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Université august 20, 1955 Skikda

Course support

Boussaha El hadi

Cryogenic Processes

Semester 6

Teaching unit UED 3.2

Specialty: Process Engineering

Level: 3rd year

Skikda 2023

These courses are intended for Third Year Process Engineering students to deepen their knowledge in the field of Cryogenic Processes, something useful for practical use in the chemical and petrochemical industries.

Semestre :*6*
Unité d'enseignement : UED 3.2
Matière1 : Procédés cryogéniques
VHS: 22h30 (Cours: 1h30)
Crédits : 1
Coefficient : 1

Objectifs de l'enseignement:

Présenter les différents procédés dans le domaine du froid et de la cryogénie ; Quelques applications dans le domaine des basses températures.

Connaissances préalables recommandées:

Phénomènes de transfert de chaleur ; Thermodynamique et les outils mathématiques (équations différentielles et calcul intégral).

Contenu de la matière:

Introduction générale : La cryogénie et ses domaines d'applications **(1 semaine)**

Chapitre 1 : **(2 semaines)**
Technologie du vide : Importance du vide en cryogénie ; Systèmes de production du vide.

Chapitre 2 : **(4semaines)**
Procédés de séparation et de purification des fluides cryogéniques : Procédé de séparation : système idéal ; Procédés de séparation – Rectification ; Rôle et description de la vanne de Joule Thomson ; Procédés de séparation de l'air.

Chapitre 3 : **(5 semaines)**
Procédés de liquéfaction des gaz permanents : Procédé de liquéfaction Linde-Hampson ; Procédé de liquéfaction Linde-Hampson à double compression ; Procédé de liquéfaction de Claude.

Chapitre 4 : **(3 semaines)**
Applications cryogéniques : Découverte de la supraconductivité ; Application dans l'agroalimentaire.

Mode d'évaluation:

Examen: 100%.

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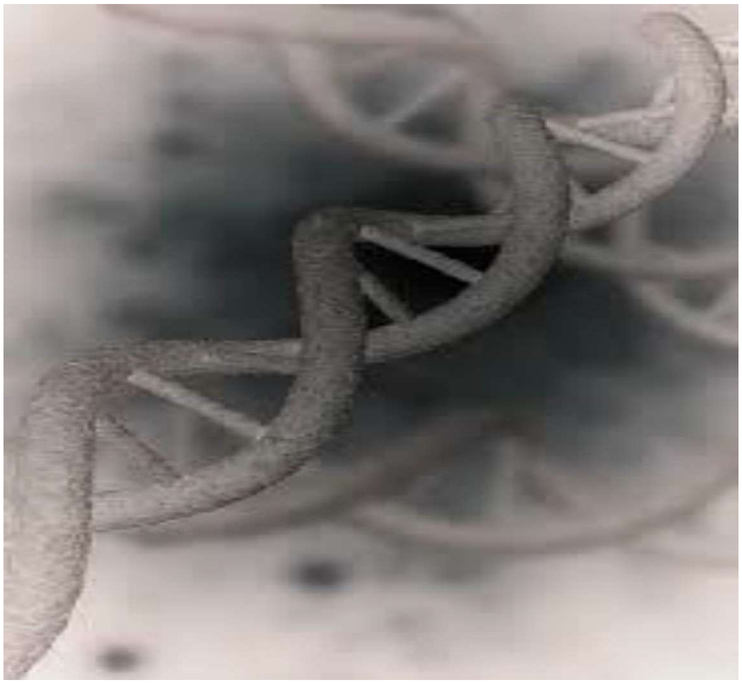
General introduction to Cryogenics



Faculty of Technology
Department of Process Engineering

Level: 3th Process Engineering

General introduction to Cryogenics

A. History

Historically around 1790 Van Marum was the first to liquefy ammonia by compressing it under 6 atmospheres. Various gases were thus liquefied. These gases all have a critical temperature above ambient temperature.

B. Principe

For gases whose critical temperature is below ambient temperature, the first liquefaction tests were carried out in France and Switzerland in 1877.

In 1895, Linde succeeded in manufacturing large quantities of liquid air for the first time. Linde's machine will be perfected by Claude in 1905. These machines use expansion cycles.

We can distinguish three main families of cryogenic thermodynamic processes

- Joule-Thomson isenthalpic expansion processes
- Inverse Brayton cycles with isentropic expansion
- Mixed processes combining isenthalpic expansion and isentropic expansion (Claude cycle)

C. Definition of Cryogenics

Cryogenics is the study and production of bass temperatures (less than −150°Cor 120K) in order to understand the physical phenomena that occur there. The limit of −153.15°C represents the limit from which the gases in the air liquefy.

D. Applications of cryogenics

a. Mechanical

Subjecting tools, die casting dies, forgings, jigs and accessories etc. to cryogenic heat treatment extends their lifespan. By subjecting it to recycling under cryogenic temperatures, the scrap metal is transformed into raw material, this is mainly the case used for PVC…

b. Medical and food preservation

Cryotherapy is a new technique in which harmful tissue is destroyed by freezing it at a cryogenic temperature. Typically used in cases with localized cancer.

Cryogenic systems are now being developed to preserve blood cells, plasma cells, human organs and animal organs at cryogenic temperatures.

Cryogenics consists of the preservation of food by very rapid freezing, “freezing” the food (it is preserved in the state in which it was at the time of cryogenics). To do this, the food is immersed in liquid nitrogen.

c. Gas industry

Storing liquids at cryogenic temperatures has made it easier to transport liquefied gas around the world.

The use of inert gases in the welding industry has led to increased demand for gas production in the recent past.

Cryogens like LOX, LH2 (propellant and propellant) are used in rocket propulsion.

d. Superfluidity

Superfluidity is a phase of matter characterized by the total absence of viscosity. Thus, superfluids, placed in a closed loop, can flow indefinitely without friction. The science that studies superfluidity is called “quantum hydrodynamics”. Superfluidity is used in cryogenic refrigerators and as a “quantum solvent” in spectroscopic techniques.

e. Icing

The icing process is a cryogenic system for recovering volatile organic compounds (VOCs) in gas flows. Liquid nitrogen cools the gas flow loaded with solvents. The VOCs condense and freeze to form snow which is then removed using stainless steel filters.

Liquid nitrogen is used as a pre-cooler in most cryogenic systems.

f. Applications – Supraconductivité

Superconductivity is a phenomenon encountered in certain materials at very low temperatures; it is characterized by the total absence of electrical resistance and the cancellation of the magnetic field inside the material. It is used for medical imaging and particle accelerators. It also allows energy to be stored and controlled thermonuclear fusion to be carried out.

g. Space

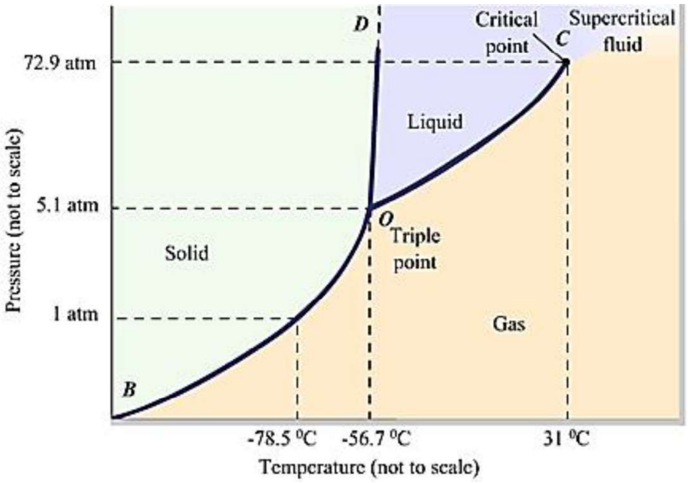
- Infrared (IR) sensor cooling Spatial simulation
- Cryogenic engines are powered by cryogenic thrusters.
- Liquid hydrogen is used as fuel to power the rocket.
- Liquid oxygen is used as an oxidant
- Development of Miniature and Small Cryo-coolers for Satellites for Improved Earth Observation Accuracy and Reliability

E. Phase diagram (P, T)

Different phases of a pure body depending on the variables: pressure and temperature

Balance curvescorresponding to a change of state:

- Solid-gas: sublimation curve
- Solid-liquid: melting curve
- Liquid-gas: vaporization curve



Phase diagram (P, T)

- **Point triple (T**p): coexistence of the three phases in equilibrium (sol/liq/gas)
- **Critical point** (Cp) beyond which there is no longer any difference between the liquid and the gas: monophasic supercritical state
- **Vapor pressure**: pressure of the gas in equilibrium with the liquid or the solid. By reducing the pressure on the bath by pumping gas, the temperature of the bath decreases.

➢ Sensible heat

Quantity of heat exchanged without phase transition but with a change in T°

$Q = m.cp.\Delta T$

Q: Heat input (J)

m : masse (kg)

cp: specific heat (J.kg-1.K-1)

ΔT: temperature difference (K)

- **Latent heat**

Quantity of heat exchanged during a phase transition without change in T°

$Q = m.Lv$

Q: Heat input (J)

m: mass of transformed liquid (kg)

Lv: latent heat of vaporization (J.kg-1)

F. Heat relationship- temperature

- **Cryogenic fluid cooling:**

- Use of a gas brought to a low temperature which heats up on contact with the object to be cooled (variable temperature):

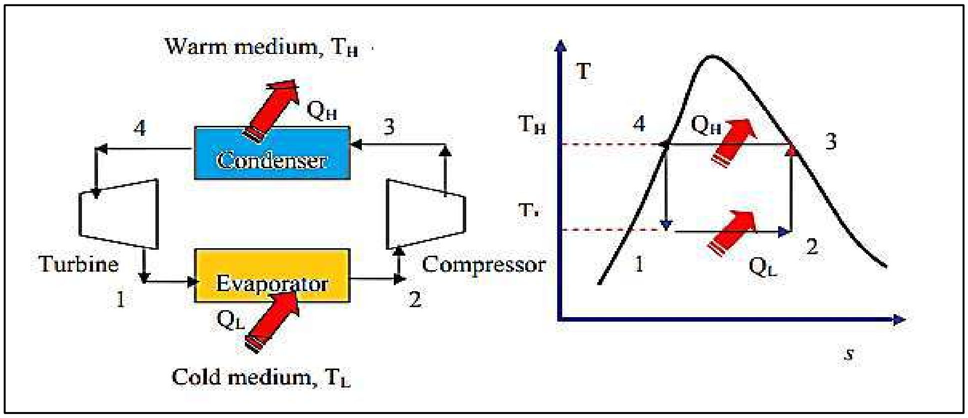
Use of the *sensible heat alone for refrigeration of a gas*

- Use of a saturated liquid as a refrigerant for objects to be maintained at low temperature (superconducting components, physics experiment, etc.):

Use of the *latent heat of vaporization* or (sensible heat of cold vapors) *for the Liquefaction of a gas*

- **The Reversed Carnot Cycle**

Reversing the Carnot cycle does reverse the directions of heat and work interactions. A refrigerator or heat pump that operates on the reversed Carnot cycle is called a Carnot refrigerator or a Carnot heat pump.



components for Carnot refrigerator.

Carnot refrigerator diagram T-s

- **Refrigeration cycle**

Ideal thermal Carnot machine:

Heat flows in direction of decreasing temperature, from high-temperature to low temperature regions. The transfer of heat from a low-temperature to high-temperature requires a refrigerator and/or heat pump. Refrigerators and heat pumps are essentially the same device; they only differ in their objectives.

The performance of refrigerators and heat pumps is expressed in terms of Coefficient of *Performance (COP):*

$$COP = \frac{Q_F}{W} = \frac{T_F}{T_C - T_F}$$

Efficiency of the Carnot cycle (ideal machine):

$$\eta = \frac{W}{Q_C} = 1 - \frac{T_F}{T_C} < 1$$

Exercise

1- A thermal machine operates between a hot source at 200 K and a cold source at 100 K. At each cycle, the system borrows from the hot source a quantity of heat $Q_1 = 100$ J and transfers to the cold source a quantity of heat $Q_2 = 25$ J for work provided: W= 75 J.

a- Is the cycle described by the machine possible?

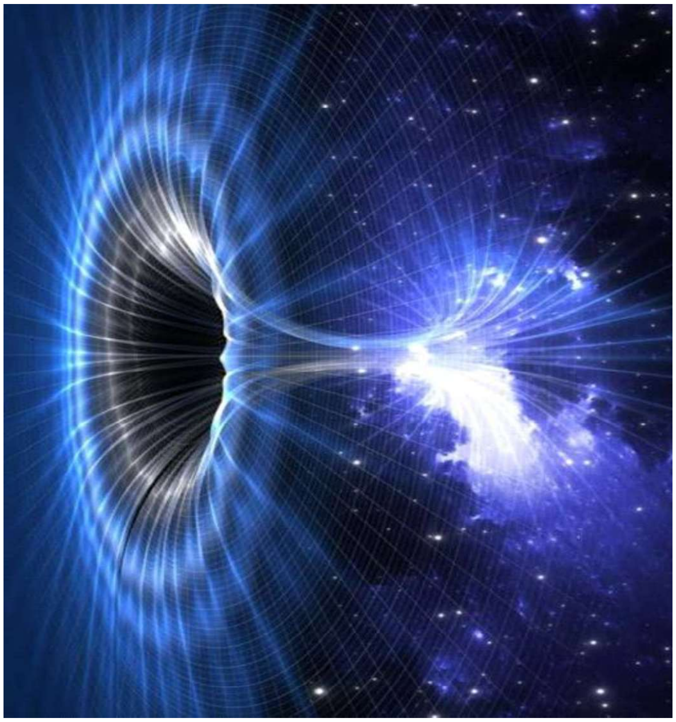
b- Otherwise, what is the principle that does not allow the creation of this machine?

2- A heat engine operates following a CARNOT cycle between two temperature sources T1=800K and T_2=200K.

Calculate the work provided by the motor during each cycle, knowing that it absorbs a quantity of heat Q=8 kJ.

Chapter I

Vacuum technology



I. Introduction

In the infinitely large, the cosmos in which a vacuum is the rule, or the infinitely small, the atom where the distances between nuclei and electrons are very great compared to the size of these particles, it is the vacuum that predominates.

I.1 Definition of vacuum

EMPTY represents the total absence of matter and has an essentially philosophical meaning ("horror vacui", the horror of the void). In technical terms, the term VACUUM is used to describe a space in which the pressure is lower than atmospheric pressure. The ABSOLUTE VACUUM is considered to be the absence of matter in a portion of volume, but it is not achievable. It is better to define it as the best vacuum that can be generated within a given space, given the impossibility of completely eliminating all gases (hydrogen, oxygen, nitrogen, neon and argon are examples of permanent gases). We often hear vacuum referred to as a physical entity, in opposition to the notion of pressure. In reality, pressure is the only unit of measurement, both for values above atmospheric pressure and for values below.

In the atmosphere that surrounds us there are a considerable number of air molecules that we breathe. If all the molecules were juxtaposed, with no space between them, they would occupy just over one thousandth of the volume available to them, and they would still have room to move.

To create a vacuum in a volume is to evacuate the molecules, thereby lowering the pressure. This is easily achieved by using a vacuum pump to extract the air from a sealed enclosure. The quality of the vacuum is then defined by the residual air pressure, generally expressed as a bar. Only a partial vacuum can be achieved with this process, whatever the temperature.

.

I.2 Purpose of vacuum technology

Vacuum technology plays a very important role these days, both in industry and in research, because it allows pressures below atmospheric to be achieved by reducing the quantity of matter present in the form of gas or vapour.

It is therefore essential to master the modern tools that make up these installations. It's not just a question of knowing how to use a pump or a pressure gauge, it's also a question of knowing how to choose, from the whole range of possible means, the one or ones that correspond to the desired aim. Then the atomic nature of energy became a relevant issue, and the study of the gaseous state took on its full importance. With the development of inventions linked to electricity, it was necessary to simultaneously deepen knowledge and perfect techniques.

I.3 Vacuum applications

Vacuum technology brings together all the solutions for producing, regulating and measuring vacuum. It provides access to pressures below atmospheric and has many industrial applications. This technology involves the manufacture of sealed enclosures from which the gases inside are extracted. The pressure is reduced until it approaches a vacuum, characterised by the absence of all matter.

In practice, it is not possible to achieve a perfect vacuum. The term "vacuum quality" is used to specify the pressure range achieved.

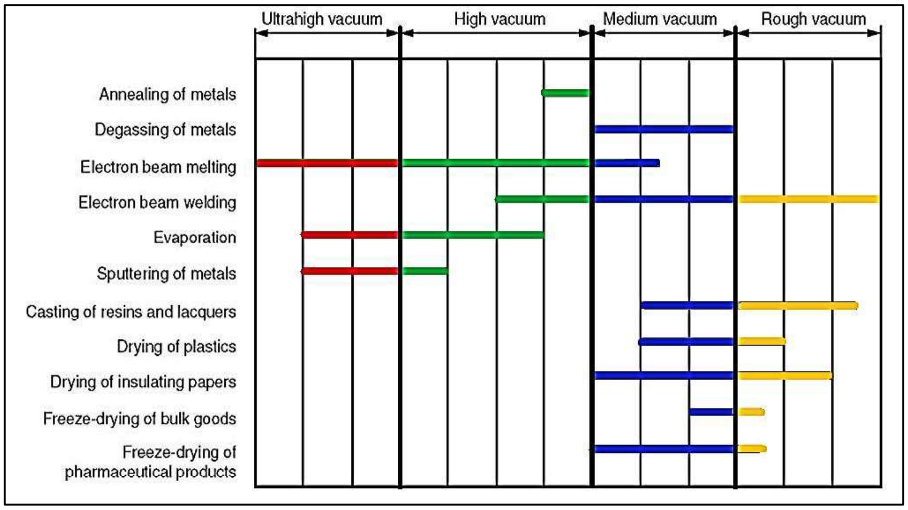
• **Research**	Mechanical use of atmospheric pressure (Patm)
	Displacement of a thermodynamic equilibrium
• **Industry**	Reduction in oxygen concentration
	Allowing light particles to pass through

Vacuum applications

I.4 Different areas of vacuum use

There is no such thing as a "perfect" **vacuum**, which is in fact a very low pressure; a vacuum considered to be excellent (10^{-8} Pa) still contains 2.4 million molecules per cubic centimetre at 294 K.

To describe the quality of the vacuum, we distinguish 4 domains which characterise the quantity of material remaining in relation to a volume. Vacuum is measured in pascals (Pa, unit o the international system) or, more commonly in industry, in millibars (mbar; 1 mbar = 100 Pa), or in torr.



Different areas of vacuum use

I.5 Special characteristics of vacuum

The special characteristics of low pressure (vacuum) are used in a wide variety of fields. Many manufactured products, and the raw materials from which they are derived, use vacuum techniques during their development or manufacturing studies. The drop in pressure enables isostatic stresses to be applied, chemical attack to be mitigated, surface properties to be changed, certain species to be eliminated, matter or radiation to be transported without diffusion, and thermal or acoustic insulation to be created.

Vacuum is used in the metallurgical industry to prepare metals and alloys with high properties; in the mechanical industry for heat treatment and modification of surface compositions; in the chemical industry for concentration, distillation, drying and freeze-drying operations; and in the food industry for preservation and cooking for catering.

The electrical and electronics industries use it to dry and impregnate windings, and to manufacture lighting lamps, television tubes and almost all electronic components.

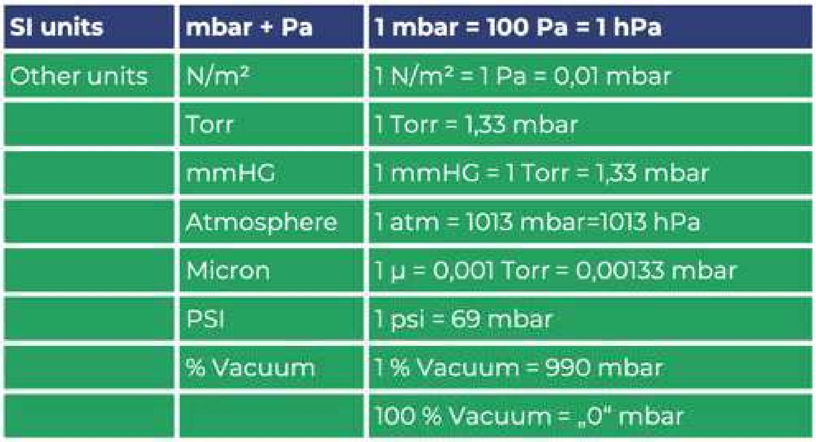
I.6 Pressure units used

PRESSURE is defined as the result of a Force (F) acting perpendicular to a unit area (S). It is often represented by the formula:

$$P = F/S$$

Gases are made up of a large number of particles in perpetual motion. When these particles collide with a surface, they produce thrust, which can be measured as a force. The pressure is the sum of all the forces produced by the particles per unit area. When they are in thermodynamic equilibrium, the particles making up the gases are distributed uniformly in space, the pressure and composition of the gases being uniform at all points in the container.

The International System (SI) unit of measurement is the Pascal [Pa], representing the pressure resulting from a force of one Newton [N] applied to a surface area of one square metre [m2]. However, the Pascal is a relatively small unit compared with those we used to refer to in the past. Multiples of this unit are therefore frequently used: 1 hPa = 100 Pa (1 mbar), 1 kPa = 1,000Pa (0.1 bar), MPa = 1 million Pa (10 bar). The use of bar and mbar is still tolerated, with Pa and its multiples gradually replacing the large number of other pressure measurement units that were widely used (mmHg, mmH2O, Torr, atm, psi). The table below shows the most widely used pressure measurement units, with the corresponding conversion factors.



SI units	mbar + Pa	1 mbar = 100 Pa = 1 hPa
Other units	N/m²	1 N/m² = 1 Pa = 0,01 mbar
	Torr	1 Torr = 1,33 mbar
	mmHG	1 mmHG = 1 Torr = 1,33 mbar
	Atmosphere	1 atm = 1013 mbar=1013 hPa
	Micron	1 µ = 0,001 Torr = 0,00133 mbar
	PSI	1 psi = 69 mbar
	% Vacuum	1 % Vacuum = 990 mbar
		100 % Vacuum = „0" mbar

Pressure measurement units

I.7 Importance of vacuum in cryogenics

Vacuum technology is closely linked to the development of cryogenics or low-temperature technology. The term "low temperature" refers to any temperature below -196°C, the liquefaction point of nitrogen (under 1 atm). The term "very low temperature" is reserved for ***temperatures*** below -269°C (liquefaction point of helium under 1 atm). Cryogenics covers all the techniques involved in the production, storage and use of cryogenic fluids. Proper isolation of these fluids requires a very high vacuum Cryogenics has complemented vacuum technology and opened up many new possibilities, such as:

- Food preservation using liquid nitrogen
- Suspension of metabolism
- The study of superconductivity (absence of electrical resistance)
- The study of superfluidity (the absence of viscosity in a liquid)
- transforming all kinds of materials into a fine powder
- The treatment of certain skin diseases such as warts

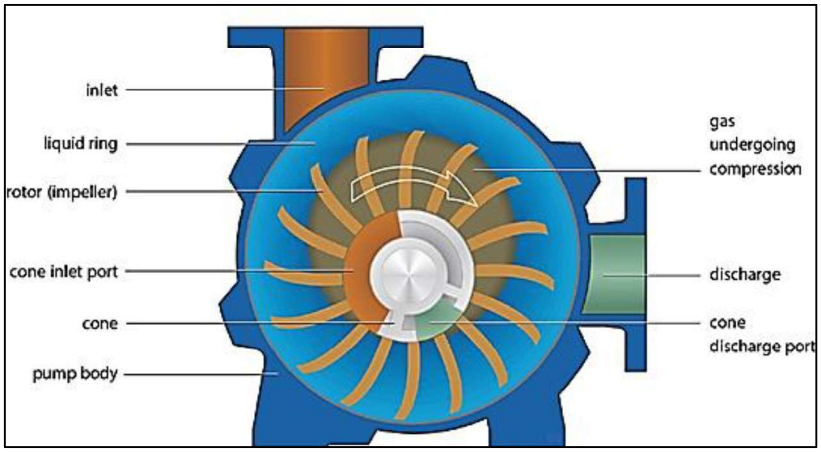
1.8 The vacuum production systems

1.8 .1 Vacuum pumps

By definition (standard NF X 10-501), a ***vacuum pump is*** "a device for creating, improving or maintaining a vacuum". It is therefore a machine capable of extracting gaseous molecules from a reservoir and evacuating them either into the ambient air or into another reservoir.

A vacuum pump must be capable of lowering the pressure in a tank, since pressure is proportional to the number of gaseous molecules present in the tank. The pressure also depends on the temperature and, depending on the temperature, liquids with a high vapour pressure and easily sublimable substances may also need to be taken into account.

The vacuum pump must be able to draw in a certain flow, compress it and discharge it at a pressure higher than the suction pressure.



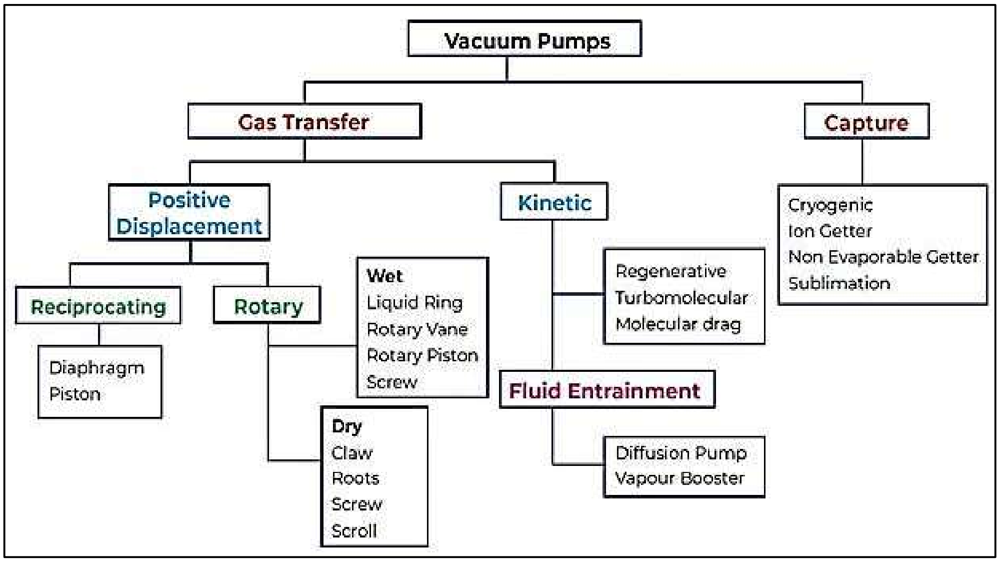
Vacuum pump

- Operation of the liquid ring vacuum pump

A pump that can operate at atmospheric pressure is called 'primary', and 'secondary' when it requires a medium vacuum to prime itself. When the gas is sucked in, compressed and then discharged, the pump is said to be an "extraction" or "transfer" pump (by compression and volume reduction or by compression and molecular entrainment).

Some pumps use the properties of sorption or condensation: these are called fixing pumps. The following diagram summarises the main pumping methods used.

A pump will be characterised by its priming pressure, its ultimate vacuum, its volumetric flow rate (expressed in m^3 /h, 1 m^3 /s, 1 dm^3 /s, 1 or m^3 /mn and its compression ratio in the case of extraction pumps.



Vacuum pump uses

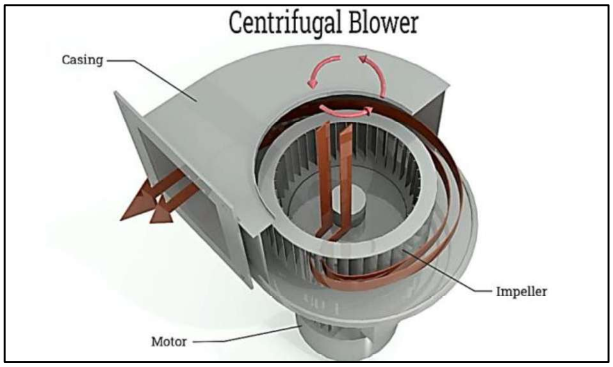
In this section we will give two examples of pumps for:

a. Transfer pumps

- **Centrifugal blowers**

A centrifugal blower is a motor or vacuum pump that moves air using the centrifugal force created by the rotation of an impeller that pulls air or fluids into the blower and pushes it out through the blower's outlet. They are made up of an impeller, housing, and drive mechanism, with the impeller being the key element that has a series of blades mounted on a central hub connected to a fan shaft.

The speed and efficiency of centrifugal blowers make them adaptable to a wide range of applications, including various types of dryers and HVAC systems.



Centrifugal blowers

b. Cryopumps

The use of cryopumps as primary pumps combined with ion pumps or the use of liquid helium cryopumps is becoming increasingly common.

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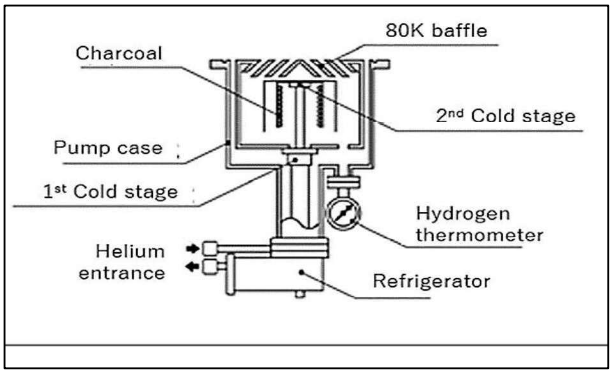


Cryopump structure

Cryogenics already plays a major role in research and industry (aerospace, health, microcomputing, agri-food, etc.). Awareness of the most common vacuum techniques is therefore essential

Exercise

- What is a vacuum lifting system?

- Vacuum technology: what is low, medium or high vacuum

- Vacuum technology: how to create a vacuum

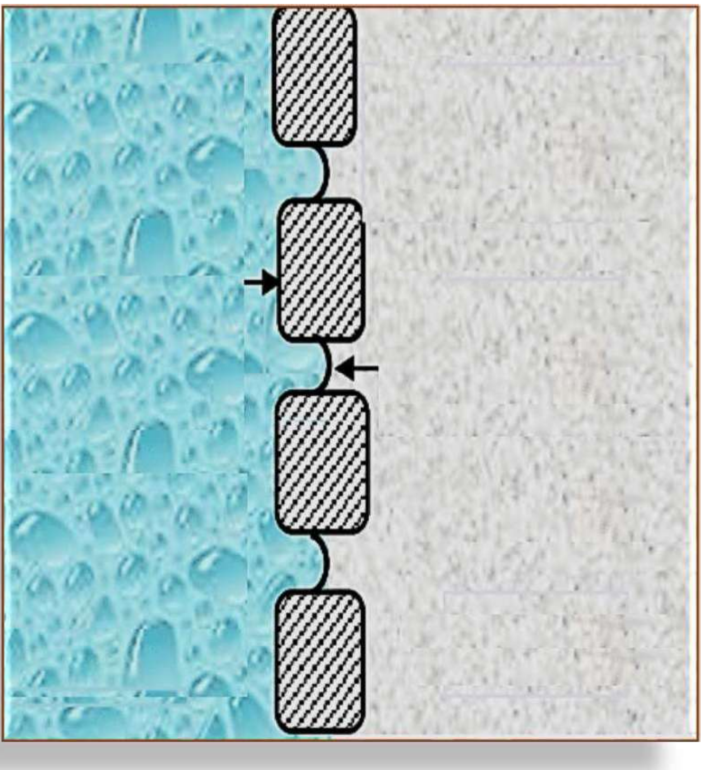
Define

- Cryopumps:
- Root pumps:
- Screw pumps:
- Rotary vane pumps.

- What are the Components of the vacuum system

Chapitre II

Separation and purification processes of cryogenic fluids



II. Introduction

The use of cryogenic liquids (cryogens or cryofluids) derived from liquefied gases, generally produced using industrial processes, and is currently the most widespread means of obtaining and maintaining low temperatures. A cryogenic bath provides a source of refrigeration at a constant temperature.

II.1 Cryogenic fluids

A cryogenic liquid is a liquefied gas, cooled to a temperature below its boiling point of -150°C (-238°F) and kept in a liquid state. Argon, helium, hydrogen, nitrogen and oxygen are the industrial gases most commonly transported, handled and stored in liquid form at cryogenic temperature.

II.1.1 Types of cryogenic liquids

Cryogenic liquids are gases at normal temperatures and pressures, but share the characteristics of being extremely cold and occupying very large volumes as they pass from the liquid to the gaseous state.

Cryogenic liquids have specific properties, but most of them fall into one of three categories:

Inert gases: These gases do not react chemically in any appreciable way, nor do they sustain combustion. Examples: nitrogen, helium, neon, argon and krypton.

- **Flammable gas**: Some cryogenic liquids release a gas that can burn in air, such as hydrogen, methane and liquid natural gas.
- **Oxygen**: Many materials considered non-combustible can burn in the presence of liquid oxygen; for example, there can be an explosive reaction between liquid oxygen and organic materials. The hazards and precautions involved in handling liquid oxygen should be considered separately.

II.1.2 Characteristics of cryogenic fluids

The characteristics of some cryogenic fluids are shown in the table below:

Gas	Boiling point (°C)	Gas expansion volume	Toxicity
Acetylene	-84	-	+
Hydrochloric acid	-85	-	+
Nitrogen	-195	696 à 1	-
Argon	-185	847 à 1	-
Carbon dioxide	-78	553 à 1	+
Helium 3	-269	757 à 1	-
Helium 4	-268	757 à 1	-
Hydrogen	-252	851 à 1	-
Methane	-161	578 à 1	-
Carbon monoxide	-192		++
Oxygen	-183	860 à 1	-
Boron trifluoride	-100		+

🟨 Frequently used

Properties of cryogenic fluids

II.1.3 Hazards of cryogenic liquids

Flammable:

Some cryogenic liquids, such as hydrogen, methane and acetylene, are very strong.

Explosives:

Oxidising cryogenic fluids such as oxygen and liquid air can cause violent reactions in the presence of reducing substances.

Irritants:

Contact with the skin or mucous membranes, particularly the eyes, may cause severe burns comparable to thermal burns.

Toxic:

Most cryogenic fluids are non-toxic or only slightly toxic.

Nitrogen or argon in its liquid state, left in contact with air, becomes enriched with oxygen and can be dangerous when heated.

II.2 Cryogenic fluid separation processes

The separation of gas mixtures is the use of techniques to separate gases from each other, either to give several products or to purify a single product.

Numerous methods can be used, either at ambient temperature or at lower temperatures (cryogenic distillation and fractional condensation). The most common gas mixtures are air and natural gas.

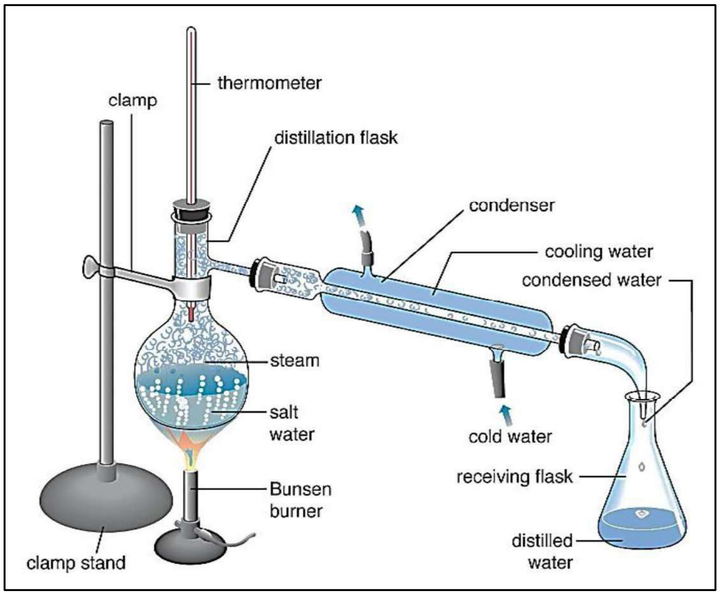
Some of the products of separation may be required in a liquid state. In this case, separation and liquefaction are combined in the same unit.

In other cases, liquefaction is an end in itself; this is the case for **natural gas**, for transport by sea, and also for **hydrogen**, for use as rocket fuel (Ariane...).

Numerous techniques based on certain physical or physico-chemical properties of the constituents of gas mixtures can be used to separate them. Among these, we will look at the most widely used industrially: fractional distillation and condensation, cryogenic distillation and permeation.

II.2.1 Distillation

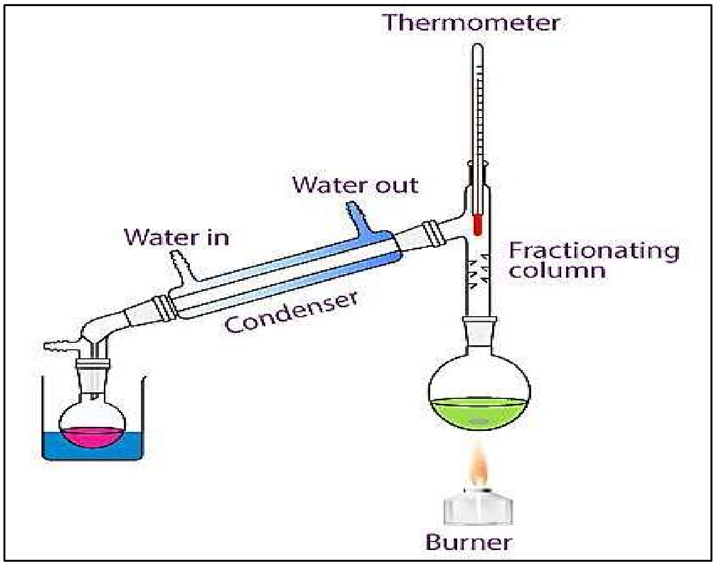
Distillation is a process for separating mixtures of liquid substances with different boiling temperatures and collecting them in gaseous form. This vaporisation may be followed by condensation by cooling (liquefaction).



Distillation device

II.2.1.1. Fractional distillation,

Rectification is a separation process based on fractionation. Its aim is to separate the different constituents of a mixture of miscible with different boiling temperatures. It uses the same principle as conventional distillation, but is distinguished by the use of a fractionation column, which allows better discrimination between the constituents of the mixture.



Fractional distillation device

II.2.1.2. Cryogenic distillation

It is carried out on a liquefied gas. The gas is compressed and then rapidly decompressed, which cools and liquefies it. By gradually heating the gas, which has become liquid, and adjusting the different boiling temperatures, its various components are separated. Cryogenic distillation is generally only used for very high volumes, for economic reasons due to its non-linear cost-scaling relationship.

Liquefying natural gas

To liquefy it, natural gas undergoes several successive treatments:

- **Purification** :

This involves extracting carbon dioxide (CO_2) from natural gas, as well as hydrogen sulphide (H_2S) and other sulphur compounds;

- **Dehydration**:

During this operation, water (H_2O) and mercury (Hg) are removed from the gas to prevent blockage of the cryogenic exchangers following the formation of hydrates and to avoid corrosion of certain parts of the installation.

- **Pre-cooling** :

Once pre-cooled, natural gas undergoes a series of distillations to isolate the heavier hydrocarbons and butane.

- **Liquefaction**:

Compression and **cooling** at constant pressure, followed by expansion, lower its temperature to -160°C, bringing it to a **liquid state.**

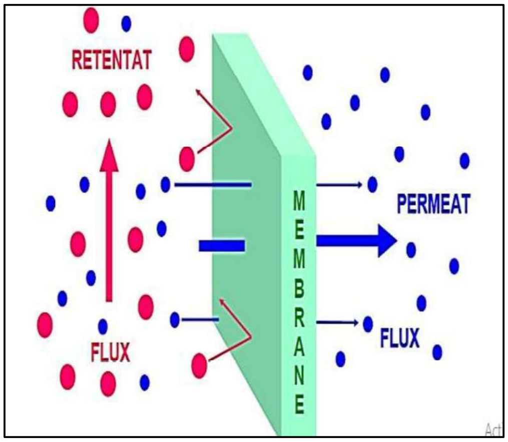
- **LNG storage**

LNG is stored at atmospheric pressure in large cylindrical tanks with high thermal insulation to keep the gas in a liquid state (at -160°C) with minimum evaporation.

Note: 600 m^3 of natural gas in its liquid state occupies a volume of only 1 m^3 (at atmospheric pressure).

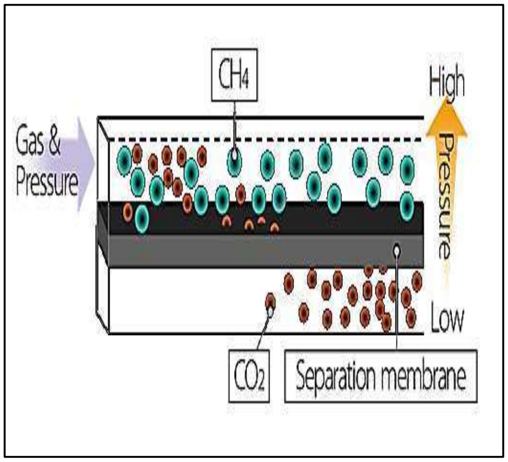
II.2.1.3. Permeation

The permeation process involves the diffusion of molecules that form the permeate, usually through a membrane or an interface. With the presence of a semi-permeable membrane, gas separation is known as selective permeation.



The permeation process

The partial pressure difference across the membrane during gas purification using a separation membrane causes gas permeation while allowing only the target gas to pass.



Natural gas separation membrane

The membranes used, the areas of industrial applications and the advantages of the permeation process are summarised below:

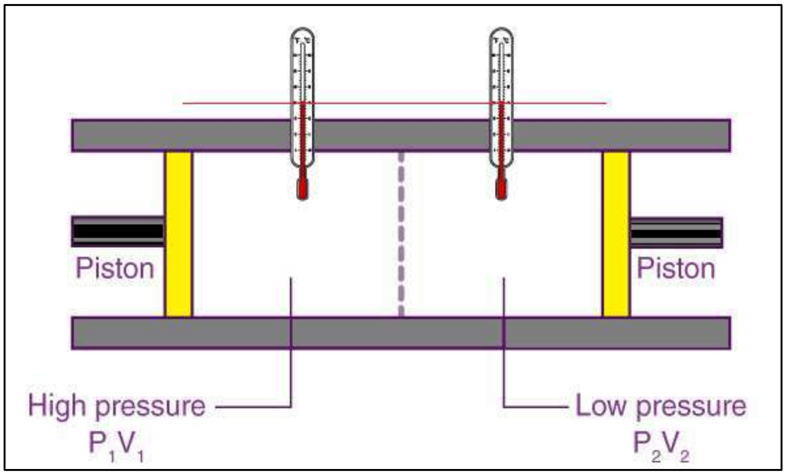
Membranes	Industrial applications	Benefits
Elastomers Glassy plastomers Semi-crystalline polymers Semi-rigid polymers	Recovery Dehydration of : air and hydrocarbons Natural gas purification NG	-Low power consumption -Compact equipment -Easy automation -High level of safety

Membranes industrial applications

II.3. Joule Thomson valve

II.3.1. Description of the Thompson Joule valve

This is a valve whose role is to relieve the pressure of the fluid (gas or liquid) passing through it (an MR liquid in the case of our study). It consists of a valve body through which the fluid flows, a control mechanism, a servomotor that regulates the flow and accessories specific to each particular application.



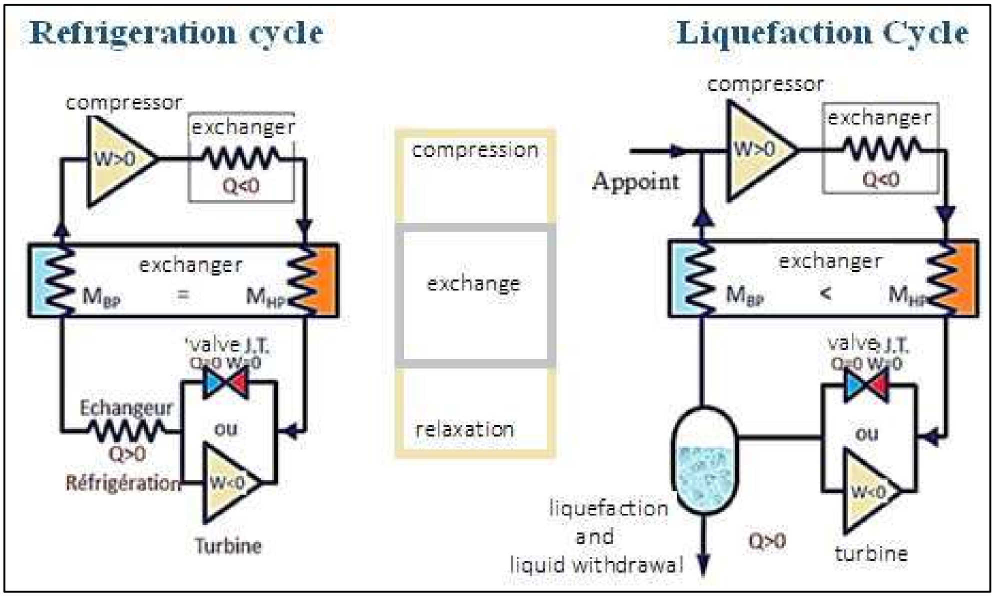
Behaviour of a fluid in the J-T valve

II.3.2. Joule-Thomson effect

The irreversible (isenthalpic) expansion of a theoretically perfect gas through a valve or orifice does not cause any change in the temperature of the gas. In the case of a real gas, expansion under pressure is often accompanied by cooling. This is the Joule-Thomson effect, highlighted by the work of James Prescott Joule and William Thomson in 1852. The Joule-Thomson (JT) effect is exploited in all primary LNG liquefaction processes to cool the feed gas or refrigerant streams. This effect is facilitated by a control valve known as the Joule-Thomson valve (or J.T. valve).

Joule Thomson valve **(J.T. valve)** is used in the following two cycles:

- **Refrigeration cycle**
- **Liquefaction Cycle**

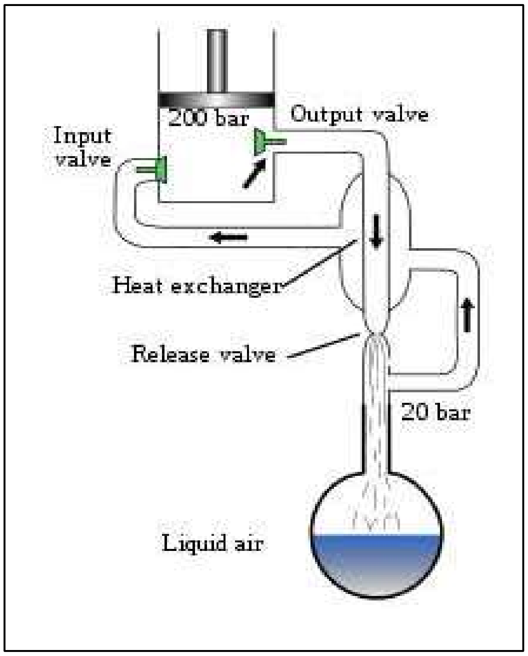


Principle of refrigeration and liquefaction processes

The "Joule-Thomson effect" was successfully used by Carl von Linde to liquefy air, and this refrigeration cycle has since been called the "Linde cycle".

The process involves compressing the gas at high pressure and cooling it to ambient temperature. It is then brought to a temperature as close as possible to the temperature of the liquefied gas in a counter-current exchanger with the unliquefied gas at low pressure.

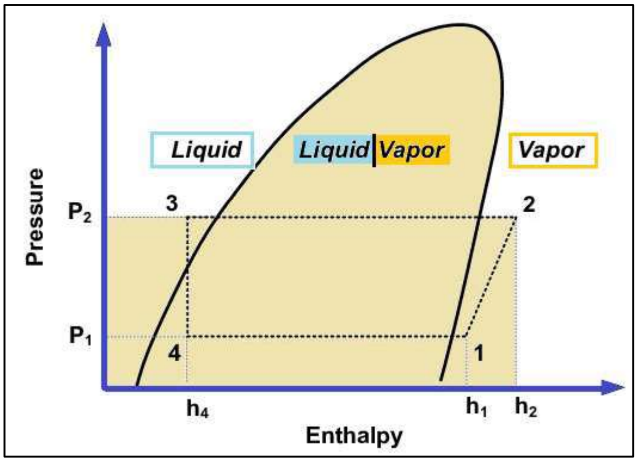
The cold high-pressure gas undergoes **expansion through a valve**, where a further reduction in temperature is sufficient to partially liquefy it. The liquid is separated and the gas is returned to the compressor after cooling the high-pressure gas. Fresh gas is topped up at the compressor inlet to compensate for the liquid produced.



Linde process schematic

II.3.3. Enthalpy diagram

Enthalpy represents the energy contained in a fluid or, more precisely, the total energy gained or lost by a fluid during the refrigeration cycle. It is expressed in kJ/kg (Kilojoule/Kilogramme of fluid), with the enthalpy scale on the x-axis of the diagram. An enthalpy of 200 kJ/kg means that 1 kg of refrigerant will potentially contain 200 kJ of energy.



Enthalpy diagram

In the refrigeration circuit, changes of state, exchanges and heat transfer mean that the fluid will give up or absorb energy during the process.

II.3.4. Form for operating the refrigeration cycle:

1. **Mass flow rate of circulating refrigerant**

Qm = Qo / ΔHev

Qm = Mass flow rate of circulating refrigerant in kg / s

Qo = Cooling capacity in kW

ΔHev = enthalpy change between evaporator outlet and inlet in kJ / kg

2. Volume of fluid drawn in by the compressor

$$Va = Qm. Vme. 3600$$

Va = Volume of fluid drawn in by the compressor in m^3/h

q m = Mass flow rate of circulating refrigerant in kg / s

Vme = Compressor inlet mass volume in m^3/kg

3. Compression ratio

$$t = P\ ref. / P\ asp.$$

t = Compression ratio

P ref. = Discharge pressure in bar absolute

P asp. = Suction pressure in bar absolute

- *If head losses are negligible, the formula becomes :*

$t = Pk / Po$

t = Compression ratio

Pk = Condensing pressure in bar absolute

Po = Evaporating pressure in bar absolute

4. Volumetric efficiency

$$\eta v = 1 - 0.05.t$$

ηv = Volumetric efficiency

t = Compression ratio

5. **Volume of fluid swept by the compressor**

$$\mathbf{Vb = Va / \eta v}$$

Vb = Volume of fluid swept by the compressor in m^3/ h

Va = Volume of fluid drawn in by the compressor in m^3/h

ηv = Volumetric efficiency

6. **Theoretical compressor power**

$$\mathbf{P_{thCP} = Qm.\ \Delta Hcp}$$

P_{thCP} = Theoretical compressor power in kW

Qm = Mass flow rate of circulating refrigerant in kg / s

ΔHcp = enthalpy change between compressor outlet and inlet in kJ / kg

7. **Power to be supplied to the compressor shaft**

$$\mathbf{P_f = P_{thCP} / (\eta i\ .\ \eta m)}$$

P_f = Power to be supplied to the compressor shaft in kW

P_{thCP} = Theoretical compressor power in kW

ηi Indicated efficiency (equal to volumetric efficiency)

ηm Mechanical efficiency

8. **Electric motor power output**

$$\mathbf{P_u = P_f / \eta_{tr}}$$

P_u = Output power of the electric motor in kW

P = Power to be supplied to the compressor shaft in kW

η_{tr} = Transmission efficiency

9. Power absorbed by the electric motor

$$Pa = Pu / \eta el$$

Pa = Power absorbed by the electric motor in kW

Pu = Output power of the electric motor in kW

ηel = Electrical efficiency

10. Power rejected at the condenser

$$Pcd = Qm \, . \, \Delta Hcd$$

Pcd = Power rejected at the condenser in kW

Qm = Mass flow rate of circulating refrigerant in kg / s

ΔHcd enthalpy variation between condenser inlet and outlet in kJ / kg

11. Cooling coefficient of performance

$$COP_f = Qo / Pa$$

COP_f = Cooling coefficient of performance

Qo = Cooling capacity in kW

Pa = Power absorbed by the electric motor in kW

12. Carnot coefficient of performance

$$COP_{ct} = To / (Tk - To)$$

COP_{ct} = Carnot coefficient of performance

To = Evaporation temperature in degrees K

Tk = Condensing temperature in degrees K

13. Plant efficiency

$$\eta = COP_f / COP_{ct}$$

η = Plant efficiency

COP_f = Cooling coefficient of performance

COP_{ct} = Carnot coefficient of performance

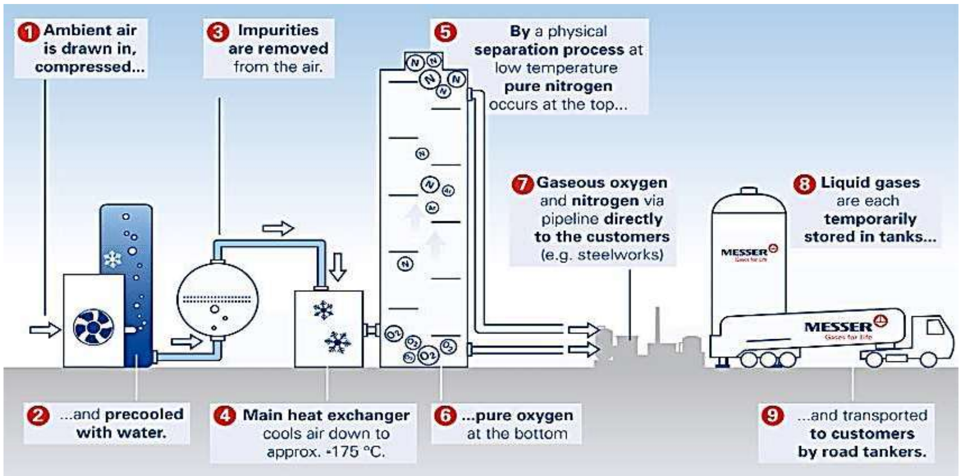
II.4. Air separation processes

Techniques for separating gases are used either to produce several products or to purify a single product. In the case of gases contained in ambient air, they are separated according to the principle of low-temperature rectification, using their different boiling points (cryogenic distillation and fractional condensation). Air is one of the gaseous mixtures most concerned by these separation processes, given its various components such as nitrogen (N2) and oxygen (O2), argon (Ar) and other rare inert gases which are used for many purposes in different sectors of industry.

II.4.1. Cryogenic separation

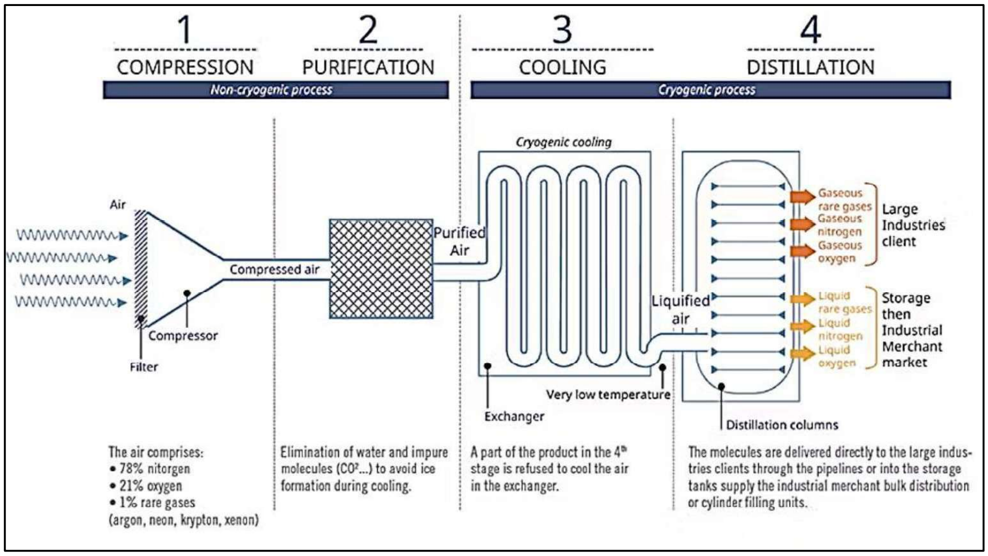
In general, it is only used for the separation of air components because of its cost-effectiveness for production, making it possible to obtain high-purity nitrogen, oxygen and argon in liquid and gaseous form in very large volumes. The equipment used in this separation process generally consists of cryogenic pumps and brazed heat exchangers. The latter ensure efficient heat transfer in a small footprint.

- **Air separation stages.**



Air separation unit operation

The cryogenic air separation process comprises the following steps:



Stages in the air fractionation process

II.4.2. Non-cryogenic air separation process

Non-cryogenic air separation processes use pressure reversal adsorption or separation by means of semi-permeable membranes.

II.4.2.1. Pressure swing adsorption (PSA)

Also known as pressure swing adsorption (PSA). PSA is based on physical adsorption on the surface of a solid, in which highly volatile, low-polarity compounds are practically not adsorbed. This technology is widely used to produce oxygen or nitrogen by air separation**.**

The process is based on the following main phases:

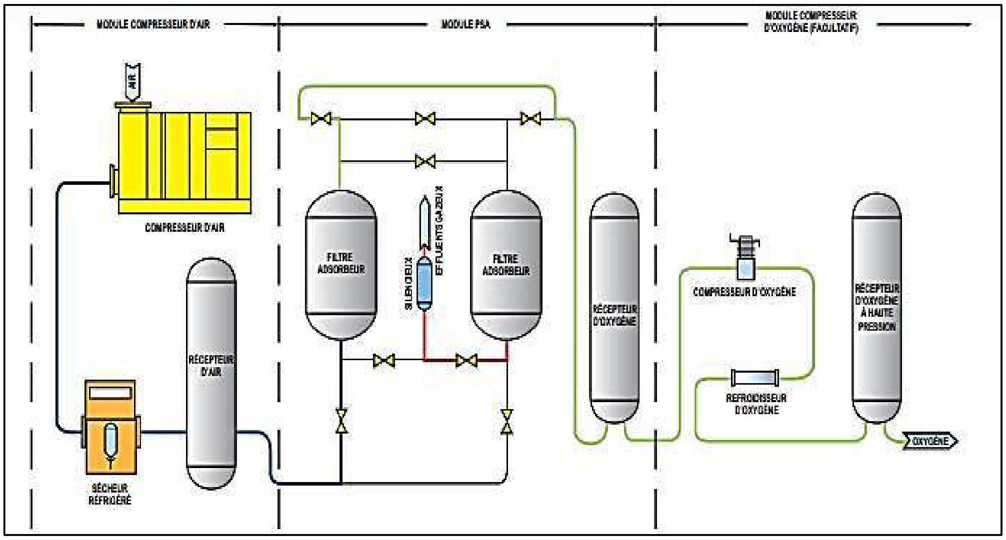
- The compressed air (78% nitrogen, 21% oxygen, < 1% argon) is filtered, de-oiled and dried, and the operating pressure is regulated automatically.

- The air passes through the molecular sieves, where the nitrogen is adsorbed by the zeolite, increasing the oxygen concentration by up to 95%.

- On leaving the molecular sieve, the oxygen produced is sent to the buffer tank via a multifunction block. The nitrogen is eliminated via a silent exhaust and discharged to the outside.

- Some of the oxygen produced is used to help desorb nitrogen from one column when the other column is producing oxygen (and vice versa).

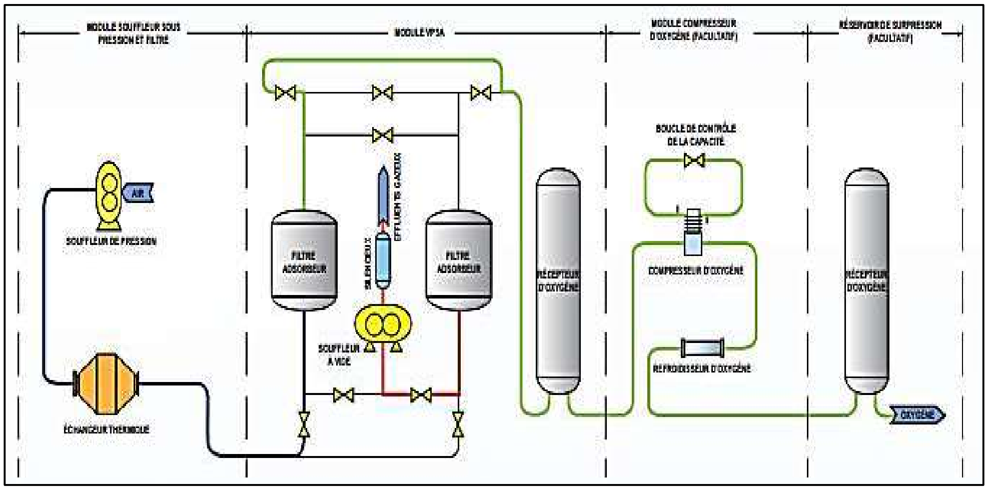
- A pneumatic and automatic column balancing system ensures a continuous flow of oxygen.



Conventional PSA plant producing oxygen from air

II.4.2.2. Vacuum assisted adsorption (VSA or VPSA)

In this variant of the process, a distinction is made between VSA (acronym for Vacuum Swing Adsorption), in which all phases take place at or below atmospheric pressure, and VPSA (Vacuum Pressure Swing Adsorption), which alternates between pressures below and above atmospheric. Since vacuum creation facilities are required, this process is justified when the quantity of adsorbents needs to be minimised. The Vacuum Assisted Pressure Reversal Adsorption (VAPRA) process facilitates the regeneration or desorption stage by using a vacuum blower.



Classic VPSA installation

II.4.2.3. Air membrane separation process

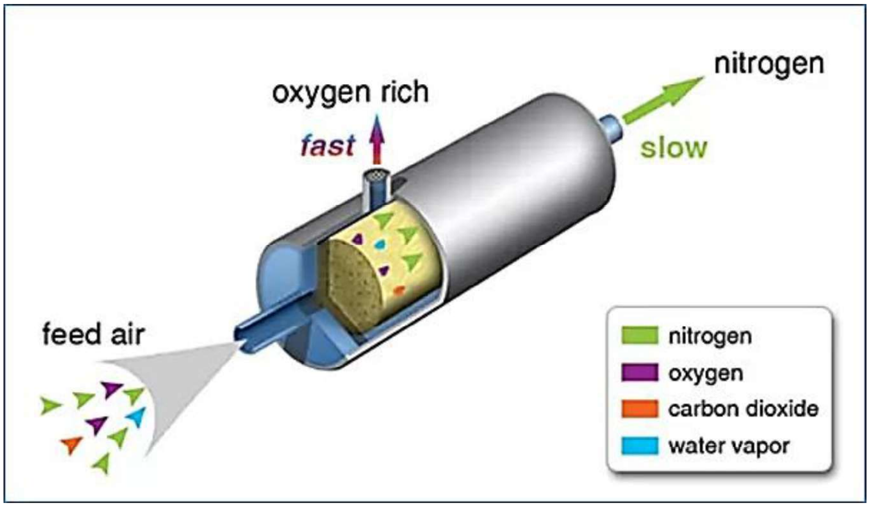
Uses a selective permeation system based on the difference in partial pressure between the two sides of a dense non-porous membrane, generally made of polymer.

Membrane separators can be used for:

- Hydrogen recovery
- Nitrogen production
- Eliminating carbon dioxide

The gas fed to the separator must be free of dust, liquid water or oil. Pre-treatment must be applied. To avoid any condensation of water along the tube, the gas is pre-heated to ensure a safety margin above its dew point.

In the case of compressed air, it passes through the tube, allowing oxygen, carbon dioxide and water vapour to pass through the membrane. At the other end of the tube, a gas freed of these elements and therefore enriched in nitrogen is obtained. A membrane separator typically produces nitrogen at 95 - 99.5% purity, with a residual moisture content of <10ppm. This depends on the purity of the feed, the working pressure and the desired recovery rate.



Membrane separation process

Chapter III

Permanent gas liquefaction processes

III. Introduction

Liquefaction of gases consists of removing energy from them in order to cool them from ambient temperature to the dew point, then condensing the saturated vapor. There are several gas liquefaction processes; in this chapter we will focus on those which treat permanent gases, pure or mixed. Some gases under pressure are obtained in the liquid state at relatively low temperatures, others remain there even at practically high temperatures, also called liquid gas.

III.1. Gaz permanents

Is a gas that cannot liquefy at room temperature by simply increasing pressure without cooling. There are ten pure bodies which meet the antes definition, summarized as follows:

- Seven simple bodies
- Three compound bodies

In the industrial field there are three mixtures of gases:

Air, natural gas (NG) and synthetic gas...

Seven simple bodies	Three compound bodies	Gas mixtures
He Helium	CO Carbon monoxide	Air
H_2 Hydrogen		
With Neon	CH_4 Methane	Gaz naturel (GN)
N_2 Nitrogen		
Ar Argon		
O_2 Oxygen	NO Nitric oxide	Synthetic gas
Kr Krypton		

III.2. Gas liquefaction processes

III.2.1. Liquefaction of non-permanent gases

In general, two methods are most often combined to liquefy certain gases: cooling below its boiling point and compression at ordinary temperature and because it is easier to produce both moderate cold and medium pressure than to obtain either a very high pressure, which moreover would not always be sufficient, or a cooling that is difficult to achieve.

III.2.1.1 Liquefaction cooling

The limits of this general method caused by the limitations of refrigerants force the use of other, much more efficient cooling processes such as the use of the evaporation of very volatile liquids. Lower temperatures can be obtained by boiling in vacuum or by activating evaporation by a current of air, which can be cooled beforehand and is all the more intense when a more volatile body is used. The use of gas expansion offers the possibility of working at very low temperature levels, as with Linde process case.

III.2.1.2 Compression liquefaction

The simplest way to liquefy a gas is to increase its pressure at room temperature until conditions are reached where its stable state is the liquid state. This was apparently first done around 1760 by Martin van Marum, a Dutch scientist, with ammonia. The critical temperature of ammonia is 132°C and its condensation pressure is 10 atm at 26°C. It is therefore sufficient to increase the pressure of the ammonia beyond 10 atm without exceeding 26°C in temperature to obtain it in the liquid state. This is the case for many substances whose critical temperature is higher than ambient temperature.

III.2.1.3 Liquefaction by compression and cooling

In this process, the gas is compressed to high pressure and is cooled as close as possible to the temperature of the liquefied gas in a counter-current exchanger with the non-liquefied gas at low pressure.

III.2.2. Liquefaction of permanent gases

Six gases had received the name of permanent gases, namely: oxygen, hydrogen, nitrogen, nitrogen dioxide, carbon monoxide and methane because they remained in their state despite their submission to the different liquefaction methods even at – 110 °C and under pressures varying from 27 to 50 atmospheres. It is thanks to the use of mechanical pressure associated with intense cooling that Faraday (1845) through a special device was able to liquefy this type of gas.

III.3. Cycle of Linde–Hampson

Among the gas liquefaction cycles, that of Linde-Hampson which is in particular a process for the separation of air. The cycle is characterized by the integration of regenerative cooling, a positive feedback cooling system. An absolute temperature difference to move from a simple cooling stage where the low temperatures necessary for the liquefaction of “fixed” gases are ensured by the installation of a heat exchanger.

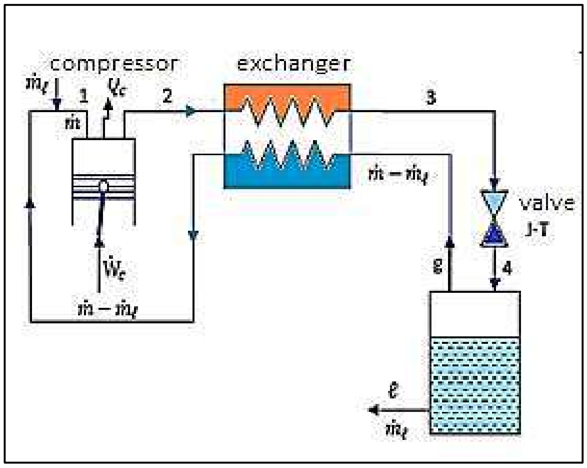
The Linde-Hampson cycle is described by the profile below showing the following four successive transformations:

1-2: Isothermal compression of the gas at the compressor,

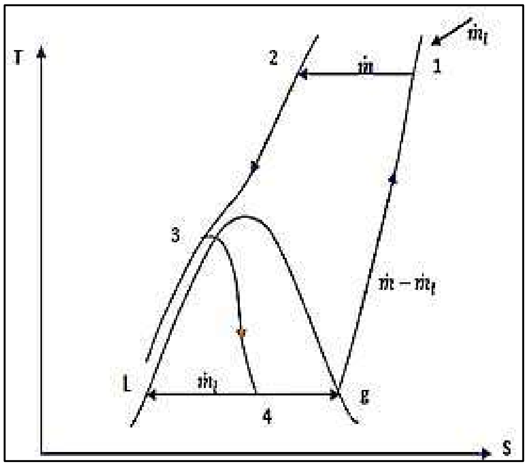
2-3: Isobaric cooling by the non-condensed gas from the previous cycle by a counter-current exchange,

3-4: At the exit of the exchanger it undergoes isenthalpic expansion - Joule-Thomson valve, 4-g-1: The vapor fraction produced returns through the heat exchanger absorbing heat from the hot side at high pressure towards the compressor,

4-f: The liquid fraction of the resulting liquid-vapor mixture is collected (state f).



Linde – Hampson Cycle



Linde – Hampson T-s diagram

- **System performance indicators**

The performance of the systems is assessed by the indicators mentioned below:

1- Expression of mechanical work spent

$$\frac{In_c}{\dot{m}} = T\,(s_1 - s_2) - (h_1 - h_2)$$

$\frac{In_c}{\dot{m}}$: The work required in relation to the mass flow rate of compressed gas in (KJ/kg)

T: Absolute gas temperature in (K)

s_1 : Specific entropy of gas at the compressor inlet in (KJ/kg °C)

s_2 : Specific entropy of gas at the compressor outlet in (KJ/kg °C)

h_1 : Specific enthalpy of the gas at the compressor inlet in (KJ/kg)

h_2: Specific enthalpy of the gas at the compressor outlet in (KJ/kg)

$\dot{m}$: Mass flow rate of the gas at the entrance to the cycle in (kg/s),

2- The fraction of the total liquefied gas flow

$$y = \frac{\dot{m}_l}{\dot{m}} => \dot{m} = \frac{\dot{m}_l}{y}$$

h_f : Specific enthalpies of the gas at the compressor outlet (KJ/kg)

3- Expression of Work required per unit mass of liquefied gas

According to the equations we obtain

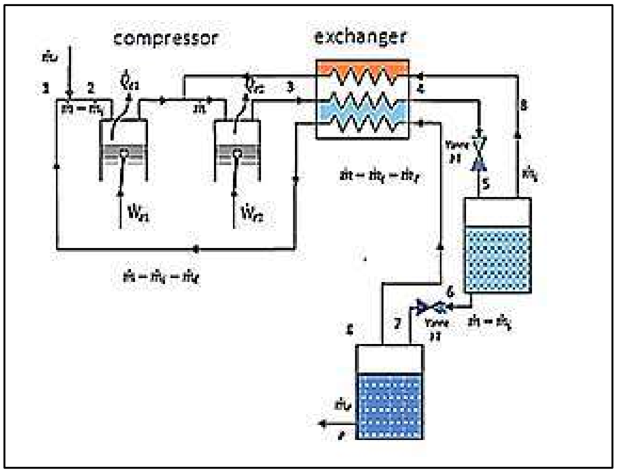
$$\frac{-\mathrm{w_c}}{\dot{m}_l} = \frac{-\mathrm{w_c}}{\mathrm{y}\,\dot{m}} = \frac{1}{\mathrm{y}}\,[T(s_1 - s_2) - (h_1 - h_2)]$$

4 - System Performance or Merit Factor

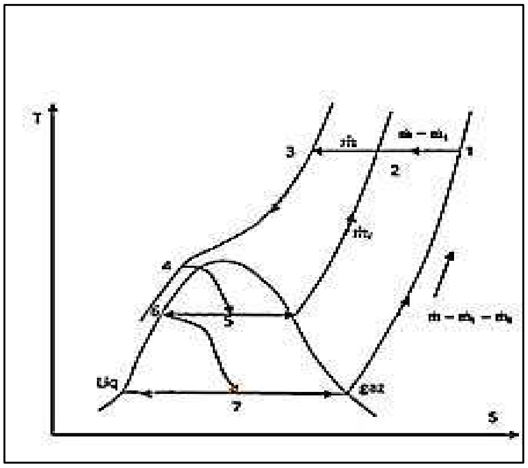
It is defined as the ratio between the work of the ideal cycle and the work of the real cycle.

$$\frac{\mathrm{w_i}}{\dot{m}_l} / \frac{\mathrm{w_c}}{\dot{m}_l} = \mathrm{y}\,\frac{T(s_1 - s_l) - (h_1 - h_l)}{T(s_1 - s_2) - (h_1 - h_2)}$$

III.4. cycle of Linde with double compression



Linde double compression cycle



Linde double compression T-s diagram

1- Energy balance

The energy balance on the control volume gives us for a compressed mass of gas ($\dot{m}$) and a mass withdrawn($\dot{m}_f$) on pointℓ, is given by:

$$\dot{m}h_3 = \dot{m}_f h_l + \dot{m}_i h_2 + (\dot{m} + \dot{m}_i + \dot{m}_f)h_1$$

$$\dot{m}(h_3 + h_1) = \dot{m}_f(h_l - h_1) + \dot{m}_i(h_2 - h_1)$$

With : $y = \frac{\dot{m}_f}{\dot{m}}$ $\quad$ $i = \frac{\dot{m}_i}{\dot{m}}$

$$y = \frac{(h_3 - h_1)}{(h_l - h_1)} - i\,\frac{(h_1 - h_2)}{(h_l - h_1)}$$

The first term is the yield for a simple Linde Hampton system, the second term means the reduction in liquid yield corresponding to the change (double compression).

2- Expression of Work per unit mass of compressed gas

In this cycle there are two compressors, each performing reversible isothermal compression.

Work per unit mass of compressed gas is defined as $\frac{w_c}{\dot{m}}$:

with: $w_c = w_{c1} + w_{c2}$

$$w_{c1} = (\dot{m} + \dot{m}_i)[(h_2 - h_1) + T(s_1 - s_2)]$$

$$w_{c2} = (\dot{m})[(h_3 - h_2) + T(s_2 - s_3)]$$

The amount of energy spent is expressed as follows:

$$w_c = w_{c1} + w_{c2}$$

$$\frac{w_c}{\dot{m}} = (h_3 - h_1) + \mathrm{T}(s_1 - s_3) - \mathrm{i}\,[(h_2 - h_1) + \mathrm{T}(s_1 - s_2)]$$

3- Expression of net Work per unit mass of liquefied gas

$$\mathrm{y} = \frac{\dot{m}_l}{\dot{m}} \Rightarrow \frac{w_c}{\dot{m}_l} = \frac{1}{\mathrm{y}}\frac{w_c}{\dot{m}}$$

$$\frac{w_c}{\dot{m}_l} = \frac{1}{y}[(h_3 - h_1) + \mathrm{T}(s_1 - s_3) - \mathrm{i}\,[(h_2 - h_1) + \mathrm{T}(s_1 - s_2)]]$$

4- System Performance or Merit Factor

Noted FOM, it is defined as the ratio between the work of the ideal cycle and the work of the real cycle.

$$\mathrm{FOM} = \frac{\mathrm{w_i}}{\dot{m}_l} / \frac{\mathrm{w_c}}{\dot{m}_l}$$

With

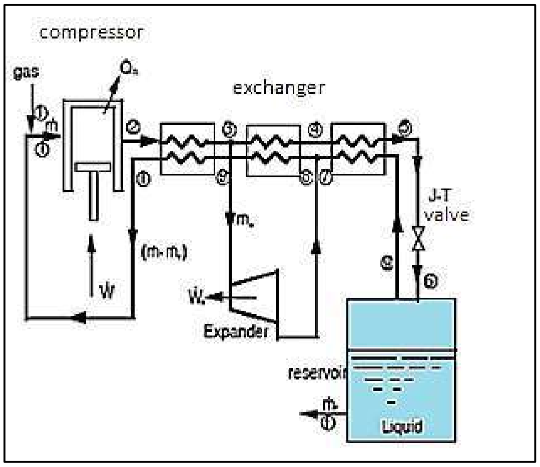
$$\frac{\mathrm{w_i}}{\dot{m}} = (h_l - h_1) - T(s_l - s_1)$$

$$\frac{\mathrm{w_i}}{\dot{m}_l} / \frac{\mathrm{w_c}}{\dot{m}_l} = \mathrm{y}\,\frac{(h_l - h_1) - T(s_l - s_1)}{[(h_3 - h_1) + \mathrm{T}(s_1 - s_3) - \mathrm{i}\,[(h_2 - h_1) + \mathrm{T}(s_1 - s_2)]]}$$

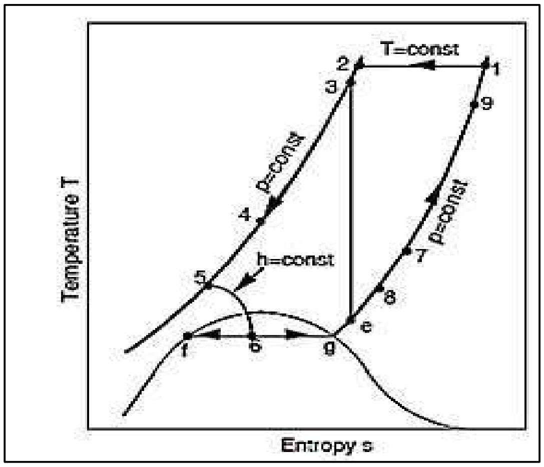
III.5. Claude's liquefaction process

Claude's liquefaction process assembles a Brayton cycle **isentropic expansion** with one or more stages and a Joule Thomson cycle **isenthalpic relaxation**, the Brayton cycle cools the Joule Thomson cycle, which makes it possible to liquefy any gas without requiring external pre-cooling.

The start of the cycle is the same as that of Linde, isothermal compression of the gas to be liquefied, a first isobaric cooling in a first exchanger (2-3). The flow is then divided in two at point 3 (see cycle) of which 15% is expanded in the turbine joins the fresh gas line (refusal of liquefaction) to pre-cool the gas at high pressure and 85% undergoes a second cooling at level of the second heat exchanger at (point 7) then sent for isenthalpic expansion.



Schematic Claude Cycle



Claude T-s diagram

1- The fraction of the total liquefied gas flow

The mass flow ratio of the fraction of gas expanded in the turbine to the total mass flow rate of the gas is given by: $x = \frac{\dot{m}_e}{\dot{m}}$

$$\mathrm{y} = \frac{\dot{\mathrm{m}}_l}{\dot{\mathrm{m}}} = \frac{(h_1 - h_2)}{(h_1 - h_l)} - x\,\frac{(h_3 - h_e)}{(h_1 - h_l)}$$

2- Expression of Work per unit mass of compressed gas

$$\frac{w_c}{\dot{\mathrm{m}}} = [\mathrm{T}(s_1 - s_2) - (h_1 - h_2)] - [\mathrm{x}(h_3 - h_e)]$$

$$\frac{w_c}{\dot{\mathrm{m}}_l} = \frac{1}{y}[[\mathrm{T}(s_1 - s_2) - (h_1 - h_2)] - [\mathrm{x}(h_3 - h_e)]$$

Exercise

1- Quote the different cases of matter and diagram their transformations.

2- What are cryogenic fluids?

3- Give a definition of liquefaction

4- What is the difference between a refrigeration installation and a cryogenic installation?

5- Justify that the J-T relaxation is an Isenthalpic relaxation.

5- Explain in brief the gas inversion curve (TP diagram)

Chapter IV

Cryogenic applications

IV. Introduction

As mentioned in the general introduction, many cryogenic applications are present in the fields: food, medical, industrial, chemical, etc. Where we discover *cryopreservation, superfluidity, cryo-grinding, cryogenic cleaning, superconductivity* the latter which will be developed in this chapter.

IV.1 Discovery of superconductivity

IV.1.1 History

In 1911 the phenomenon was discovered by a physics student, Gilles Holst, studying under the direction of physicist Dutch Kamerlingh Onnes. They showed that the resistivity electrical resistance (or electrical resistance) of mercury becomes non-measurable below a certain temperature called critical temperature T. The term non-measurable here means that the electrical resistance of mercury drops suddenly below T, so that the we can no longer define it conventionally. For this discovery, Kamerlingh Onnes received the physic's Nobel price in 1913.

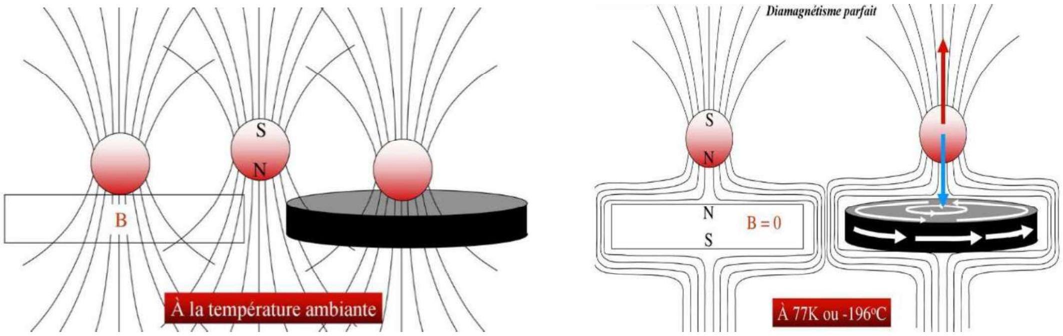
Many elements showed through experiments that they possessed superconductivity faculties, but others did not: let us cite in 1922, the leadat 7 K and in 1941, the nitride of niobiumat 16 K.

Meissner and Ochsenfeld discovered in 1933 that the magnetic field is repelled by superconductors, a phenomenon known as Meissner effect and it was in 1950 that we noticed that the critical temperature depends on isotopic mass.

A phenomenological theory explains the macroscopic properties of superconductors using the Schrödinger equation which was developed in 1950 called Ginzburg-Landau.

IV.1.2 Definition

Superconductivity (or superconduction) is a phenomenon characterized by the absence of electrical resistance and the cancellation of the magnetic field — the Meissner effect — inside certain so-called superconducting materials. It manifests itself at very low temperatures, close to absolute zero (-273.15°C) and is closely linked to the quantum characteristics of matter.



Perfect diamagnetism

Superfluidity or superfluidity has an effect similar to that of superconductivity characterizing the absence of resistance to flow, that is to say that a small disturbance that is subjected to this type of liquid never stops, in the same way that Cooper pairs move without any resistance in a superconductor.

IV.1.3 Theories

IV.1.3.1 Ginzburg-Landau theory

Ginzburg and Landau introduce a complex order parameter into their developed theory $\psi(\mathbf{r})$ characterizing superconductivity. The meaning physique why setting is $n_s(\mathbf{r}) = |\psi(\mathbf{r})|^2$ that is proportional to the density of superconducting electrons (*i.e.*of electrons constituting Cooper pairs). The starting postulate of the theory is that the density offree energy f_s may be developed into a series of the order parameter near the superconducting transition in the following form:

$$f = f_{n0} + \alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 + \frac{1}{2m^*} |(-i\hbar\nabla - q^* \mathbf{A}) \psi|^2 + \frac{\mathbf{B}^2}{2\mu_0}$$

Where f_{n0} is the free energy density in the normal zero-field state, A is the vector potential and B is the local intensity of the magnetic induction.

In the superconducting state, in the absence of field and gradients, the previous equation becomes:

$$f_s - f_n = \alpha|\psi|^2 + \frac{1}{2}\beta|\psi|^4$$

β is necessarily positive because otherwise there would be no global minimum for free energy, and therefore no equilibrium state. If $\alpha > 0$, the minimum takes place for $\psi = 0$: the material is in normal condition. The interesting case is therefore the one where $\alpha < 0$. We then have, in equilibrium, from where:

$$|\psi|^2 = |\psi_\infty|^2 \equiv -\alpha/2\beta$$

IV.1.3.2 BCS theory

This theory is based on the coupling of electrons from a metal in pairs: Cooper pairs. They form a unique, coherent state, of lower energy than that of normal metal, with unpaired electrons.

The energy difference between the superconducting state and the normal state is called *gap* of energy. This is the energy needed to pass from the superconducting state to the normal state by breaking the Cooper pairs. This energy tends towards zero when the temperature tends towards the critical temperature.

The electron-phonon interaction plays an essential role for the pairing of electrons and therefore for superconductivity

IV.2. Elementary properties

A superconductor is a material that exhibits two characteristic properties when cooled below a critical temperature T:

- Zero resistance
- Diamagnetism Perfect
- Zero resistivity
- Meissner effect

IV.3. Applications

- Magnetohydrodynamics
- Magnetic cannon
- Electromagnets
- Transport of energy
- Energy storage
- Electromagnetic confinement

IV.3.1 Classes of superconductors

IV.3.1.1 Conventional superconductors

Conventional superconductors are defined as materials having a mechanism of formation of pair of Cooper which involves the interaction electrons – phonons, others define them as being those which are well described by the BCS theory.

IV.3.1.2 Unconventional superconductors

Unconventional superconductors are materials which have superconducting properties but do not conform to the theory BCS or its extensions.

IV.3.1.3 Exotic superconductors

A material is called "exotic" when it presents, depending on the temperature, superconducting phases as well as ferromagnetic phases.

IV.4. Cryogenics in the agri-food sectors

Several cryogenic processes are used in the food industry sector such as IQF *L'Individually Quick Frozen,* which is a freezing technique suitable for small fruits and vegetables, or cheese, shrimp, etc. It allows these products to be frozen and prevents them from clumping together.

IV.4.1 Meat industry

Frozen or cooled using specific cryogenic equipment, meats are part of this type of industry.

IV.4.2 Dairy industry

Cryogenic processes such as rapid cooling after heat treatment, freezing, IQF freezing, multilayer, cutting, crusting are used before packaging milk and dairy products such as cheese and fresh or frozen dairy desserts.

IV.4.3 Snack and fish industry

New cryogenic processes make it possible to keep the color and freshness of fish and to produce **frozen snacks (**which can be consumed at any time).

IV.4.4 Agricultural industry

Cryogenic devices in the food industry today make it possible to transform certain products into prepared meals, soups and preserve fruits and vegetables from agriculture by freezing in order to use and distribute them throughout the world and use them for all year.

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You can send your feedback, reports, criticisms and others, always very much appreciated

and If by mistake or forgetting certain references are not mentioned please contact us for correction.

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Department of Process Engineering
Level: 3th Process Engineering

Assessment Test

Assessment Test

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Department of Process Engineering

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Assessment Test **Cryogenics Process**

1 Please answer true or false

N°	Questions	Answers
1	The **cryogenics** covers the whole techniques for cooling .	………
2	The boiling points of **cryogenic fluids are** **> - 150 °C.**	………
3	The decrease in pressure allows matter or radiation to be transported without diffusion.	………
4	The **cryogenic distillation** is carried out on a solidified liquid.	………
5	Any gas whose critical temperature is below ambient temperature is a **permanent gas**.	………
6	The Linde cycleuses a isenthalpic relaxation which presents no disadvantage.	………
7	The process of **Linde-Hampson liquefaction** is a process of liquefaction of gases, in particular forair separation.	………
8	The process of **icing**is a cryogenic system for recovering volatile organic compounds (VOCs) from gas flows.	………

2 Indicate the correct answer only

1	the only method that can guarantee the preservation of the cellular membranes of foods thanks is Cryogenic freezing by:	speed of cold descent.
		slow freezing by cryogenics.

2	Wich is the first gas classified in the category of permanent gases is:	Krypton (Kr)
		Neon (Ne)

3	The industry separates the constituents of the air by:	distillation
		drying

4	A gas that cannot liquefy by a simple increase in pressure at ordinary temperature, It is	permanent.
		they do not last.

5	Cryopreservation is also called:	Superfluidity.
		Cryofixation.

6	L'Ultrahigh vacuum is obtained between ….. (Applied, in the manufacture of electronic tubes, in space simulation and in satellites…. :	10^{2} Pa and 10^{-2} Well.
		10^{-5} Pa and 10^{-8} Well.

3 Complete the following sentences

N°	**Process**
1	We want **separate cryogenic fluids**…………..
2	We want **purify natural gas (NG)**……………..
3	We want **obtain primary vacuum** (up to 1 Pa)……………….
4	We want **optimize the process transfer of cryogenic fluids**…………………..
5	We want **recover VOCs from gas streams**……………….
6	We want **transporter electrical currents without any loss of'energy**…………

Exercises

Exercises :

Chapter 1: Vacuum technology

Exercise:

- **Question:** A vacuum pump reduces the pressure of a chamber from 1 atm to 0.01 atm. Calculate the pressure ratio and the percentage reduction in pressure.

Solution:

- **Given:**

Initial pressure $P_1 = 1\ \text{atm}$

Final pressure $P_2 = 0.01\ \text{atm}$

- **Pressure ratio:**

$$\text{Pressure Ratio} = \frac{P_2}{P_1} = \frac{0.01}{1} = 0.01$$

- **Percentage reduction in pressure:**

$$\text{Percentage reduction} = \left(\frac{P_1 - P_2}{P_1}\right) \times 100 = \left(\frac{1 - 0.01}{1}\right) \times 100 = 99\%$$

Chapter 2: Processes for separating and purifying cryogenic fluids

Exercise:

- **Question:** In the process of air separation, the liquid air has a temperature of 77 K. If the boiling point of oxygen is 90.2 K and nitrogen is 77.4 K, calculate the temperature difference between liquid air and oxygen and nitrogen.

Solution:

- **Given:**

Temperature of liquid air $T_{\text{air}} = 77\ \text{K}$

Boiling point of oxygen $T_{\text{O}_2} = 90.2\ \text{K}$

Boiling point of nitrogen $T_{\text{N}_2} = 77.4\ \text{K}$

- **Temperature difference between liquid air and oxygen:**

$$\Delta T_{O_2} = T_{air} - T_{O_2} = 77 - 90.2 = -13.2\ \mathrm{K}$$

- **Temperature difference between liquid air and nitrogen:**

$$\Delta T_{N_2} = T_{air} - T_{N_2} = 77 - 77.4 = -0.4\ \mathrm{K}$$

Chapter 3: Permanent gas liquefaction processes

Exercise:

- **Question:** In the Linde-Hampson liquefaction process, if 1 mole of gas is compressed to 5 times its original volume and then expanded through a valve, calculate the temperature change (ΔT) assuming the process follows the ideal gas law and the Joule-Thomson coefficient (μ) is 0.5 K·L·atm/mol.

Solution:

- **Given:**

Initial volume $V_1 = 1$ L

Final volume $V_2 = 5$ L

Initial pressure $P_1 = 1$ atm

Joule-Thomson coefficient $\mu = 0.5$ K\cdotpL\cdotpatm/mol

- **Assumption:** Ideal gas behavior (PV = nRT).

Step 1: Calculate the temperature change using the Joule-Thomson effect:
The Joule-Thomson temperature change (ΔT) can be approximated as:

$$\Delta T = \mu \cdot \left(\frac{P_2}{V_2} - \frac{P_1}{V_1}\right)$$

However, since this process assumes an ideal gas and is isenthalpic (no heat exchange), for simplicity, we can estimate the temperature change:

For ideal gas processes, the temperature change during expansion can be estimated using:

$$\Delta T \approx \mu \cdot (V_2 - V_1)$$

Substituting values :

$$\boldsymbol{\Delta T \approx 0.5 \cdot (5 - 1) = 0.5 \cdot 4 = 2\,\mathrm{K}}$$

Chapter 4: Cryogenic applications

Exercise:

- **Question:** A superconducting magnet requires cooling to 4.2 K using liquid helium. If the specific heat capacity of helium at this temperature is $C_p = 0.2$ J/g\cdotpK, and the magnet has a mass of 500 g, calculate the amount of heat required to raise the temperature of the magnet from 4.2 K to 10 K.

Solution:

- **Given:**

  Mass of the magnet $m = 500$ g

  Specific heat capacity $C_p = 0.2$ J/g\cdotpK

  Temperature change $\Delta T = 10 - 4.2 = 5.8$ K

- **Calculate the heat required:**
  The formula for heat required is:

$$Q = m \cdot C_p \cdot \Delta T$$

Substituting the given values:

$$Q = 500\,\mathrm{g} \cdot 0.2\,\mathrm{J/g\backslash cdotpK} \cdot 5.8\,\mathrm{K}$$
$$\boldsymbol{Q = 500 \cdot 0.2 \cdot 5.8 = 580\,\mathrm{J}}$$