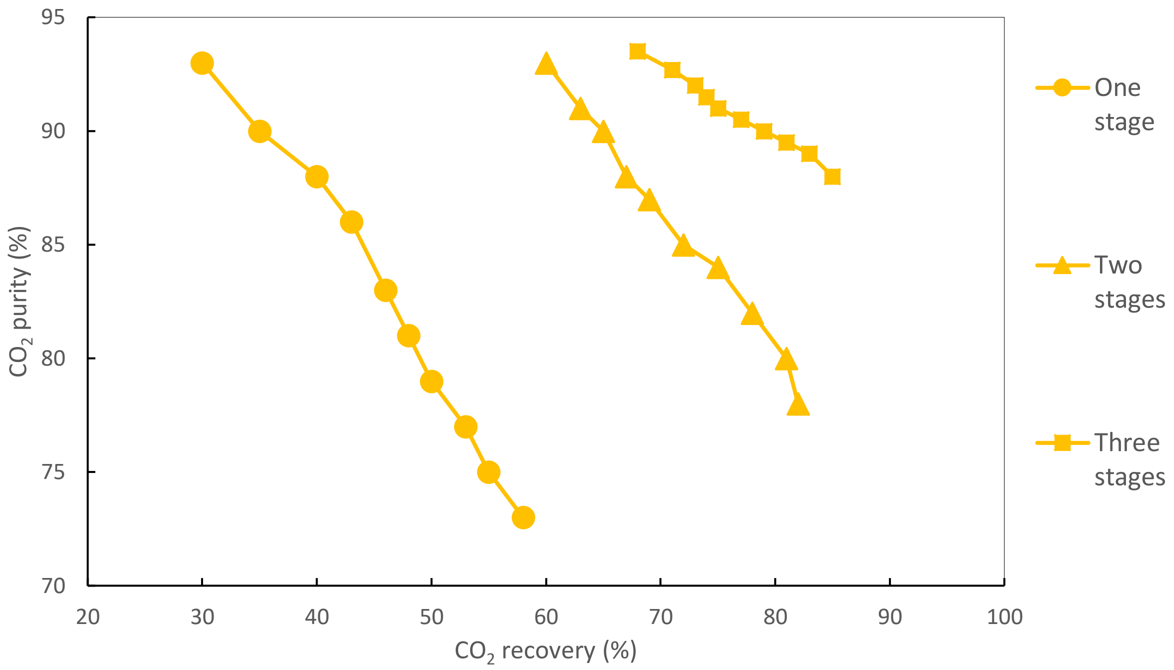


Fig 30. Variation of the carbon dioxide purity from BOG in function of the recovery obtained. (T=298K, p_f/p_p=15)

However, the costs of a single and multiple stage process are also different, both capital (investment) and operating costs. In addition, the fraction that is not recovered would be emitted (and CO_2 emissions also have an associated expense). Therefore, the optimum process design requires an economic evaluation (which is addressed in the next chapter).

When burned COG is treated, since it has higher carbon dioxide concentration, it is possible to reach high purities and recoveries with a single stage, shown in Fig 31. Therefore, for this gas, a single stage process is considered the best design.

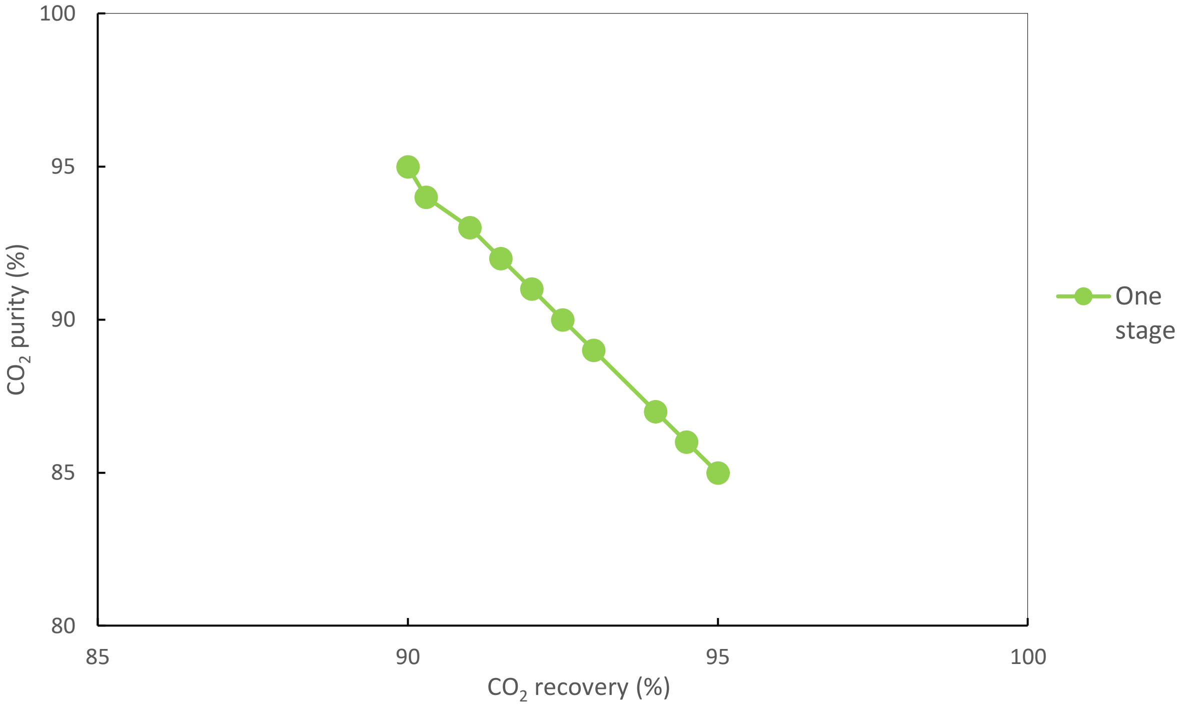


Fig 31. Variation of the carbon dioxide purity from burned COG in function of the recovery obtained.(T=298K, p_f/p_p=15)

6. ECONOMIC EVALUATION

6.1. Flue gas flow rates

In order to size the membrane separation unit and estimate its costs, the first step is to determine the amount of gas that will be treated, for the three under study: BFG, BOG and burned COG gases.

For that purpose, a model plan producing 4.2 million of tons of steel per year, with an average of 1.72 kg of carbon dioxide emitted for kg of steel produced, would have an (annual carbon dioxide production of $7{,}4 \cdot 10^6\ \mathrm{t\,CO_2}$ [«Arcelor reducirá las emisiones de CO_2 en 140»]. Approximately 40% of the emission corresponds to BFG, 45% to BOG and 15% to the burned COG *(Goyena, 2019),* considering negligible other minor sources. As indicated in table 1, carbon dioxide accounts for 23, 18 and 56 % of the BFG; BOG and burned COG streams.

The objective of this work was set at treating 10 % of the yearly emissions and an evaluation of possible potential savings after five years. Taking into account a continuous operating plant (365 days/year) and the above mentioned emissions, the gas flow rates to be treated are summarized in Table 10.

Table 10. Flow rates of gases to be treated by the membrane system

	BFG	BOG	Burned COG
Flux (mol/s)	930	1300	143

6.2. CO_2 conditioning and transport

To achieve the entry of CO_2 into a pipeline, conditioning is required and consists of four intercooled compression stages, with a pressure ratio of about 3 for each compression stage, followed by pumping *(Bolea et al., 2009).* This CO_2 is delivered at high pressures to the pipeline inlet on the mainland. The diameters of the pipes are selected, among diameters of 25" *(Brunsvold et al., 2011).*

These operating costs can be assumed, so we will say that the transport investment cost is 55000 $€_{2019}$/km, estimation based on costs suggested by (*Mikunda et al. 2019).*

6.3. Investment costs

The direct cost functions ($€_{2019}$) have been rolled back for each piece of equipment based on evaluations done with the equation showed in the section 4.4.1 (this is shown in Table 11). However, the membrane equipment costs are obtained from the literature. The membrane module is evaluated based on the costs adopted by *(Zhai and Rubin, 2008),* and the membrane frame is evaluated based on the costs suggested by *(Van der Sluijs et al., 2010).*

Finally, the investment cost for CO_2 capture is obtained by multiplying the sum of the direct costs by an indirect cost of 1.31 *(Pfeffer et al., 2011).*

Table 11. Direct cost of membrane module, rotating equipment and heat exchanger

Type of equipment	**Cost**	**Reference**
Silar membrane unit (€/m^2)	40	*Zhai and Rubin, 2008* *Van der Sluijs et al., 2010*
Expander (€/kW)	570	Rubin et al., 2016
Vacuum pump (€/kW)	800	Rubin et al., 2016
Cooler (€/m^2)	370	Rubin et al., 2016

All costs are 2019 values. If investment costs are not directly available in 2020 prices, they are corrected based on inflation (*Trading economics, 2011*). The transport investment cost is determined based on 55 €2019/km estimate based on costs suggested by (*Mikunda et al. 2019)* and the CO_2 tax emissions are set to 30 €/t *(Donat et al., 2013)*

6.4. Operating costs

The annual fixed operating costs (here including maintenance, insurance, labour and periodic replacement) are set at 5% of the investment costs of the CO_2 capture and conditioning processes *(Chauvel et al., 2003)*.

The cost associated with the periodic replacement of the membrane module will also be taken into account, this is done for an annual replacement over 5 years *(Belaissaoui et at., 2012)* with a replacement cost of 8 €$_{2019}$/m^2 *(Zero emissions platform, 2011).*

The annual pipeline fixed operating costs are set to 7000 € and a CO_2 tax emissions set to 5 €/t (*Donat et al., 2013)*. The annual variable costs of operation of the CO_2 capture, conditioning and transport systems were based on the electricity consumption shown in Table 12.

Table 12. Cost of utilities for the CO_2 capture, conditioning and transport processes

Utilities	**Cost**	**Reference**
Electricity (€$_{2019}$/kWh)	0,08	Emberger et al., 2013
$\mathrm{CO_2}$ storage costs (€/t)	5	Zero emissions platform, 2011
Labour rate (€/h)	35	Eurostat, 2019

6.5. CO_2 avoided cost

The cost of CO_2 avoided serves as a performance indicator for optimizing membrane capture. The cost of CO_2 avoided (€/tCO_2,avoided) approximates the average credit of CO_2 discounted over the duration of the project to exceed the costs associated with its capture, conditioning and transport. The annualized amount of CO_2 avoided is defined as the amount of CO_2 captured minus the direct emissions associated with the electricity consumption *(Emberger et al., 2013)* of the CCS Infrastructure.

$$\mathrm{CO_2\ avoided\ cost}\ \left[\frac{€}{\mathrm{tCO_2}}\right] = \frac{\mathrm{annualized\ investment + annual\ operational\ expenditures}}{\mathrm{annual\ amount\ of\ CO_2\ captured - annual\ direct\ emission}}$$

An example of how all these economic data were used can be seen in the appendix.

6.6. Base case results

With all the data under consideration, the economic study of the costs associated with the different options proposed is realized.

BFG

As indicated in the previous section, the SILAR membrane is not capable of achieving acceptable purities and recoveries for BFG with a single stage. Therefore, it will be checked below which of the multi-stage options gives the lowest costs. Figure 24 presents schematic of a two-stage membrane carbon dioxide capture.

The nominal values of the main measurements and costs that define the capture system are presented in the tables 10-12. The two stages of the capture system have identical material and design properties.

To achieve 80% carbon dioxide removal efficiency and 85% product purity, the pressure ratio for feed versus permeate sides is required to be about 15 for the SILAR membrane properties given in the tables 10-12. To reach this pressure ratio, the feed stream is compressed to be 15 atm ($15 \cdot 10^6$ Pa) and the permeate stream is vacuumed to be 1 atm (10^6 Pa).

The membrane system used is configured with three stages. As shown in Figure 25, the retention flow from the first stage is dispersed into the atmosphere. The retention flow of the third membrane is recycled at the entrance of the capture system, and has the same CO_2 concentration as the feed gas.

The CO_2 rich permeate stream leaving the third stage is further compressed by a compressor before being transported to a storage site. The nominal values of the main measurements and costs that define the capture system are the presented in the tables 10-12. The three stages of the capture system have identical material and design properties.

To achieve 90% carbon dioxide removal efficiency and +90% product purity, the pressure ratio for feed versus permeate sides is required to be about 13 for the membrane properties given in the the tables 10-12

The optimal p_f/p_p ratio for this membrane was already said to be 15, but as this multi-stage configuration was performed it was found to give desirable recovery and purity results with a ratio of 13). For this reason, the more economical ratio was used. To reach this pressure ratio, the feed stream is compressed to be 13 atm ($13 \cdot 10^6$ Pa) and the permeate stream is at atmospheric pressure.

In table 13 we can see the performance and cost results with and without the two and three-stage membrane system for CO_2 capture in BFG.

Table 13. Performance and cost results of plant with and without two and three-stage membrane system for CO_2 capture in the BFG.

Parameters	**Carbon dioxide capture system (BFG)**		
	Without	With two stages	With three stages
CO_2 emission (m^3/s)	7,1	1,45	0,71
%CO_2 removal efficiency	n/a	80%	90%
%CO_2 product purity	n/a	85%	+90%
Pressure ratio (p_f/p_p)	n/a	15	13
Membrane area ($10^3 m^2$)	n/a	5,5	7,1
Cost of CO_2 avoided (€/mt)	n/a	230	235
Investment costs (10^5€)	n/a	5,1	6,1
Operation costs (10^6€)	n/a	5	5,2
CO_2 tax avoided (10^6€)	n/a	-2,3	-2,6
1st Annual total cost (10^6 €)	**3**	**3,2**	**3,3**
Total expense after five years (10^6 €)	**15**	**13,9**	**13,7**
Total savings after five years (10^6 €)	**n/a**	**1,1**	**1,3**
Time to recover the inversion (years)	**n/a**	**3**	**3**

As we can see, the resulting cost of carbon dioxide avoided with two and three stage system is high enough to justify its installation, although this is an initial investment, it only takes five years to see significant savings. You can also see that the three-stage system configuration is more economical than the two-stage configuration. In the next table 14 we can also see the composition of the fluxes obtained.

Table 14. Evolution of the component molar fractions and fluxes in retentate and permeate with SILAR membrane at 298K with a BFG feed of 930 mol/s, a pressure ratio p_f/p_p of 15 (two-stages) and 13 (three-stages).

BFG (Two-stages)

	Feed		Permeate		Retentate	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	216	0,23	173	0,84	43	0,06
CO	222	0,24	10	0,05	212	0,29
H_2	44	0,05	5	0,02	40	0,06
N_2	440	0,47	15	0,07	426	0,59
O_2	7	0,01	1	0,01	6	0,01
TOTAL	930	1,00	203	1,00	727	1,00

BFG (Three-stages)

	Feed		Permeate		Retentate	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	216	0,18	194	0,95	22	0,03
CO	222	0,59	4	0,02	218	0,30
H_2	45	0,02	2	0,01	42	0,06
N_2	440	0,19	3	0,01	438	0,60
O_2	7	0,01	0	0,00	7	0,01
TOTAL	930	1,00	204	1,00	726	1,00

BOG

As indicated in the figure 27, the SILAR membrane is not capable of achieving acceptable purities and recoveries for the BOG with a single stage. Therefore, it will be checked below which of the multi-stage options gives the lowest costs.

This is done by checking the options with two and three stages, in the same way as was done with the BFGs.

In the following table 15 we can see the performance and cost results with and without the two and three-stage membrane system for CO_2 capture in BOG.

Table 15. Performance and cost results of plant with and without two and three-stage membrane system for CO_2 capture in the BOG.

Parameters	**Carbon dioxide capture system (BOG)**		
	Without	With two stages	With three stages
CO_2 emission (m^3/s)	7,6	1,5	0,76
%CO_2 removal efficiency	n/a	80%	90%
%CO_2 product purity	n/a	85%	+ 90%
Pressure ratio (Pf/Pp)	n/a	15	15
Membrane area ($10^3 m^2$)	n/a	5,6	7,4
Cost of CO_2 avoided (€/mt)	n/a	250	260
Investment costs (10^5€)	n/a	5,3	6,4
Operation costs (10^6€)	n/a	5,4	5,5
CO_2 tax avoided (10^6€)	n/a	-2,5	-2,8
1st Annual total cost (10^6 €)	**3,2**	**3,4**	**3,3**
Total expense after five years(10^6 €)	**16**	**15**	**14,5**
Total savings after five years (10^5 €)	**n/a**	**1**	**1,5**
Time to recover the inversion (years)	**n/a**	**3**	**3**

As we can see, the resulting cost of carbon dioxide avoided with two and three stage system is high enough to justify its installation. You can also see that the three-stage system configuration is more economical than the two-stage configuration. In the next table 16, we can also see the composition of the fluxes obtained.

Table 16. Evolution of the component molar fractions and fluxes in retentate and permeate, SILAR membrane at 298K with a BOG feed of 1300 mol/s, pressure ratio p_f/p_p of 15.

BOG (Two-stages)						
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	234	0,18	173	0,85	61	0,06
CO	778	0,59	25	0,12	753	0,68
H_2	31	0,02	2	0,01	29	0,03
N_2	252	0,19	3	0,01	249	0,23
O_2	6	0,01	0	0,00	5	0,01
TOTAL	1300	1,00	203	1,00	1097	1,00
BOG (Three-stages)						
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	234	0,18	210	0,94	23	0,02
CO	778	0,59	8	0,04	770	0,71
H_2	31	0,02	1	0,01	30	0,03
N_2	252	0,19	1	0,01	251	0,23
O_2	6	0,01	0	0,00	6	0,01
TOTAL	1300	1,00	220	1,00	1080	1,00

Burned COG:

As indicated in the figure 28, the SILAR membrane is capable to achieve acceptable purities and recoveries for the burned COG gases with a single stage. For this reason, the economic design will only consider the simple one stage membrane showed in the figure 10.

To achieve 90% carbon dioxide removal efficiency and 85% product purity, the pressure ratio for feed versus permeate sides is required to be about 15 for the membrane properties given in the tables 10-12. To reach this pressure ratio, the feed stream is compressed to be 15 atm ($15 \cdot 10^6$ Pa) and the permeate stream is vacuumed to be 1 atm (10^6 Pa).

The nominal values of the main measurements and costs that define the capture system are the presented in the tables 10-12. In the following table 1 we can see the performance and cost results with and without the two-stage membrane syste7m for 90% of the CO_2 capture in burned COG.

Table 17. Performance and cost results of plant with and without membrane system for 90% CO_2 capture in the burned COG.

Parameters	**Carbon dioxide capture (burned COG)**	
	Without	With one stage
CO_2 emission (m^3/s)	1,2	0,11
%CO_2 removal efficiency	n/a	90%
%CO_2 product purity	n/a	85%
Pressure ratio (Pf/Pp)	n/a	15
Membrane area ($10^2 m^2$)	n/a	3,1
Cost of CO_2 avoided (€/mt)	n/a	20
Investment costs (10^5€)	n/a	1,8
Operation costs (10^5€)	n/a	8,3
CO_2 tax avoided (10^5 €)	n/a	-4,5
1st Annual total cost (10^5 €)	4,9	5,6
Total expense after five years(10^5 €)	24,5	20,9
Total savings after five years (10^5 €)	n/a	3,6
Time to recover the inversion (years)	**n/a**	**2**

As we can see, the resulting cost of carbon dioxide avoided with the one-stage system is high enough to justify its installation. In the next table 18 we can also see the composition of the fluxes obtained.

Table 18. Evolution of the component molar fractions and fluxes in retentate and permeate with SILAR membrane at 298K with a burned COG feed of 143 mol/s, a pressure ratio p_f/p_p of 15.

BOG (One-stage)						
	Feed		**Permeate**		**Retentate**	
Component	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**	**Flow (mol/s)**	**Mol fraction**
CO_2	79	0,56	72	0,85	8	0,14
CO	13	0,09	2	0,03	11	0,18
H_2	7	0,05	2	0,02	5	0,08
N_2	21	0,15	3	0,03	18	0,31
O_2	23	0,16	6	0,07	17	0,29
TOTAL	143	1,00	84	1,00	59	1,00

7. CONCLUSIONS

Gas separation using membrane system has been evaluated for the o capture of carbon dioxide .The analysis was performed by simulation, based on membrane permeances previously published, using the solution-diffusion model with discretized membrane modules and different process design schemes.

The model has been implemented in a spreadsheet using Microsoft Excel and Visual Basic codes for the iterative calculations (saved as macros).

Three commercial polymeric gas separation membranes were selected (Silar, GENERON and PVTMS) and three flue gases (BFG, BOG and burned COG) from the steelmaking process were evaluated.

Temperature was kept at 298 K in all cases (to avoid membrane degradation) and the best performing membrane, optimum operating pressure and membrane system configuration were determined.

The best performing membrane was Silar, with PVTMS offering slightly lower fluxes. The more rigid material of the Generon membrane yielded fluxes that were one order of magnitude lower than those of the other two, and was –therefore- no considered adequate for the industrial application pursued.

It was possible to verify that working under normal conditions, the optimal working ratio p_f/p_p is 15 for the one and two stage configurations, while the three stage would be 13.

A preliminary economic study was carried out for a plant capable of reducing by 10% the carbon dioxide emitted by an iron and steelmaking factory. The membrane plant cost are $1{,}43 \cdot 10^6$ €, payback time 3 yeras savings in CO_2 taxes.

Finally, a few ideas for further work on are listed below:

- Study of the pre-treatment steps needed to remove acid gases or other potential membrane foulants from the flue gases.
- Evalution of non-polymeric membranes with a higher thermal and chemical resistance, such as metal membranes.
- Study of the influence of temperature on process performance and membrane lifetime.
- Simulations with different other membrane configurations.
- Implementation of the simulation model in Aspen Plus, in order to integrate the membrane unit with other plant equipment.

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REFERENCES

BAINS, P., PSARRAS, P. and WILCOX, J., 2017. CO 2 capture from the industry sector. *Progress in Energy and Combustion Science*, vol. 63, pp. 146-172.

BENSON, S.M. and ORR, F.M., 2008. *Carbon dioxide capture and storage*. ISBN 9780521863360.

BREDESEN, R., JORDAL, K. and BOLLAND, O., 2004. High-temperature membranes in power generation with CO2 capture. *Chemical Engineering and Processing: Process Intensification*, vol. 43, no. 9, pp. 1129-1158.

CHEN, W., YIN, X. and MA, D., 2014. A bottom-up analysis of China's iron and steel industrial energy consumption and CO2 emissions. *Applied Energy*, vol. 136, no. 2014, pp. 1174-1183.

DE MATOS, M.E., BIANCHI PEDRONI MEDEIROS, A., DE MELO PEREIRA, G.V., SOCCOL, V.T. and SOCCOL, C.R., 2017. Production and characterization of a distilled alcoholic beverage obtained by fermentation of banana waste (Musa cavendishii) from selected yeast. *Fermentation*, vol. 3, no. 4.

DEBNATH, B., MUKHERJEE, A., MULLICK, A., GHOSHDASTIDAR, S., GANGULY, S. and KARGUPTA, K., 2019. Desublimation based separation of CO2 inside a cryogenic packed bed: Performance mapping with the spatiotemporal evolution of CO2 frost. *Chemical Engineering Research and Design*, vol. 146, no. 1962, pp. 166-181.

ELSEVIER, S.A.S. and WILEY-LISS, D.A.H., 1996. Pergamon Membrane Separations Technology : Principles and Applica- readers of Chemical Engineering Science . Book Reviews The last chapter , on catalytic membrane reactors , is writ- ten by J . L . Falconer , R . D . Noble and D . B . Sperry . It begins w. , vol. 51, no. 2, pp. 325-326.

EUROPEAN COMMISSION, 2010. Communication from the Commission EUROPE 2020 A strategy for smart, sustainable and inclusive growth. *Com(2010) 2020*, vol. Brussels, no. 3 March, pp. Commission of the European Communities.

FALBO, F., TASSELLI, F., BRUNETTI, A., DRIOLI, E. and BARBIERI, G., 2014. Polyimide hollow fiber membranes for CO2 separation from wet gas mixtures. *Brazilian Journal of Chemical Engineering*, vol. 31, no. 4, pp. 1023-1034.

FARD, A.K., MCKAY, G., BUEKENHOUDT, A., AL SULAITI, H., MOTMANS, F., KHRAISHEH, M. and ATIEH, M., 2018. Inorganic membranes: Preparation and application for water treatment and desalination. *Materials*, vol. 11, no. 1.

FIGUEROA, J.D., FOUT, T., PLASYNSKI, S., MCILVRIED, H. and SRIVASTAVA, R.D., 2008. Advances in CO2 capture technology-The U.S. Department of Energy's Carbon Sequestration Program. *International Journal of Greenhouse Gas Control*, vol. 2, no. 1, pp. 9-20.

GOYENA, R., 2019. *Journal of Chemical Information and Modeling*, vol. 53, no. 9, pp. 1689-1699. ISSN 1098-6596.

HAMAD, F., KHULBE, K.C. and MATSUURA, T., 2005. Comparison of gas separation performance and morphology of homogeneous and composite PPO membranes. *Journal of Membrane Science*, vol. 256, no. 1-2, pp. 29-37.

H. Zhai, E.S. Rubin, Techno-Economic Assessment of Polymer Membrane Systems for Postcombustion Carbon Capture at Coal-Fired Power Plants, Environmental Science & Technology 47 (2013) 3006-3014.

JI, G. y ZHAO, M., 2017. Membrane Separation Technology in Carbon Capture. *Recent Advances in Carbon Capture and Storage*, no. March.

KENNISON, S., 2014. How Steel is Made Using the Basic Oxygen Steelmaking Process. ,

LINDQVIST, K., ROUSSANALY, S. and ANANTHARAMAN, R., 2014. Multi-stage membrane processes for CO2 capture from cement industry. *Energy Procedia*, vol. 63, no. 1876, pp. 6476-6483.

MALYKH, O. V., GOLUB, A.Y. and TEPLYAKOV, V. V., 2011. Polymeric membrane materials: New aspects of empirical approaches to prediction of gas permeability parameters in relation to permanent gases, linear lower hydrocarbons and some toxic gases. *Advances in Colloid and Interface Science*, vol. 164, no. 1-2, pp. 89-99.

MASTROPASQUA, L., PEGORIN, A. and CAMPANARI, S., 2020. Low fuel utilisation solid oxide fuel cell system for CO2-free hydrogen production in oil refineries. *Journal of Power Sources*, vol. 448, no. November 2019, pp. 227461.

McCoy, The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs, Carnegie Melon Univerisity, Department of Engineering and Public Policy., 2009.

Mikunda, J. van Deurzen, A. Seebregts, K. Kerssemakers, M. Tetteroo, L. Buit, Towards a CO_2 infrastructure in North-Western Europe: Legalities, costs and organizational aspects, Energy Procedia 4 (2011) 2409-2416.

POWELL, C.E. y QIAO, G.G., 2006. Polymeric CO2/N2 gas separation membranes for the capture of carbon dioxide from power plant flue gases. *Journal of Membrane Science*, vol. 279, no. 1-2, pp. 1-49.

RAMSTEIN, C., DOMINIONI, G., ETTEHAD, S., LAM, L., QUANT, M., ZHANG, J., MARK, L., NIEROP, S., BERG, T., LEUSCHNER, P., MERUSI, C., KLEIN, N. and TRIM, I., 2019. *State and Trends of Carbon Pricing 2019*.

Romeo, I. Bolea, Y. Lara, J.M. Escosa, Optimization of intercooling compression in CO2 capture systems, Applied Thermal Engineering 29 (2009) 1744-1751.

Roussanaly, J.P. Jakobsen, E.H. Hognes, A.L. Brunsvold, Benchmarking of CO_2 transport technologies: Part I—Onshore pipeline and shipping between two onshore areas, International Journal of Greenhouse Gas Control 19C (2013).

Roussanaly, R. Anantharaman, K. Lindqvist, H. Zhai, E. Rubin, Membrane properties required for post-combustion CO_2 capture at coal-fired power plants, Journal of Membrane Science 511 (2016) 250-264.

RUBIN, E.S., MANTRIPRAGADA, H., MARKS, A., VERSTEEG, P. and KITCHIN, J., 2012. The outlook for improved carbon capture technology. *Progress in Energy and Combustion Science*, vol. 38, no. 5, pp. 630-671.

SCHOLES, C.A., CHEN, G.Q., STEVENS, G.W. and KENTISH, S.E., 2011. Nitric oxide and carbon monoxide permeation through glassy polymeric membranes for carbon dioxide separation. *Chemical Engineering Research and Design*, vol. 89, no. 9, pp. 1730-1736..

SCHOLES, C.A., SMITH, K.H., KENTISH, S.E. and STEVENS, G.W., 2010. CO2 capture from pre-combustion processes - Strategies for membrane gas separation. *International Journal of Greenhouse Gas Control*, vol. 4, no. 5, pp. 739-755.

SHEN, X., CHEN, L., XIA, S., XIE, Z. and QIN, X., 2018. Burdening proportion and new energy-saving technologies analysis and optimization for iron and steel production system. *Journal of Cleaner Production*, vol. 172, pp. 2153-2166.

SIMMONS, T., 2000. Co2 Emissions From Stationary Combustion of Fossil Fuels. *IPPC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, pp. 15-40. Available in: http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

SPIRIN, N.A., YAROSHENKO, Y.G. and LAVROV, V. V., 2016. Development of heat-transfer circuits in the blast furnace. *IOP Conference Series: Materials Science and Engineering*, vol. 150, no. 1.

STRATHMANN, H., 2012. Mercury , Mercury Alloys ,and Mercury Compounds : Ullmann ' s Encyclopedia of Industrial Chemistry : Wiley InterS Mercury , Mercury Alloys , and Mercury Mercury , Mercury Alloys , and Mercury Compounds : Ullmann ' s Encyclopedia of Industrial Chemist. , pp. 1-32..

Trading Economics, Trading Economics database on Euro area inflation rate, 2011.

VACCARELLI, M., CARAPELLUCCI, R. and GIORDANO, L., 2014. Energy and economic analysis of the CO2 capture from flue gas of combined cycle power plants. *Energy Procedia*2, vol. 45, pp. 1165-1174.

Van Der Sluijs, C.A. Hendriks, K. Blok, Feasibility of polymer membranes for carbon dioxide recovery from flue gases, Energy Conversion and Management 33 (1992) 429-436.

VALIA, H.S., 1994. Coke production for blast furnace ironmaking. *Blast Furnace Ironmaking*, vol. 2, no. Figure 1, pp. 10.1-10.9.

WANKAT, P.C., 2004. *Separation Process Engineering*.

WANKAT, P.C., 2017. *Separation process engineering : includes mass transfer analysis LK - https://UnivofPretoria.on.worldcat.org/oclc/959849902*.

WORLD STEEL ASSOCIATION, 2018. Sustainability indicators 2003-2017, no. October. available in: https://www.worldsteel.org/steel-by-topic/sustainability/sustainability-indicators.html.

XU, J., WANG, Z., QIAO, Z., WU, H., DONG, S., ZHAO, S. and WANG, J., 2019a. Post-combustion CO 2 capture with membrane process: Practical membrane performance and appropriate pressure. *Journal of Membrane Science* [en línea], vol. 581, no. March, pp. 195-213. ISSN 18733123. DOI 10.1016/j.memsci.2019.03.052. available in: https://doi.org/10.1016/j.memsci.2019.03.052.

XU, J., WANG, Z., QIAO, Z., WU, H., DONG, S., ZHAO, S. and WANG, J., 2019b. Post-combustion CO 2 capture with membrane process: Practical membrane performance and appropriate pressure. *Journal of Membrane Science*, vol. 581, no. November 2018, pp. 195-213.

ZHAO, L., RIENSCHE, E., BLUM, L. and STOLTEN, D., 2010. Multi-stage gas separation membrane processes used in post-combustion capture: Energetic and economic analyses. *Journal of Membrane Science*, vol. 359, no. 1-2, pp. 160-172.

APPENDIX

LIST OF SYMBOLS AND ABBREVIATIONS

GHG: Greenhouse gases

PFC: Perfluorocarbons

ppm: Parts per million

WMO: World Metheorogical Organization

BF: Blast furnace

EAF: Electrical arc furnace

BFG: Blast furnace gases

BOF: Basic oxygen furnace

BOS: Basic oxygen steelmaking

BOG: Basic oxygen gases

COG: Coke oven gases

WGS: Water gas shift

PSA: Pressure swing adsorption

PP: Polypropylene

PA: Polyamide

CC: Capture cost

CR: Capture ratios

FIGURES

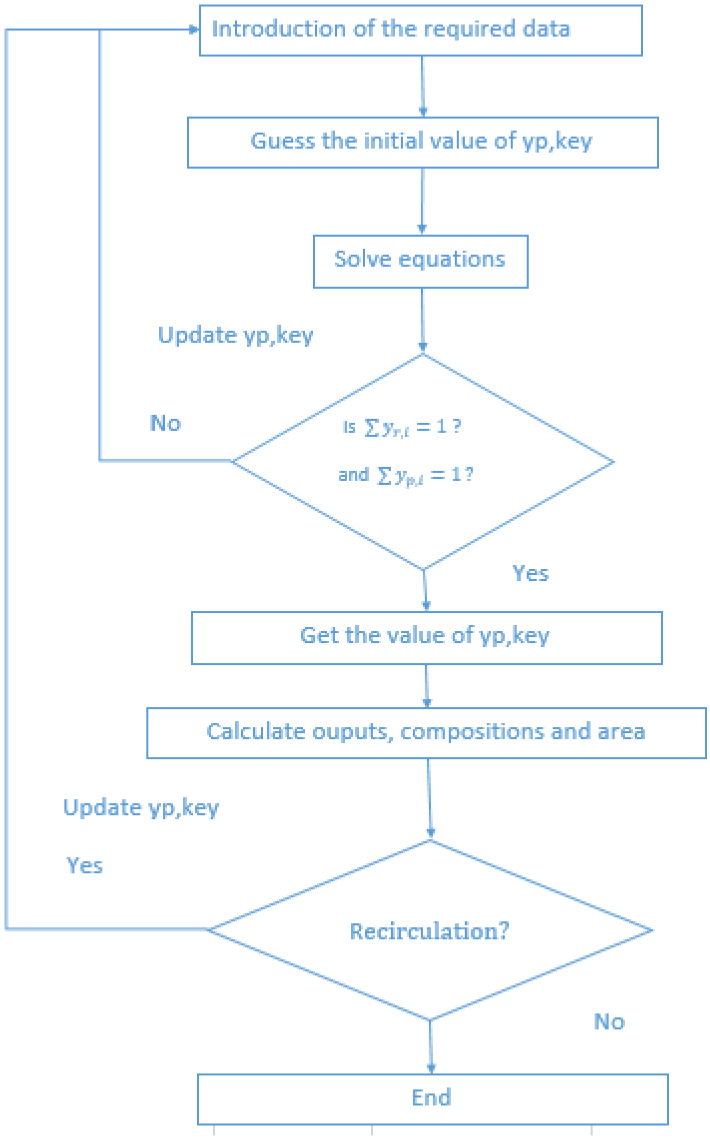

Fig 32. Diagram of the design process

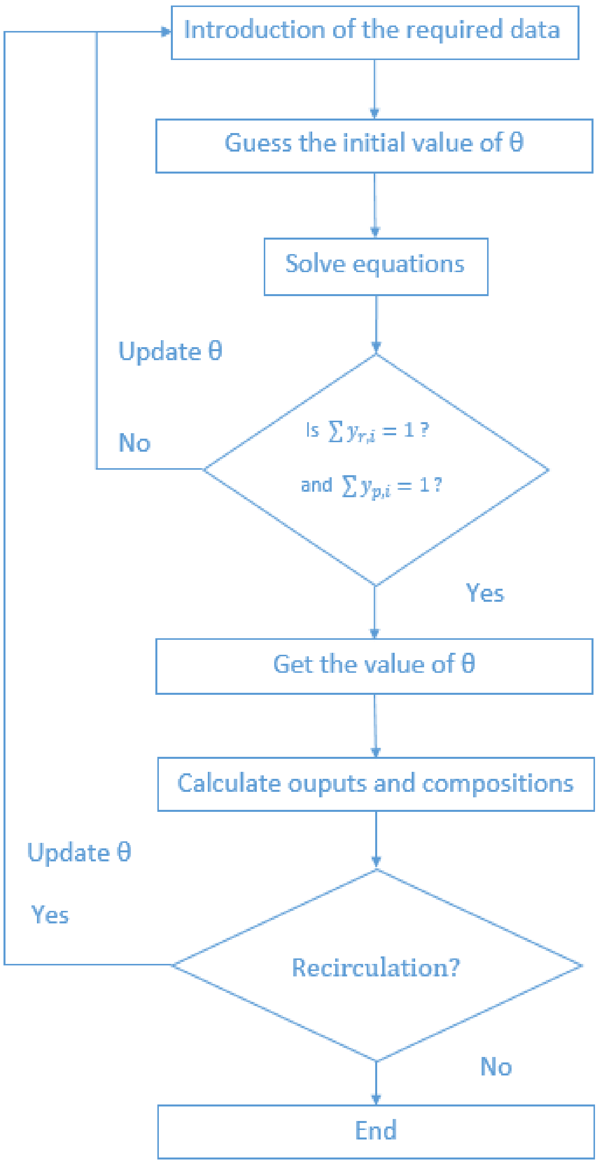

Fig 33. Diagram of the simulation process

CALCULATIONS

The annual production of tons of carbon dioxide, produced by the model plant analysed in the cost section, is obtained as:

$$\frac{1{,}76\ t\ CO_2}{t\ steel} \cdot \frac{4{,}2 \cdot 10^6\ t\ steel}{year} = \frac{7{,}4 \cdot 10^6\ t\ CO_2}{year}$$

As for the amount of steel gas flows produced, they are calculated as

- <u>BFG:</u>

$$\frac{7{,}4 \cdot 10^6\ \mathrm{t\ CO_2}}{\mathrm{year}} \cdot \frac{\mathrm{year}}{\mathrm{365days}} \cdot \frac{\mathrm{day}}{\mathrm{86400s}} \cdot \frac{10^6 \mathrm{g\ C0_2}}{\mathrm{t\ CO_2}} \cdot \frac{\mathrm{1mol\ CO_2}}{\mathrm{44g\ CO_2}} \cdot \frac{\mathrm{1mol\ BFG}}{\mathrm{0{,}23mol\ CO_2}} \cdot 0{,}4 \cdot 0{,}1 = \frac{\mathrm{930\ mol\ BFG}}{\mathrm{s}}$$

- <u>BOG:</u>

$$\frac{7{,}4 \cdot 10^6\ \mathrm{t\ CO_2}}{\mathrm{year}} \cdot \frac{\mathrm{year}}{\mathrm{365\ days}} \cdot \frac{\mathrm{day}}{\mathrm{86400s}} \cdot \frac{10^6 \mathrm{g\ C0_2}}{\mathrm{t\ CO_2}} \cdot \frac{\mathrm{1\ mol\ CO_2}}{\mathrm{44\ g\ CO_2}} \cdot \frac{\mathrm{1mol\ BOG}}{\mathrm{0{,}18\ mol\ CO_2}} \cdot 0{,}45 \cdot 0{,}1 = \frac{\mathrm{1300\ mol\ BOG}}{\mathrm{s}}$$

- <u>Burned COG:</u>

$$\frac{7{,}4 \cdot 10^6\ \mathrm{t\ CO_2}}{\mathrm{year}} \cdot \frac{\mathrm{year}}{\mathrm{365days}} \cdot \frac{\mathrm{day}}{\mathrm{86400s}} \cdot \frac{10^6 \mathrm{g\ C0_2}}{\mathrm{t\ CO_2}} \cdot \frac{\mathrm{1mol\ CO_2}}{\mathrm{44\ g\ CO_2}} \cdot \frac{\mathrm{1mol\ burned\ COG}}{\mathrm{0{,}56mol\ CO_2}} \cdot 0{,}15 \cdot 0{,}1 = \frac{\mathrm{143mol\ burned\ COG}}{\mathrm{s}}$$

Cost calculation for a two-stage gas treatment (BFG) plant

This section explains the cost calculations required for the treatment of BFG gases using a two-stage plant. These calculations are similar for each of the cases shown in Section 6.4 and are applicable to each case.

Inversion costs

- **Initial membrane costs**

$$5{,}5 \cdot 10^3\ m^2 \cdot \frac{40\ €}{m^2} = 2{,}2 \cdot 10^5 €$$

- **Replacement membrane costs**

$$2 \cdot 10^3\ m^2 \cdot 5 \cdot \frac{7€}{m^2} = 7 \cdot 10^4 €$$

- **Transport investment cost**

$$55000 \frac{€}{km} \cdot km = 55000€$$

- **Compresor cost**

$$20000 \frac{€}{ud} \cdot 2\ ud = 40000€$$

- **Expander cost**

$$18000 \frac{€}{ud} \cdot 1\ ud = 18000€$$

- **Total inversión cost**

$$2{,}2 \cdot 10^5 € + 7 \cdot 10^4 € + 55000€ + 40000€ + 18000€ = 403000€$$

Operation Costs

- **Compressor costs**

$$E_{cp} = \frac{F}{\eta_{cp}} \frac{\gamma RT}{\gamma - 1}\left[(\varphi)^{\frac{\gamma-1}{\gamma}} - 1\right] = \frac{930\ mol/s}{0{,}85} \cdot \frac{1{,}4 \cdot \frac{0{,}082 \cdot 10^2 m^3 Pa \cdot 298K}{molK}}{1{,}4 - 1} \cdot \left[15^{\frac{1{,}4-1}{1{,}4}} - 1\right] = 1{,}1 \cdot 10^5\ W$$

$$E_{cp} = \frac{F}{\eta_{cp}} \frac{\gamma RT}{\gamma - 1}\left[(\varphi)^{\frac{\gamma-1}{\gamma}} - 1\right] = \frac{90\ mol/s}{0{,}85} \cdot \frac{1{,}4 \cdot \frac{0{,}082 \cdot 10^2 m^3 Pa \cdot 298K}{molK}}{1{,}4 - 1} \cdot \left[15^{\frac{1{,}4-1}{1{,}4}} - 1\right] = 1 \cdot 10^4\ W$$

$$Annual\ compresor\ operation\ cost = (1{,}1 \cdot 10^5 + 1 \cdot 10^4)W \cdot \frac{1kW}{1000W} \cdot \frac{800€}{kW} = 9{,}6 \cdot 10^4 €$$

- **Expander costs**

$$E_{ex} = \eta_{ex} F \frac{\gamma R T}{\gamma - 1}\left[1 - \left(\frac{1}{\varphi}\right)^{\frac{\gamma-1}{\gamma}}\right] = \frac{840 \cdot 0{,}85\, mol}{s} \cdot \frac{1{,}4 \cdot \frac{0{,}082 \cdot 10^{2} m^{3} Pa \cdot 298K}{molK}}{1{,}4 - 1} \cdot \left[1 - \left(\frac{1}{15}\right)^{\frac{1{,}4-1}{1{,}4}}\right] = 3 \cdot 10^{5}\, W$$

$$Annual\ expansor\ operation\ cost = 3 \cdot 10^{6}\, W \cdot \frac{1kW}{1000W} \cdot \frac{570€}{kW} = 1{,}6 \cdot 10^{5}€$$

- **Cooler costs**

$$2 \cdot \frac{370€}{m^{2}} \cdot \frac{\pi}{4}\left(25\ inches \cdot \frac{2{,}54\ cm}{inch} \cdot \frac{1m}{100cm}\right)^{2} \cdot 240 \cdot 8 = 6 \cdot 10^{5}€$$

- **Transport, storage and labour costs**

$$7000 \frac{€}{km} \cdot km\ + 10t \cdot \frac{5€}{t} + 35 \frac{€}{h} \cdot \frac{8h}{day} \cdot 240\ days = 74250€$$

- **Anual fixed operating costs**

$$74250€ \cdot 0{,}05 = 3715€$$

- **Total operation costs**

$$(9{,}6 \cdot 10^{4}\ € + 1{,}6 \cdot 10^{5}€ + 6 \cdot 10^{5}€ + 774250€ + 3715€) \cdot 1.31 = 2{,}1 \cdot 10^{6}\ €$$

$\mathbf{CO_2}$ avoided cost

$$\mathrm{CO_2\ avoided\ cost}\ \left[\frac{€}{\mathrm{tCO_2}}\right] = \frac{403000€ + 2{,}1 \cdot 10^{6}\ €}{26 - 1{,}8} = 1{,}05 \cdot 10^{5} \frac{€}{\mathrm{tCO_2}}$$

Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

MASTER'S DEGREE FINAL PROJECT

MASTER IN CHEMICAL ENGINEERING

TECHNO-ECONOMIC STUDY OF THE SEPARATION OF GASES FROM IRON AND STEEL MAKING BY MEMBRANE TECHNOLOGY

(Programmed codes)

D. Roy Menéndez Muñoz
TUTOR: Susana Luque Rodríguez

Oviedo, 9 July 2020

Appendix

1. DESIGN CODE

DESIGN CODE

‘In this section you enter the visual basic, this will serve as an interactive screen from which to enter the operation data.’

VISUAL BASIC DESIGN CODE

```
Private Sub Ejecute1_Click()
Range("D34") = yCO2
Range("D35") = yCO
Range("D36") = yH2
Range("D37") = yN2
Range("D38") = yO2
Range("D42") = FEEDGAS
Range("G34") = PCO2
Range("G35") = PCO
Range("G36") = PH2
Range("G37") = PN2
Range("G38") = PO2
Range("J33") = PF
Range("J35") = PP
Range("J37") = Temperature
Range("J40") = CP
Range("J42") = ypCO2
Range("E34") = y_CO2.Value
Range("E35") = y_CO.Value
Range("E36") = y_H2.Value
Range("E37") = y_N2.Value
Range("E38") = y_O2.Value
```

```
Range("E42") = FEED_GAS.Value
Range("H34") = P_CO2.Value
Range("H35") = P_CO.Value
Range("H36") = P_H2.Value
Range("H37") = P_N2.Value
Range("H38") = P_O2.Value
Range("K33") = P_F.Value
Range("K35") = P_P.Value
Range("K35") = TEMPE_RATURE.Value
Range("K40") = C_P.Value
Range("K42") = yp_CO2.Value
ActiveWindow.ScrollColumn = 1
    Range("D19").Select
    ActiveCell.FormulaR1C1 = "Data"
    Range("D27").Select
    ActiveCell.FormulaR1C1 = "Etape 1"
    Range("D31").Select
    ActiveCell.FormulaR1C1 = "INPUTS"
    Range("E33").Select
    ActiveCell.FormulaR1C1 = "FEED COMPOSITION"
    Range("E39").Select
    ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
    Range("G31").Select
    ActiveCell.FormulaR1C1 = "MEMBRANE PROPERTIES"
    Range("J31").Select
    ActiveCell.FormulaR1C1 = "OPERATION CONDITIONS"
```

```
    Range("H33").Select

    ActiveCell.FormulaR1C1 = "GASES PERMEABILITIES (mol/m2*s*Pa)"

End Sub

Private Sub Escape_Click()

Unload Me

End Sub

Private Sub UserForm_Click()

End Sub
```

‘From this section the process of segmentation of the membrane equipment into 10 sub-stages begins, After this, an iterative process is carried out.’

‘This is necessary in order to reach the equilibrium of the different molar fractions.’

DESIGN MACROS CODE

```
Sub DESIGN()
' DESIGN Macro’
    Range("C48").Select
    ActiveCell.FormulaR1C1 = "Calculations 1st membrane"
    Range("C53").Select
    ActiveCell.FormulaR1C1 = "Section 1"
    Range("C56").Select
    ActiveCell.FormulaR1C1 = "yp,key CO2"
    Range("C57").Select
    ActiveCell.FormulaR1C1 = "yr,key CO2"
    Range("D56").Select
    ActiveCell.FormulaR1C1 = "=R42C11"
    Range("D57").Select
    ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[-23]C[1])/(1-(R40C11/10))"
    Range("D58").Select
    ActiveWindow.SmallScroll Down:=3
    Range("C59").Select
    ActiveCell.FormulaR1C1 = "Fp/A"
    Range("D59").Select
    ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
    Range("C61").Select
    ActiveCell.FormulaR1C1 = "Km,CO2"
```

```
Range("C62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("C63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("C64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("C65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("D61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"

Range("D62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"

Range("D63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"

Range("D64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("D65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("D66").Select

ActiveWindow.SmallScroll Down:=15

Range("C68").Select
```

```
ActiveCell.FormulaR1C1 = "RESULTS"

Range("C69").Select

ActiveWindow.SmallScroll Down:=9

Range("D74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("D77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("D78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("D79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("D80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("D81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("E76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("E77").Select

ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"

Range("E78").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("E79").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("E80").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("E81").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("E82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("E83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("D85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("E85").Select
ActiveCell.FormulaR1C1 = "=R[-43]C-RC[3]"
Range("D88").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
Range("E88").Select
ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"
Range("E89").Select
ActiveCell.FormulaR1C1 = "=R[-1]C"
Range("G77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
Range("G78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("G79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("G80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("G81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("H76").Select
```

```
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("H77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("H78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("G85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("H85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*R[-43]C[-3]"
Range("G88").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("H88").Select
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-46]C[-3]"
Range("H89").Select
ActiveWindow.SmallScroll Down:=0
ActiveWindow.ScrollColumn = 2
ActiveWindow.ScrollColumn = 3
ActiveWindow.ScrollColumn = 4
```

```
ActiveWindow.ScrollColumn = 5
ActiveWindow.ScrollColumn = 6
ActiveWindow.ScrollColumn = 7
ActiveWindow.ScrollColumn = 8
ActiveWindow.ScrollColumn = 9
ActiveWindow.ScrollColumn = 10
ActiveWindow.SmallScroll Down:=-15
Range("K53").Select
ActiveCell.FormulaR1C1 = "Section 2"
Range("K56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("K57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("L56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("L57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("K59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("L59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("K61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("K62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("K63").Select
```

```
ActiveCell.FormulaR1C1 = "Km,H2"
Range("K64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("K65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("L61").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("L62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("L63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"
Range("L64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"
Range("L65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"
Range("L66").Select
ActiveWindow.SmallScroll Down:=18
Range("L74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("L77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
```

```
Range("L78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("L79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("L80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("L81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("M76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("M77").Select
ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"
Range("M78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("M79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("M80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("M81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("M82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("M83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("L85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
```

```
Range("M85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("L88").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
Range("M88").Select
ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"
Range("M89").Select
ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"
Range("O77").Select
ActiveCell.FormulaR1C1 = "CO2"
Range("O78").Select
ActiveCell.FormulaR1C1 = "CO"
Range("O79").Select
ActiveCell.FormulaR1C1 = "H2"
Range("O80").Select
ActiveCell.FormulaR1C1 = "N2"
Range("O81").Select
ActiveCell.FormulaR1C1 = "O2"
Range("P76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("P77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("P78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("P79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("P80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("O85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("P85").Select

ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"

Range("O88").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("P88").Select

ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"

Range("P89").Select

ActiveWindow.SmallScroll ToRight:=7

ActiveWindow.SmallScroll Down:=-21

Range("S53").Select

ActiveCell.FormulaR1C1 = "Section 3"

Range("S56").Select

ActiveCell.FormulaR1C1 = "yp,key CO2"

Range("S57").Select

ActiveCell.FormulaR1C1 = "yr,key CO2"

Range("T56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("T57").Select
```

```
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("S59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("T59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("S61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("S62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("S63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("S64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("S65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("T61").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("T62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("T63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"
Range("T64").Select
ActiveCell.FormulaR1C1 = _
```

```
    "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("T65").Select

ActiveCell.FormulaR1C1 = _

    "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("T66").Select

ActiveWindow.SmallScroll Down:=21

Range("T74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("T77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("T78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("T79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("T80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("T81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("U76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("U77").Select

ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"

Range("U78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("U79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
```

```
Range("U80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("U81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("U82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("U83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("T85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("U85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("T88").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
Range("U88").Select
ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"
Range("U89").Select
ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"
Range("W77").Select
ActiveCell.FormulaR1C1 = "CO2"
Range("W78").Select
ActiveCell.FormulaR1C1 = "CO"
Range("W79").Select
ActiveCell.FormulaR1C1 = "H2"
Range("W80").Select
ActiveCell.FormulaR1C1 = "N2"
```

```
Range("W81").Select
ActiveCell.FormulaR1C1 = "O2"
Range("X76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("X77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("X78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("X79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("X80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("X81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("X82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("W85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("X85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"
Range("W88").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("X88").Select
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"
Range("X89").Select
ActiveWindow.ScrollColumn = 18
```

```
ActiveWindow.ScrollColumn = 19
ActiveWindow.ScrollColumn = 20
ActiveWindow.ScrollColumn = 21
ActiveWindow.ScrollColumn = 22
ActiveWindow.SmallScroll Down:=-12
Range("AA53").Select
ActiveCell.FormulaR1C1 = "Section 4"
Range("AA56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("AA57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("AB56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AB57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("AA59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AB59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("AA61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("AA62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("AA63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("AA64").Select
```

```
ActiveCell.FormulaR1C1 = "Km,N2"
Range("AA65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("AB61").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("AB62").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("AB63").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"
Range("AB64").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"
Range("AB65").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"
Range("AB66").Select
ActiveWindow.SmallScroll Down:=15
Range("AB74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("AB77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("AB78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
```

```
Range("AB79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("AB80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AB81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("AC76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("AC77").Select
ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"
Range("AC78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AC79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AC80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AC81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AC82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("AC83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("AB85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("AC85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
```

```
Range("AB88").Select

ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"

Range("AC88").Select

ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"

Range("AC89").Select

ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"

Range("AC90").Select

ActiveWindow.ScrollColumn = 23

ActiveWindow.ScrollColumn = 24

ActiveWindow.ScrollColumn = 25

Range("AE77").Select

ActiveCell.FormulaR1C1 = "CO2"

Range("AE78").Select

ActiveCell.FormulaR1C1 = "CO"

Range("AE79").Select

ActiveCell.FormulaR1C1 = "H2"

Range("AE80").Select

ActiveCell.FormulaR1C1 = "N2"

Range("AE81").Select

ActiveCell.FormulaR1C1 = "O2"

Range("AF76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("AF77").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"

Range("AF78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("AF79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AE85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("AF85").Select

ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"

Range("AE88").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("AF88").Select

ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"

Range("AF89").Select

ActiveWindow.ScrollColumn = 24

ActiveWindow.ScrollColumn = 25

ActiveWindow.ScrollColumn = 26

ActiveWindow.ScrollColumn = 27

ActiveWindow.ScrollColumn = 28

ActiveWindow.ScrollColumn = 29

ActiveWindow.ScrollColumn = 30

ActiveWindow.ScrollColumn = 31

ActiveWindow.ScrollColumn = 32
```

```
ActiveWindow.SmallScroll Down:=-18
Range("AI53").Select
ActiveCell.FormulaR1C1 = "Section 5"
Range("AI56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("AI57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("AJ56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AJ57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("AI59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AI59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AJ59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("AI61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("AI62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("AI63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("AI64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("AI65").Select
```

```
ActiveCell.FormulaR1C1 = "Km,O2"

Range("AJ61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"

Range("AJ62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"

Range("AJ63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"

Range("AJ64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("AJ65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("AJ74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("AJ75").Select

ActiveWindow.SmallScroll Down:=12

Range("AJ77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("AJ78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("AJ79").Select

ActiveCell.FormulaR1C1 = "yr,H2"
```

```
Range("AJ80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AJ81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("AK76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("AK77").Select
ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"
Range("AK78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AK79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AK80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AK81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("AK82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("AK83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("AJ85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("AK85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("AJ88").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
```

```
Range("AK88").Select
ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"
Range("AK89").Select
ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"
Range("AM77").Select
ActiveCell.FormulaR1C1 = "CO2"
Range("AM78").Select
ActiveCell.FormulaR1C1 = "CO"
Range("AM79").Select
ActiveCell.FormulaR1C1 = "H2"
Range("AM80").Select
ActiveCell.FormulaR1C1 = "N2"
Range("AM81").Select
ActiveCell.FormulaR1C1 = "O2"
Range("AN76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("AN77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("AN78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("AN79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("AN80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("AN81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("AN82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AM85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("AN85").Select

ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"

Range("AM88").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("AN88").Select

ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"

Range("AN89").Select

ActiveWindow.ScrollColumn = 33

ActiveWindow.ScrollColumn = 34

ActiveWindow.ScrollColumn = 35

ActiveWindow.ScrollColumn = 36

ActiveWindow.ScrollColumn = 37

ActiveWindow.ScrollColumn = 38

ActiveWindow.ScrollColumn = 39

ActiveWindow.ScrollColumn = 40

ActiveWindow.SmallScroll Down:=-12

Range("AQ53").Select

ActiveCell.FormulaR1C1 = "Section 6"

Range("AQ56").Select

ActiveCell.FormulaR1C1 = "yp,key CO2"

Range("AQ57").Select

ActiveCell.FormulaR1C1 = "yr,key CO2"
```

```
Range("AR56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AR57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("AQ59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AR59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("AQ61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("AQ62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("AQ63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("AQ64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("AQ65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("AR61").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("AR62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("AR63").Select
ActiveCell.FormulaR1C1 = _
```

```
    "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"

Range("AR64").Select

ActiveCell.FormulaR1C1 = _

    "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("AR65").Select

ActiveCell.FormulaR1C1 = _

    "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("AR66").Select

ActiveWindow.SmallScroll Down:=15

Range("AR74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("AR77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("AR78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("AR79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("AR80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("AR81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("AS76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("AS77").Select

ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"

Range("AS78").Select
```

```
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("AS79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("AS80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("AS81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("AS82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AS83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("AR85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("AS85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("AR88").Select

ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"

Range("AS88").Select

ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"

Range("AS89").Select

ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"

Range("AU77").Select

ActiveCell.FormulaR1C1 = "CO2"

Range("AU78").Select

ActiveCell.FormulaR1C1 = "CO"

Range("AU79").Select
```

```
ActiveCell.FormulaR1C1 = "H2"

Range("AU80").Select

ActiveCell.FormulaR1C1 = "N2"

Range("AU81").Select

ActiveCell.FormulaR1C1 = "O2"

Range("AV76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("AV77").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"

Range("AV78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AU85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("AV85").Select

ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"

Range("AU88").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("AV88").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"
Range("AV89").Select
ActiveWindow.ScrollColumn = 41
ActiveWindow.ScrollColumn = 42
ActiveWindow.ScrollColumn = 43
ActiveWindow.ScrollColumn = 44
ActiveWindow.ScrollColumn = 45
ActiveWindow.ScrollColumn = 46
ActiveWindow.ScrollColumn = 47
ActiveWindow.ScrollColumn = 48
ActiveWindow.SmallScroll Down:=-15
Range("AY53").Select
ActiveCell.FormulaR1C1 = "Section 7"
Range("AY56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("AY57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("AZ56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AZ57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("AY59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AZ59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-
3]C)"
Range("AY61").Select
```

```
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("AY62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("AY63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("AY64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("AY65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("AZ59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("AZ61").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("AZ62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("AZ63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"
Range("AZ64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"
Range("AZ65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"
```

```
Range("AZ66").Select

ActiveWindow.SmallScroll Down:=15

Range("AZ74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("AZ77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("AZ78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("AZ79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("AZ80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("AZ81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("BA76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("BA77").Select

ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"

Range("BA78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BA79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BA80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BA81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
```

```
Range("BA82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("BA83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("AZ85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("BA85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("AZ88").Select

ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"

Range("BA88").Select

ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"

Range("BA89").Select

ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"

Range("BC77").Select

ActiveCell.FormulaR1C1 = "CO2"

Range("BC78").Select

ActiveCell.FormulaR1C1 = "CO"

Range("BC79").Select

ActiveCell.FormulaR1C1 = "H2"

Range("BC80").Select

ActiveCell.FormulaR1C1 = "N2"

Range("BC81").Select

ActiveCell.FormulaR1C1 = "O2"

Range("BD76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
```

```
Range("BD77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("BD78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BD79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BD80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BD81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BD82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BC85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("BD85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"
Range("BC88").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("BD88").Select
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"
Range("BD89").Select
ActiveWindow.ScrollColumn = 47
ActiveWindow.ScrollColumn = 48
ActiveWindow.ScrollColumn = 49
ActiveWindow.ScrollColumn = 50
ActiveWindow.ScrollColumn = 51
```

```
ActiveWindow.ScrollColumn = 52
ActiveWindow.ScrollColumn = 53
ActiveWindow.ScrollColumn = 54
ActiveWindow.ScrollColumn = 55
ActiveWindow.ScrollColumn = 56
ActiveWindow.ScrollColumn = 57
ActiveWindow.SmallScroll Down:=-18
Range("BG53").Select
ActiveCell.FormulaR1C1 = "Section 8"
Range("BG56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("BG57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("BH56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("BH57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("BG59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("BH59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("BG61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("BG62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("BG63").Select
```

```
ActiveCell.FormulaR1C1 = "Km,H2"

Range("BG64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("BG65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("BH61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"

Range("BH62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"

Range("BH63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"

Range("BH64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("BH65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("BH66").Select

ActiveWindow.SmallScroll Down:=12

Range("BH74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("BH75").Select

ActiveWindow.SmallScroll Down:=3
```

```
Range("BH77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("BH78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("BH79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("BH80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("BH81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("BI76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("BI77").Select

ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"

Range("BI78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BI79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BI80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BI81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"

Range("BI82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("BI83").Select

ActiveCell.FormulaR1C1 = "SOLVER"
```

```
Range("BH85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("BI85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("BH88").Select

ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"

Range("BI88").Select

ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"

Range("BI89").Select

ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"

Range("BK77").Select

ActiveCell.FormulaR1C1 = "CO2"

Range("BK78").Select

ActiveCell.FormulaR1C1 = "CO"

Range("BK79").Select

ActiveCell.FormulaR1C1 = "H2"

Range("BK80").Select

ActiveCell.FormulaR1C1 = "N2"

Range("BK81").Select

ActiveCell.FormulaR1C1 = "O2"

Range("BL76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("BL77").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"

Range("BL78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("BL79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BK85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("BL85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"
Range("BK88").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("BL88").Select
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"
Range("BL89").Select
ActiveWindow.ScrollColumn = 56
ActiveWindow.ScrollColumn = 57
ActiveWindow.ScrollColumn = 58
ActiveWindow.ScrollColumn = 59
ActiveWindow.ScrollColumn = 60
ActiveWindow.ScrollColumn = 61
ActiveWindow.ScrollColumn = 62
ActiveWindow.ScrollColumn = 63
ActiveWindow.ScrollColumn = 64
```

```
ActiveWindow.ScrollColumn = 65
ActiveWindow.ScrollColumn = 66
ActiveWindow.ScrollColumn = 67
ActiveWindow.ScrollColumn = 66
ActiveWindow.ScrollColumn = 65
ActiveWindow.SmallScroll Down:=-15
Range("BO53").Select
ActiveCell.FormulaR1C1 = "Section 9"
Range("BO56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("BO57").Select
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("BP56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("BP57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("BO59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("BP59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-
3]C)"
Range("BO61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("BO62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("BO63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
```

```
Range("BO64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("BO65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("BP61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"

Range("BP62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"

Range("BP63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"

Range("BP64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"

Range("BP65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"

Range("BP66").Select

ActiveWindow.SmallScroll Down:=15

Range("BP74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("BP77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("BP78").Select
```

```
ActiveCell.FormulaR1C1 = "yr,CO"
Range("BP79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("BP80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("BP81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("BQ76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("BQ77").Select
ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"
Range("BQ78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BQ79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BQ80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BQ81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BQ82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BQ83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("BP85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("BQ85").Select
```

```
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("BP88").Select

ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"

Range("BQ88").Select

ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"

Range("BQ89").Select

ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"

Range("BS77").Select

ActiveCell.FormulaR1C1 = "CO2"

Range("BS78").Select

ActiveCell.FormulaR1C1 = "CO"

Range("BS79").Select

ActiveCell.FormulaR1C1 = "H2"

Range("BS80").Select

ActiveCell.FormulaR1C1 = "N2"

Range("BS81").Select

ActiveCell.FormulaR1C1 = "O2"

Range("BT76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("BT77").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"

Range("BT78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BT79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BT80").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BT81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BT82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BS85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("BT85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"
Range("BS88").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("BT88").Select
ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"
Range("BT89").Select
ActiveWindow.ScrollColumn = 64
ActiveWindow.ScrollColumn = 65
ActiveWindow.ScrollColumn = 66
ActiveWindow.ScrollColumn = 69
ActiveWindow.ScrollColumn = 70
ActiveWindow.ScrollColumn = 73
ActiveWindow.SmallScroll Down:=-15
Range("BW53").Select
ActiveCell.FormulaR1C1 = "Section 10"
Range("BW56").Select
ActiveCell.FormulaR1C1 = "yp,key CO2"
Range("BW57").Select
```

```
ActiveCell.FormulaR1C1 = "yr,key CO2"
Range("BX56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("BX57").Select
ActiveCell.FormulaR1C1 = "=((-R40C11/10)*R[-1]C+R[20]C[-7])/(1-(R40C11/10))"
Range("BW59").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("BX59").Select
ActiveCell.FormulaR1C1 = "=R34C8*(R33C11*R[-2]C-R35C11*R[-3]C)/(R42C8*R[-3]C)"
Range("BW61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("BW62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("BW63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("BW64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("BW65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("BX61").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R34C8/R42C8))/(R[-2]C+R35C11*(R34C8/R42C8))"
Range("BX62").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R35C8/R42C8))/(R[-3]C+R35C11*(R35C8/R42C8))"
Range("BX63").Select
```

```
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-4]C+R35C11*(R36C8/R42C8))"
Range("BX64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-5]C+R35C11*(R37C8/R42C8))"
Range("BX65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-6]C+R35C11*(R38C8/R42C8))"
Range("BX66").Select
ActiveWindow.SmallScroll Down:=12
Range("BX74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("BX75").Select
ActiveWindow.SmallScroll Down:=9
Range("BX77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("BX78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("BX79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("BX80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("BX81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("BY76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
```

```
Range("BY77").Select
ActiveCell.FormulaR1C1 = "=R[-20]C[-1]"
Range("BY78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BY79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BY80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BY81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R40C11/10)"
Range("BY82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BY83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("BX85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("BY85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("BX88").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
Range("BY88").Select
ActiveCell.FormulaR1C1 = "=(R[-3]C[3]/R[-29]C[-1])"
Range("BY89").Select
ActiveCell.FormulaR1C1 = "=RC[-8]+R[-1]C"
Range("CA77").Select
ActiveCell.FormulaR1C1 = "CO2"
```

```
Range("CA78").Select
ActiveCell.FormulaR1C1 = "CO"
Range("CA79").Select
ActiveCell.FormulaR1C1 = "H2"
Range("CA80").Select
ActiveCell.FormulaR1C1 = "N2"
Range("CA81").Select
ActiveCell.FormulaR1C1 = "O2"
Range("CB76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("CB77").Select
ActiveCell.FormulaR1C1 = "=R[-21]C[-4]"
Range("CB78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("CA85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("CB85").Select
ActiveCell.FormulaR1C1 = "=(R40C11/10)*RC[-11]"
```

```
Range("CA88").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("CB88").Select

ActiveCell.FormulaR1C1 = "=R[-3]C/R[-3]C[-11]"

Range("CB89").Select

ActiveWindow.ScrollColumn = 72

ActiveWindow.ScrollColumn = 65

ActiveWindow.ScrollColumn = 11

ActiveWindow.ScrollColumn = 1

ActiveWindow.SmallScroll Down:=30

Range("D98").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("D99").Select

ActiveWindow.SmallScroll Down:=6

Range("C102").Select

ActiveCell.FormulaR1C1 = "Etape 1"

Range("C106").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("D106").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[73]"

Range("C109").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("C110").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("C111").Select

ActiveCell.FormulaR1C1 = "yr,H2"
```

```
Range("C112").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("C113").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("D108").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("D109").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D110").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D111").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D112").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D113").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D114").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("C117").Select
ActiveCell.FormulaR1C1 = "RETENTATE (m3/s)"
Range("D117").Select
ActiveCell.FormulaR1C1 = "=SUM(R[3]C:R[7]C)"
Range("C120").Select
ActiveCell.FormulaR1C1 = "Qr,CO2"
Range("C121").Select
ActiveCell.FormulaR1C1 = "Qr,CO"
```

```
Range("C122").Select
ActiveCell.FormulaR1C1 = "Qr,H2"
Range("C123").Select
ActiveCell.FormulaR1C1 = "Qr,N2"
Range("C124").Select
ActiveCell.FormulaR1C1 = "Qr,O2"
Range("D119").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPONENTS (m3/s)"
Range("D120").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"
Range("D121").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"
Range("D122").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"
Range("D123").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"
Range("D124").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"
Range("C128").Select
ActiveCell.FormulaR1C1 = "AREA NEDDED (m2)"
Range("D128").Select
ActiveCell.FormulaR1C1 = _
    "=R[-40]C[1]+R[-40]C[9]+R[-40]C[17]+R[-40]C[25]+R[-40]C[33]+R[-40]C[41]+R[-40]C[49]+R[-40]C[57]+R[-40]C[65]+R[-40]C[73]"
Range("E103").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("F106").Select
```

```
            ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

            Range("G106").Select

            ActiveCell.FormulaR1C1 = _

               "=R[-21]C[1]+R[-21]C[9]+R[-21]C[17]+R[-21]C[25]+R[-21]C[33]+R[-21]C[41]+R[-
21]C[49]+R[-21]C[57]+R[-21]C[65]+R[-21]C[73]"

            Range("F109").Select

            ActiveCell.FormulaR1C1 = "yp,CO2"

            Range("F110").Select

            ActiveCell.FormulaR1C1 = "yp,CO"

            Range("F111").Select

            ActiveCell.FormulaR1C1 = "yp,H2"

            Range("F112").Select

            ActiveCell.FormulaR1C1 = "yp,N2"

            Range("F113").Select

            ActiveCell.FormulaR1C1 = "yp,O2"

            Range("G108").Select

            ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

            Range("G109").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G110").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
```

```
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

          Range("G111").Select

          ActiveCell.FormulaR1C1 = _

             "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

          Range("G112").Select

          ActiveCell.FormulaR1C1 = _

             "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

          Range("G113").Select

          ActiveCell.FormulaR1C1 = _

             "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

          Range("G114").Select

          ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

          Range("F117").Select

          ActiveCell.FormulaR1C1 = "PERMEATE (m3/s)"

          Range("G117").Select

          ActiveCell.FormulaR1C1 = "=SUM(R[3]C:R[7]C)"

          Range("F120").Select

          ActiveCell.FormulaR1C1 = "Qp,CO2"

          Range("F121").Select
```

```
ActiveCell.FormulaR1C1 = "Qp,CO"

Range("F122").Select

ActiveCell.FormulaR1C1 = "Qp,H2"

Range("F123").Select

ActiveCell.FormulaR1C1 = "Qp,N2"

Range("F124").Select

ActiveCell.FormulaR1C1 = "Qp,O2"

Range("G119").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPONENTS (m3/s)"

Range("G120").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"

Range("G121").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"

Range("G122").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"

Range("G123").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"

Range("G124").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"

Range("G125").Select
```

```
        ‘In this section, the solver command is used to achieve logical and viable results.’
            SolverOk SetCell:="$E$82", MaxMinVal:=3, ValueOf:=1, ByChange:= _

"$D$56,$L$56,$T$56,$AB$56,$AJ$56,$AR$56,$AZ$56,$BH$56,$BP$56,$BX$56",
Engine:=1 _
            , EngineDesc:="GRG Nonlinear"
          SolverOk SetCell:="$E$82", MaxMinVal:=3, ValueOf:=1, ByChange:= _

"$D$56,$L$56,$T$56,$AB$56,$AJ$56,$AR$56,$AZ$56,$BH$56,$BP$56,$BX$56",
Engine:=1 _
            , EngineDesc:="GRG Nonlinear"
          SolverSolve
        End Sub
```

2. SIMULATION CODE

‘In this section you enter the visual basic, this will serve as an interactive screen from which to enter the operation data.’

SIMULATION VISUAL BASIC CODE

```
Private Sub Ejecute1_Click()

Range("D34") = yCO2

Range("D35") = yCO

Range("D36") = yH2

Range("D37") = yN2

Range("D38") = yO2

Range("D42") = FEEDGAS

Range("G34") = PCO2

Range("G35") = PCO

Range("G36") = PH2

Range("G37") = PN2

Range("G38") = PO2

Range("J33") = PF

Range("J35") = PP

Range("J37") = Temperature

Range("J40") = Area

Range("J42") = CP

Range("E34") = y_CO2.Value

Range("E35") = y_CO.Value

Range("E36") = y_H2.Value

Range("E37") = y_N2.Value

Range("E38") = y_O2.Value

Range("E42") = FEED_GAS.Value

Range("H34") = P_CO2.Value
```

```
Range("H35") = P_CO.Value

Range("H36") = P_H2.Value

Range("H37") = P_N2.Value

Range("H38") = P_O2.Value

Range("K33") = P_F.Value

Range("K35") = P_P.Value

Range("K37") = TEMPE_RATURE.Value

Range("K40") = A_rea.Value

Range("K42") = C_P.Value

ActiveWindow.ScrollColumn = 1

   Range("D19").Select

   ActiveCell.FormulaR1C1 = "Data"

   Range("D27").Select

   ActiveCell.FormulaR1C1 = "Etape 1"

   Range("D31").Select

   ActiveCell.FormulaR1C1 = "INPUTS"

   Range("E33").Select

   ActiveCell.FormulaR1C1 = "FEED COMPOSITION"

   Range("E39").Select

   ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

   Range("G31").Select

   ActiveCell.FormulaR1C1 = "MEMBRANE PROPERTIES"

   Range("J31").Select

   ActiveCell.FormulaR1C1 = "OPERATION CONDITIONS"

   Range("H33").Select

   ActiveCell.FormulaR1C1 = "GASES PERMEANCES (mol/m2*s*Pa)"
```

‘From this section the process of segmentation of the membrane equipment into 10 sub-stages begins, After this, an iterative process is carried out.’

‘This is necessary in order to reach the equilibrium of the different molar fractions.’

SIMULATION CODE

```
Sub SIMULATION()'
' SIMULATION Macro'
    Range("C48").Select
    ActiveCell.FormulaR1C1 = "Calculations 1st membrane"
    Range("C53").Select
    ActiveCell.FormulaR1C1 = "Section 1"
    Range("C56").Select
    ActiveCell.FormulaR1C1 = "Sigma"
    Range("C57").Select
    ActiveCell.FormulaR1C1 = "Fp/A"
    Range("D56").Select
    ActiveCell.FormulaR1C1 = "=R42C11"
    Range("D57").Select
    ActiveCell.FormulaR1C1 = "=(R[-1]C*R[-15]C[1])/(R40C11/10)"
    Range("C61").Select
    ActiveCell.FormulaR1C1 = "Km,CO2"
    Range("C62").Select
    ActiveCell.FormulaR1C1 = "Km,CO"
    Range("C63").Select
    ActiveCell.FormulaR1C1 = "Km,H2"
    Range("C64").Select
    ActiveCell.FormulaR1C1 = "Km,N2"
```

```
Range("C65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("D61").Select
ActiveCell.FormulaR1C1 = "=(R33C11*R34C8)/(R[-4]C+R35C11*R34C8)"
Range("D62").Select
ActiveCell.FormulaR1C1 = "=(R33C11*R35C8)/(R[-5]C+R35C11*R35C8)"
Range("D63").Select
ActiveCell.FormulaR1C1 = "=(R33C11*R36C8)/(R[-6]C+R35C11*R36C8)"
Range("D64").Select
ActiveCell.FormulaR1C1 = "=(R33C11*R37C8)/(R[-7]C+R35C11*R37C8)"
Range("D65").Select
ActiveCell.FormulaR1C1 = "=(R33C11*R38C8)/(R[-8]C+R35C11*R38C8)"
Range("C68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("C69").Select
ActiveWindow.SmallScroll Down:=21
Range("D74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("D75").Select
ActiveWindow.SmallScroll Down:=3
Range("D77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("D78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("D79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
```

```
Range("D80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("D81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("E76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("E77").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"

Range("E78").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"

Range("E79").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("E80").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("E81").Select

ActiveCell.FormulaR1C1 = "=R[-43]C/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("E82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("E83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("D85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("E85").Select

ActiveCell.FormulaR1C1 = "=R[-43]C-RC[3]"

Range("D88").Select

ActiveCell.FormulaR1C1 = "Cut point "
```

```
Range("E88").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
Range("G77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
Range("G78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("G79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("G80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("G81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("H76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("H77").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("H82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
```

```
Range("G85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("H85").Select

ActiveCell.FormulaR1C1 = "=R[-43]C[-3]*R[3]C[-3]"

Range("D88").Select

ActiveCell.FormulaR1C1 = "Cut point "

Range("E88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"

Range("E89").Select

ActiveWindow.ScrollColumn = 2

ActiveWindow.ScrollColumn = 3

ActiveWindow.ScrollColumn = 4

ActiveWindow.ScrollColumn = 5

ActiveWindow.ScrollColumn = 6

ActiveWindow.ScrollColumn = 7

ActiveWindow.ScrollColumn = 8

ActiveWindow.ScrollColumn = 9

ActiveWindow.SmallScroll Down:=-9

Range("K53").Select

ActiveCell.FormulaR1C1 = "Section 2"

Range("K56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("K57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("L56").Select

ActiveCell.FormulaR1C1 = "=R42C11"
```

```
Range("L57").Select
ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"
Range("K61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("K62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("K63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("K64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("K65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("L61").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"
Range("L62").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"
Range("L63").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
Range("L64").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("L65").Select
ActiveCell.FormulaR1C1 = _
```

```
    "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"

Range("K68").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("L74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("L75").Select

ActiveWindow.SmallScroll Down:=9

Range("L77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("L78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("L79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("L80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("L81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("M76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("M77").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"

Range("M78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"

Range("M79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("M80").Select
```

```
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("M81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("M82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("M83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("L85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("M85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("L88").Select

ActiveCell.FormulaR1C1 = "Cut point "

Range("M88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"

Range("O77").Select

ActiveCell.FormulaR1C1 = "yp,CO2"

Range("O78").Select

ActiveCell.FormulaR1C1 = "yp,CO"

Range("O79").Select

ActiveCell.FormulaR1C1 = "yp,H2"

Range("O80").Select

ActiveCell.FormulaR1C1 = "yp,N2"

Range("O81").Select

ActiveCell.FormulaR1C1 = "yp,O2"

Range("P76").Select
```

```
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("P76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("P77").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("P82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("O85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("P85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("P86").Select

ActiveWindow.ScrollColumn = 10

ActiveWindow.ScrollColumn = 11

ActiveWindow.ScrollColumn = 12

ActiveWindow.ScrollColumn = 13

ActiveWindow.ScrollColumn = 14

ActiveWindow.ScrollColumn = 15
```

```
ActiveWindow.SmallScroll Down:=-12

Range("S53").Select

ActiveCell.FormulaR1C1 = "Section 3"

Range("S56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("S57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("T56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("T57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("S61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("S62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("S63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("S64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("S65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("T61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"

Range("T62").Select

ActiveCell.FormulaR1C1 = _
```

```
    "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"
Range("T63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
Range("T64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("T65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"
Range("S68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("S69").Select
ActiveWindow.SmallScroll Down:=12
Range("T74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("T77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("T78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("T79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("T80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("T81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
```

```
Range("U76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("U77").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"

Range("U78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"

Range("U79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("U80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("U81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("U82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("U83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("T85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("U85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("T88").Select

ActiveCell.FormulaR1C1 = "Cut point "

Range("T82").Select

Selection.Cut Destination:=Range("U87")

Range("U88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
```

```
Range("W77").Select

ActiveCell.FormulaR1C1 = "yp,CO2"

Range("W78").Select

ActiveCell.FormulaR1C1 = "yp,CO"

Range("W79").Select

ActiveCell.FormulaR1C1 = "yp,H2"

Range("W80").Select

ActiveCell.FormulaR1C1 = "yp,N2"

Range("W81").Select

ActiveCell.FormulaR1C1 = "yp,O2"

Range("X76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("X77").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("X78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("X79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("X80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("X81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("X82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("X79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("X80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("W85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("X85").Select
ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"
Range("X86").Select
ActiveWindow.ScrollColumn = 14
ActiveWindow.ScrollColumn = 15
ActiveWindow.ScrollColumn = 16
ActiveWindow.ScrollColumn = 17
ActiveWindow.ScrollColumn = 18
ActiveWindow.ScrollColumn = 19
ActiveWindow.ScrollColumn = 20
ActiveWindow.ScrollColumn = 21
ActiveWindow.ScrollColumn = 22
ActiveWindow.ScrollColumn = 23
ActiveWindow.ScrollColumn = 24
ActiveWindow.SmallScroll Down:=-9
Range("AA53").Select
ActiveCell.FormulaR1C1 = "Section 4"
Range("AA56").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("AA57").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AB56").Select
```

```
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AB57").Select
ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"
Range("AA61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
Range("AA62").Select
ActiveCell.FormulaR1C1 = "Km,CO"
Range("AA63").Select
ActiveCell.FormulaR1C1 = "Km,H2"
Range("AA64").Select
ActiveCell.FormulaR1C1 = "Km,N2"
Range("AA65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("AB61").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"
Range("AB62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"
Range("AB63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
Range("AB64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("AB65").Select
```

```
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"
Range("AA68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("AA69").Select
ActiveWindow.SmallScroll Down:=6
Range("AB74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("AB77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("AB78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("AB79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("AB80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AB80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AB81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("AC76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("AC77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("AC78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
```

```
Range("AC79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("AC80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("AC81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("AC82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AC83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("AB85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("AC85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("AB88").Select

ActiveCell.FormulaR1C1 = "Cut point "

Range("AC88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"

Range("AE77").Select

ActiveCell.FormulaR1C1 = "yp,CO2"

Range("AE78").Select

ActiveCell.FormulaR1C1 = "yp,CO"

Range("AE79").Select

ActiveCell.FormulaR1C1 = "yp,H2"

Range("AE80").Select

ActiveCell.FormulaR1C1 = "yp,N2"
```

```
Range("AE81").Select

ActiveCell.FormulaR1C1 = "yp,O2"

Range("AF76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("AF77").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AF82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AE85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("AF85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("AF86").Select

ActiveWindow.ScrollColumn = 23

ActiveWindow.ScrollColumn = 24

ActiveWindow.ScrollColumn = 25

ActiveWindow.ScrollColumn = 26

ActiveWindow.ScrollColumn = 27
```

```
ActiveWindow.ScrollColumn = 28

ActiveWindow.ScrollColumn = 29

ActiveWindow.ScrollColumn = 30

ActiveWindow.ScrollColumn = 31

ActiveWindow.ScrollColumn = 32

ActiveWindow.SmallScroll Down:=-3

Range("AI53").Select

ActiveCell.FormulaR1C1 = "Section 5"

Range("AI56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("AI57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("AJ56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("AJ57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("AI61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("AI61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("AI62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("AI63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("AI64").Select

ActiveCell.FormulaR1C1 = "Km,N2"
```

```
Range("AI65").Select
ActiveCell.FormulaR1C1 = "Km,O2"
Range("AJ61").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"
Range("AJ62").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"
Range("AJ63").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
Range("AJ64").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("AJ65").Select
ActiveCell.FormulaR1C1 = _
   "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"
Range("AI68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("AJ74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("AJ77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("AJ78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("AJ79").Select
```

```
ActiveCell.FormulaR1C1 = "yr,H2"
Range("AJ80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AJ81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("AK76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("AK77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("AK78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
Range("AK79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"
Range("AK80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"
Range("AK81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"
Range("AK82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("AK83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("AJ85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("AK85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("AJ88").Select
```

```
ActiveCell.FormulaR1C1 = "Cut point "

Range("AK88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"

Range("AM77").Select

ActiveCell.FormulaR1C1 = "yp,CO2"

Range("AM78").Select

ActiveCell.FormulaR1C1 = "yp,CO"

Range("AM79").Select

ActiveCell.FormulaR1C1 = "yp,H2"

Range("AM80").Select

ActiveCell.FormulaR1C1 = "yp,N2"

Range("AM81").Select

ActiveCell.FormulaR1C1 = "yp,O2"

Range("AN76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("AN77").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AN78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AN79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AN80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AN81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AN82").Select
```

```
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("AM85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("AN85").Select
ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"
Range("AN86").Select
ActiveWindow.ScrollColumn = 33
ActiveWindow.ScrollColumn = 34
ActiveWindow.ScrollColumn = 35
ActiveWindow.ScrollColumn = 36
ActiveWindow.ScrollColumn = 37
ActiveWindow.ScrollColumn = 38
ActiveWindow.ScrollColumn = 39
ActiveWindow.ScrollColumn = 40
Range("AQ53").Select
ActiveCell.FormulaR1C1 = "Section 6"
Range("AQ56").Select
ActiveCell.FormulaR1C1 = "Sigma"
Range("AQ57").Select
ActiveCell.FormulaR1C1 = "Fp/A"
Range("AR56").Select
ActiveCell.FormulaR1C1 = "=R42C11"
Range("AR57").Select
ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"
Range("AQ61").Select
ActiveCell.FormulaR1C1 = "Km,CO2"
```

```
Range("AQ62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("AQ63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("AQ64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("AQ65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("AR61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"

Range("AR62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"

Range("AR63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"

Range("AR64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"

Range("AR65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"

Range("AQ68").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("AR74").Select
```

```
ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("AR77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"

Range("AR78").Select

ActiveCell.FormulaR1C1 = "yr,CO"

Range("AR79").Select

ActiveCell.FormulaR1C1 = "yr,H2"

Range("AR80").Select

ActiveCell.FormulaR1C1 = "yr,N2"

Range("AR81").Select

ActiveCell.FormulaR1C1 = "yr,O2"

Range("AS76").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"

Range("AS77").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"

Range("AS78").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"

Range("AS79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("AS80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("AS81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("AS82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AS83").Select
```

```
ActiveCell.FormulaR1C1 = "SOLVER"
Range("AR85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("AS85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("AR88").Select
ActiveCell.FormulaR1C1 = "Cut point "
Range("AS88").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
Range("AU77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
Range("AU78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("AU79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("AU80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("AU81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("AU85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("AV76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("AV77").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("AV78").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("AV82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("AU85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("AV85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("AV86").Select

ActiveWindow.ScrollColumn = 41

ActiveWindow.ScrollColumn = 42

ActiveWindow.ScrollColumn = 43

ActiveWindow.ScrollColumn = 44

ActiveWindow.ScrollColumn = 45

ActiveWindow.ScrollColumn = 46

ActiveWindow.ScrollColumn = 47

ActiveWindow.ScrollColumn = 48

ActiveWindow.ScrollColumn = 49

Range("AY53").Select

ActiveCell.FormulaR1C1 = "Section 7"

Range("AY56").Select
```

```
ActiveCell.FormulaR1C1 = "Sigma"

Range("AY57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("AZ56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("AZ57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("AY61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("AY62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("AY63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("AY64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("AY65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("AZ61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"

Range("AZ62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"

Range("AZ63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
```

```
Range("AZ64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("AZ65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"
Range("AY68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("AZ74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("AZ77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("AZ78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("AZ79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("AZ80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("AZ81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("BA76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("BA77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("BA78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
```

```
Range("BA79").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"

Range("BA80").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"

Range("BA81").Select

ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"

Range("BA82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("BA83").Select

ActiveCell.FormulaR1C1 = "SOLVER"

Range("AZ85").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("BA85").Select

ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"

Range("AZ88").Select

ActiveCell.FormulaR1C1 = "Cut point "

Range("BA88").Select

ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"

Range("BC77").Select

ActiveCell.FormulaR1C1 = "yp,CO2"

Range("BC78").Select

ActiveCell.FormulaR1C1 = "yp,CO"

Range("BC79").Select

ActiveCell.FormulaR1C1 = "yp,H2"

Range("BC80").Select

ActiveCell.FormulaR1C1 = "yp,N2"
```

```
Range("BC81").Select

ActiveCell.FormulaR1C1 = "yp,O2"

Range("BC85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("BD76").Select

ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"

Range("BD77").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BD78").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BD79").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BD80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BD81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BD82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("BD85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("BD86").Select

ActiveWindow.ScrollColumn = 50

ActiveWindow.ScrollColumn = 51

ActiveWindow.ScrollColumn = 52

ActiveWindow.ScrollColumn = 53

ActiveWindow.ScrollColumn = 54
```

```
ActiveWindow.ScrollColumn = 55

ActiveWindow.ScrollColumn = 56

ActiveWindow.ScrollColumn = 57

Range("BG53").Select

ActiveCell.FormulaR1C1 = "Section 8"

Range("BG56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("BG57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("BH56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("BH57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("BG61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("BG62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("BG63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("BG64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("BG65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("BH61").Select

ActiveCell.FormulaR1C1 = _

    "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"
```

```
Range("BH62").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"
Range("BH63").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"
Range("BH64").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"
Range("BH65").Select
ActiveCell.FormulaR1C1 = _
    "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"
Range("BG68").Select
ActiveCell.FormulaR1C1 = "RESULTS"
Range("BH74").Select
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("BH77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("BH78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("BH79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("BH80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("BH81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
```

```
Range("BI76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("BI77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("BI78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
Range("BI79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"
Range("BI80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"
Range("BI81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"
Range("BI82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BI83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("BH85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("BI85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("BH88").Select
ActiveCell.FormulaR1C1 = "Cut point "
Range("BI88").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
Range("BK77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
```

```
Range("BK78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("BK79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("BK80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("BK81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("BL76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("BL77").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL81").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BL82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BK85").Select
ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
Range("BL85").Select
ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"
```

```
Range("BL86").Select

ActiveWindow.ScrollColumn = 58

ActiveWindow.ScrollColumn = 59

ActiveWindow.ScrollColumn = 60

ActiveWindow.ScrollColumn = 61

ActiveWindow.ScrollColumn = 62

ActiveWindow.ScrollColumn = 63

ActiveWindow.ScrollColumn = 64

ActiveWindow.ScrollColumn = 65

ActiveWindow.ScrollColumn = 66

ActiveWindow.ScrollColumn = 67

Range("BO53").Select

ActiveCell.FormulaR1C1 = "Section 9"

Range("BO56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("BO57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("BP56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("BP57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("BO61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"

Range("BO62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("BO63").Select
```

```
ActiveCell.FormulaR1C1 = "Km,H2"

Range("BO64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("BO65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("BP61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"

Range("BP62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"

Range("BP63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"

Range("BP64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"

Range("BP65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"

Range("BO68").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("BP74").Select

ActiveCell.FormulaR1C1 = "OUTPUTS"

Range("BP77").Select

ActiveCell.FormulaR1C1 = "yr,CO2"
```

```
Range("BP78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("BP79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("BP80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("BP81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("BQ76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("BQ77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("BQ78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
Range("BQ79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"
Range("BQ80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"
Range("BQ81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"
Range("BQ82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BQ83").Select
ActiveCell.FormulaR1C1 = "SOLVER"
Range("BP85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
```

```
Range("BQ85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("BP88").Select
ActiveCell.FormulaR1C1 = "Cut point "
Range("BQ88").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
Range("BS77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
Range("BS78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("BS79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("BS80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("BS81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("BT76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("BT77").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BT78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BT79").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("BT80").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
```

```
Range("BT81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("BT82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("BS85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("BT85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("BT86").Select

ActiveWindow.ScrollColumn = 68

ActiveWindow.ScrollColumn = 69

ActiveWindow.ScrollColumn = 70

ActiveWindow.ScrollColumn = 71

ActiveWindow.ScrollColumn = 72

Range("BW53").Select

ActiveCell.FormulaR1C1 = "Section 10"

Range("BW56").Select

ActiveCell.FormulaR1C1 = "Sigma"

Range("BW57").Select

ActiveCell.FormulaR1C1 = "Fp/A"

Range("BX56").Select

ActiveCell.FormulaR1C1 = "=R42C11"

Range("BX57").Select

ActiveCell.FormulaR1C1 = "=(R[-1]C*R[28]C[-7])/(R40C11/10)"

Range("BW61").Select

ActiveCell.FormulaR1C1 = "Km,CO2"
```

```
Range("BW62").Select

ActiveCell.FormulaR1C1 = "Km,CO"

Range("BW63").Select

ActiveCell.FormulaR1C1 = "Km,H2"

Range("BW64").Select

ActiveCell.FormulaR1C1 = "Km,N2"

Range("BW65").Select

ActiveCell.FormulaR1C1 = "Km,O2"

Range("BX61").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R34C8/R42C8))/(R[-4]C+R35C11*(R34C8/R42C8))"

Range("BX62").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R35C8/R42C8))/(R[-5]C+R35C11*(R35C8/R42C8))"

Range("BX63").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R36C8/R42C8))/(R[-6]C+R35C11*(R36C8/R42C8))"

Range("BX64").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R37C8/R42C8))/(R[-7]C+R35C11*(R37C8/R42C8))"

Range("BX65").Select

ActiveCell.FormulaR1C1 = _

   "=(R33C11*(R38C8/R42C8))/(R[-8]C+R35C11*(R38C8/R42C8))"

Range("BW68").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("BX74").Select
```

```
ActiveCell.FormulaR1C1 = "OUTPUTS"
Range("BX77").Select
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("BX78").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("BX79").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("BX80").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("BX81").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("BY76").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("BY77").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-21]C[-1])"
Range("BY78").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-22]C[-1])"
Range("BY79").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-23]C[-1])"
Range("BY80").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-24]C[-1])"
Range("BY81").Select
ActiveCell.FormulaR1C1 = "=RC[-8]/(1+(R[-16]C[-1]-1)*R[-25]C[-1])"
Range("BY82").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("BY83").Select
```

```
ActiveCell.FormulaR1C1 = "SOLVER"
Range("BX85").Select
ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"
Range("BY85").Select
ActiveCell.FormulaR1C1 = "=RC[-8]-RC[3]"
Range("BX88").Select
ActiveCell.FormulaR1C1 = "Cut point "
Range("BY88").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[-1]"
Range("CA77").Select
ActiveCell.FormulaR1C1 = "yp,CO2"
Range("CA78").Select
ActiveCell.FormulaR1C1 = "yp,CO"
Range("CA79").Select
ActiveCell.FormulaR1C1 = "yp,H2"
Range("CA80").Select
ActiveCell.FormulaR1C1 = "yp,N2"
Range("CA81").Select
ActiveCell.FormulaR1C1 = "yp,O2"
Range("CB76").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
Range("CB77").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB78").Select
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"
Range("CB79").Select
```

```
ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("CB80").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("CB81").Select

ActiveCell.FormulaR1C1 = "=R[-16]C[-4]*RC[-3]"

Range("CB82").Select

ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

Range("CA85").Select

ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"

Range("CB85").Select

ActiveCell.FormulaR1C1 = "=RC[-11]*R[3]C[-3]"

Range("CB86").Select

ActiveWindow.ScrollColumn = 71

ActiveWindow.ScrollColumn = 66

ActiveWindow.ScrollColumn = 19

ActiveWindow.ScrollColumn = 1

ActiveWindow.SmallScroll Down:=42

Range("D98").Select

ActiveCell.FormulaR1C1 = "RESULTS"

Range("C102").Select

ActiveCell.FormulaR1C1 = "Etape 1"

Range("C106").Select

ActiveCell.FormulaR1C1 = "RETENTATE (mol/s)"

Range("D106").Select

ActiveCell.FormulaR1C1 = "=R[-21]C[73]"

Range("C109").Select
```

```
ActiveCell.FormulaR1C1 = "yr,CO2"
Range("C110").Select
ActiveCell.FormulaR1C1 = "yr,CO"
Range("C111").Select
ActiveCell.FormulaR1C1 = "yr,H2"
Range("C112").Select
ActiveCell.FormulaR1C1 = "yr,N2"
Range("C113").Select
ActiveCell.FormulaR1C1 = "yr,O2"
Range("D108").Select
ActiveCell.FormulaR1C1 = "RETENTATE COMPOSITION"
Range("D109").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D110").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D111").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D112").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D113").Select
ActiveCell.FormulaR1C1 = "=R[-32]C[73]"
Range("D114").Select
ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"
Range("C117").Select
ActiveCell.FormulaR1C1 = "RETENTATE (m3/s)"
Range("D117").Select
```

```
ActiveCell.FormulaR1C1 = "=SUM(R[3]C:R[7]C)"

Range("C120").Select

ActiveCell.FormulaR1C1 = "Qr,CO2"

Range("C121").Select

ActiveCell.FormulaR1C1 = "Qr,CO"

Range("C122").Select

ActiveCell.FormulaR1C1 = "Qr,H2"

Range("C123").Select

ActiveCell.FormulaR1C1 = "Qr,N2"

Range("C124").Select

ActiveCell.FormulaR1C1 = "Qr,O2"

Range("D119").Select

ActiveCell.FormulaR1C1 = "RETENTATE COMPONENTS (m3/s)"

Range("D120").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"

Range("D121").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"

Range("D122").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"

Range("D123").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"

Range("D124").Select

ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C4*R37C11*8.314)/R33C11"

Range("C128").Select

ActiveCell.FormulaR1C1 = "CUT POINT"

Range("D128").Select
```

```
          ActiveCell.FormulaR1C1 = _
             "=R[-40]C[1]+R[-40]C[9]+R[-40]C[17]+R[-40]C[25]+R[-40]C[33]+R[-40]C[41]+R[-
40]C[49]+R[-40]C[57]+R[-40]C[65]+R[-40]C[73]"
          Range("E103").Select
          ActiveCell.FormulaR1C1 = "OUTPUTS"
          Range("F106").Select
          ActiveCell.FormulaR1C1 = "PERMEATE (mol/s)"
          Range("G106").Select
          ActiveCell.FormulaR1C1 = _
             "=R[-21]C[1]+R[-21]C[9]+R[-21]C[17]+R[-21]C[25]+R[-21]C[33]+R[-21]C[41]+R[-
21]C[49]+R[-21]C[57]+R[-21]C[65]+R[-21]C[73]"
          Range("F109").Select
          ActiveCell.FormulaR1C1 = "yp,CO2"
          Range("F110").Select
          ActiveCell.FormulaR1C1 = "yp,CO"
          Range("F111").Select
          ActiveCell.FormulaR1C1 = "yp,H2"
          Range("F112").Select
          ActiveCell.FormulaR1C1 = "yp,N2"
          Range("F113").Select
          ActiveCell.FormulaR1C1 = "yp,O2"
          Range("G108").Select
          ActiveCell.FormulaR1C1 = "PERMEATE COMPOSITION"
          Range("G109").Select
          ActiveCell.FormulaR1C1 = _
             "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
```

```
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G110").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G111").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G112").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G113").Select

            ActiveCell.FormulaR1C1 = _

               "=((R85C8*R[-32]C[1])+(R85C16*R[-32]C[9])+(R85C24*R[-
32]C[17])+(R85C32*R[-32]C[25])+(R85C40*R[-32]C[33])+(R85C48*R[-
32]C[41])+(R85C56*R[-32]C[49])+(R85C64*R[-32]C[57])+(R85C72*R[-
32]C[65])+(R85C80*R[-32]C[73]))/R106C7"

            Range("G114").Select

            ActiveCell.FormulaR1C1 = "=SUM(R[-5]C:R[-1]C)"

            Range("F117").Select
```

```
ActiveCell.FormulaR1C1 = "PERMEATE (m3/s)"
Range("G117").Select
ActiveCell.FormulaR1C1 = "=SUM(R[3]C:R[7]C)"
Range("F120").Select
ActiveCell.FormulaR1C1 = "Qp,CO2"
Range("F121").Select
ActiveCell.FormulaR1C1 = "Qp,CO"
Range("F122").Select
ActiveCell.FormulaR1C1 = "Qp,H2"
Range("F123").Select
ActiveCell.FormulaR1C1 = "Qp,N2"
Range("F124").Select
ActiveCell.FormulaR1C1 = "Qp,O2"
Range("G119").Select
ActiveCell.FormulaR1C1 = "PERMEATE COMPONENTS (m3/s)"
Range("G120").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"
Range("G121").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"
Range("G122").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"
Range("G123").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"
Range("G124").Select
ActiveCell.FormulaR1C1 = "=(R[-11]C*R106C7*R37C11*8.314)/R35C11"
Range("G125").Select
```

```
    ‘In this section, the solver command is used to achieve logical and viable results.’


        SolverOk SetCell:="$E$82", MaxMinVal:=3, ValueOf:=1, ByChange:= _


"$D$56,$L$56,$T$56,$AB$56,$AJ$56,$AR$56,$AZ$56,$BH$56,$BP$56,$BX$56",
Engine:=1 _
            , EngineDesc:="GRG Nonlinear"
        SolverOk SetCell:="$E$82", MaxMinVal:=3, ValueOf:=1, ByChange:= _


"$D$56,$L$56,$T$56,$AB$56,$AJ$56,$AR$56,$AZ$56,$BH$56,$BP$56,$BX$56",
Engine:=1 _
            , EngineDesc:="GRG Nonlinear"
        SolverSolve
    End Sub
```