K14. Vacuum Technology and Triple Point of Nitrogen

I. OBJECTIVE OF THE EXPERIMENT

Determine the effective throughput (pumping kinetics) and the limiting pressure of a vane pump and a diffusion pump.
Study the temperature-pressure diagram of nitrogen, in particular the triple point.

II. PHENOMENOLOGY

II.1. VACUUM TECHNOLOGY

When installing a vacuum pump, two fundamental parameters come into play. The work pressure, which is not to be confused with the limiting pressure, and the time required to reach it. These two parameters depend on the pump, and the vacuum chamber. In the SI unit system, the unit for pressure is the *Pascal* ($1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$), but we often use the $\mathrm{mbar} = 100\ \mathrm{Pa}$ or the Torr i.e. mm de Hg $= 133.322\ \mathrm{Pa}$.

Limiting pressure

The limiting pressure that can be reached in a vacuum setup is given by the equilibrium between the pumping throughput and the leakage and outgassing of the walls. The equipment must be kept as clean as possible, and most importantly remain dry. Condensable vapor leaves the system through outgassing, after heating the walls by a few hundred degrees. Nitrogen traps can be placed between the gas source and the vacuum chamber as another means of purification.

Pumping speed

The pumping speed (volumetric throughput) through a surface is defined by the volume of gas that crosses it per unit time. The volume is measured according to the pressure of the surface. The pumping rate depends on the type of the pump (vane, diffusion, etc.) on the used liquid (silicone oil) and also the pressure. When designing a vacuum setup, always choose a pumping group with a speed well above that which would maintain the desired limit pressure.

Pump sizing

The effective throughput of a pump *S* can be determined form pumping dynamics. During the pumping process, the pressure inside a chamber of volume *V* evolves according to:

$$\frac{dP}{dt} = -\frac{S(P)}{V}\left(P - P_0\right)$$

where P_0 is the limiting pressure of the pump. In the region where the S can be supposed constant, we can integrate this equation, yielding:

$$\ln\left(\frac{P_2 - P_0}{P_1 - P_0}\right) = -\frac{S}{V}t$$

In this equation, t represents the amount of time required to get from a pressure P_1 to a lower pressure P_2.

II.2. STATES OF MATTER

Matter is made of different particle: atoms, molecules, ions, etc. These particles are subject to thermal agitation, and their speed depend on temperature. These particles interact with one another, and the forces determine the macroscopic aspect of matter: we call these different aspect phases (solid, liquid, gaseous). We also call phase any homogeneous part of a material that has the same physical and chemical properties. Examples:

- A homogeneous mixture of O_2 and N_2 represents a single gaseous phase
- a mixture of water and ice, i.e. the mixture of two chemically identical but physically distinct bodies represents two phases.

The interaction forces between particles depend on the temperature, the pressure and the volume that represent the thermodynamic variables of matter.

Phase changes

FUSION-SOLIDIFICATION

Bodies of crystalline form switch from the solid phase to the liquid phase or conversely in very specific conditions. If we supply heat to the body, it’s temperature rises until it starts switching to the liquid phase. We call this the fusion process. At that point, the temperature remains constant and the energy supplied in the form of heat is consumed by the work necessary to beat the cohesion forces of the solid (Fig. 1). The amount of work required to melt a unit of mass of a pure body at the fusion temperature, is called latent heat. The inverse process is called solidification. The solidification of a liquid generally includes a volume change. For most liquids, the volume decreases when solidifying. Therefore, an increased pressure increases the fusion temperature. However, certain liquids (water, bismuth) and certain alloys expand in volume when solidifying (ice floats in water). Therefore, an increase in pressure reduces their fusion point.

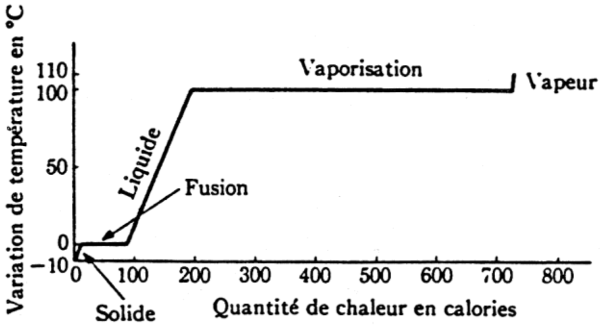


Figure 1: Amount of heat required to transform $1\,\mathrm{g}$ of ice at $-10\ ^\circ\mathrm{C}$ into vapor at $100\ ^\circ\mathrm{C}$.

EVAPORATION-CONDENSATION

If we place a liquid in a vase, it reaches an equilibrium state. The molecules continually leave the surface to become vapor molecules. This is called evaporation. On the other hand, the vapor molecules constantly hit the surface of the liquid and penetrate it. When the amount of particles exiting the water is equal to the amount entering it, we call the vapor saturated. The pressure of the saturated vapor is called saturation pressure. It is defined by the substance and the temperature. Evaporation is a cooling process, since it is the more energetic molecules leave the liquid. A fast evaporation can freeze the rest of the liquid.

The energy supplied to the system in the form of heat produces, on the one had the work required to beat the intermolecular forces of part of the liquid, and on the other hand the work due to the volume increase. The latent heat of vaporization for a liquid at a given temperature is the amount of heat required to vaporize a unit mass of the liquid at that temperature and at the equilibrium pressure. The latent heat of vaporization depends on the temperature: it decreases temperature increases. At a certain critical point (see below), the latent heat of vaporization vanishes.

When heating a liquid-vapor mixture in a closed body, we can see that the liquid-vapor limit disappears at a given time. The temperature at which this phenomenon appears is called the critical point. While the gas is being heated, the density of the liquid decrease, and the density of the gas increases, until they are both equal. Above this temperature, the liquid can't exist, under any pressure. To liquefy a gas, it is necessary to increase the pressure, but simultaneously reduce the temperature. A phase sunder the critical temperature is called vapor, above, it is called gas.

HUMIDITY

At any given time, water is present in the atmosphere under one or several different phases (solid, liquid, vapor). Invisible vapors are always present in large or small quantities. The quantity of vapor required for the saturation depends on the temperature. If the air isn't saturated, we can saturate it either by adding vapor or reducing the temperature. The temperature at which the air must be cooled to produce this saturation is called the dew point. The condensation of water will only occur if there are impurities on which the condensation can form. These can be small salt crystals, smoke particles, etc.

The absolute humidity represents the mass of water vapor per unit volume in the air. Relative humidity is defined by the ratio of the vapor pressure to the saturating vapor pressure at that pressure (Fig. 2). It's generally expressed as a percentage. It's one of the most important parameters of meteorology. When the dew point is over the freezing point, small water droplets form. When it is under the the freezing point, ice crystals form instead. Frost, clouds and fog are examples of this. Physicists use the phase change to visualize certain nuclear phenomena. The device that is used is called Wilson chamber, or fog chamber. A cylinder containing saturated vapors is closed by a piston or by a diaphragm. When increasing the volume by pulling the piston, the gas cools, and the saturated vapors condense on the ions formed by ionizing particles.

SUBLIMATION

Sublimation is the direct transformation from the solid state to the gaseous state, without going through the liquid state. This is through which laundry that is hung to dry in the winter can freeze and still dry. Solid CO_2 sublimates into gas, without humidifying the walls of its container. The smell of camphor or naphthalene at room temperature proves that they sublimate.

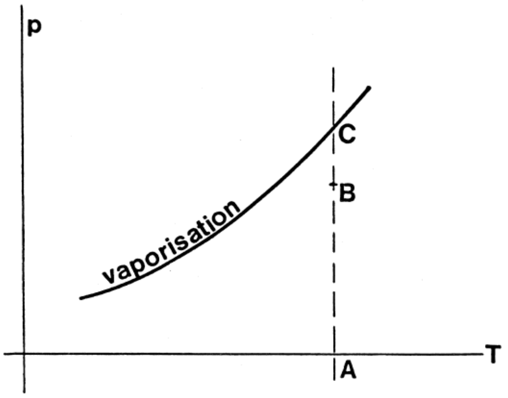


Figure 2: AB Vapor pressure at temperature A
AC Saturating vapor pressure at temperature A
AB/AC relative humidity. A

TRIPLE POINT

The three phases of a body can coexist at a temperature and pressure that are the coordinates of the triple point on a (T, p) diagram. At this point, the three curves join (vaporization, fusion and sublimation). The vaporization curve can be extended under the triple point, which indicates a supercooled state. These points of the curve represent metastable equilibrium states. The vaporization curve of the supercooled liquid is always above the sublimation curve. For instance, water and ice have the same vapor tension (4.58 Torr) at the triple point ($T_T = 0.0096\ °\mathrm{C}$), but at $-10\ °\mathrm{C}$ the vapor tension is 2.15 Torr for supercooled water and 1.95 Torr for ice.

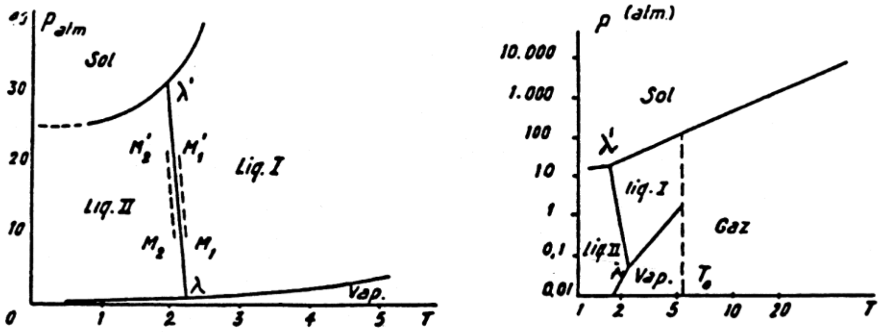


Figure 3: Helium at low temperature

LIQUID HELIUM

At low temperature, helium has a very specific behavior. It has no triple point in the general sense of the term. At very low temperatures and pressures, the liquid phase is more stable than the gaseous phase. There exist two liquid phases He_1 stable at rather high temperatures, and He_2 stable at very low temperatures. There is an equilibrium curve between both liquids (Fig. 3).

At the triple point λ ($T = 2.2\ \mathrm{K}$; $p = 3.9$ Torr) the two liquids and the vapor coexist. At the point λ' ($T = 1.75\ \mathrm{K}$; $p = 30\ \mathrm{atm}$) the two liquids and the solid coexist.

The liquid He_1 is very mobile and volatile. Its vaporization heat is only of 5 calories. The He_2 liquid has very strange properties: it's extremely mobile and 200 more heat conductive than copper. The transformation of He_1 into He_2 occurs with ni volume change or latent heat exchange. The internal energy doesn't change. However, under constant, pressure, we observe a discontinuous specific heat.

All the processes caused by the variation of the three thermodynamic variables, i.e. T , V and p can be illustrated in the three dimensional space and its projection on the planes (p,V) , (p,T) , (V,T) .

The figure 4 represents the (V,T,p) space as well as the projections on the aforementioned spaces

The curves contained in the T,p plane correspond to the isochoric processes (at constant volume), those of the V,T plane are isochoric (at constant pressure) and those of the V,p are isothermal (constant temperature). The separation surfaces in the (V,T,p) space are intersected by the planes $V=cst, T=cst, p=cst$ according to the corresponding projection lines.

The slope $\frac{dp}{dt}$ at any boundary between two phases i and j is given by the Clausius-Clapeyron equation and is connected to the latent heat $L_{i,j}$:

$$\frac{dp}{dt}=\frac{L_{i,j}}{T\Delta V_{i,j}} \tag{1}$$

where $\Delta V_{i,j}=V_j-V_i$ represents the volume difference of the considered body in both phases I and j. The latent heat $L_{i,j}$ is defined as the heat required to transform one unit of phase i into the phase j at equilibrium (i.e. slowly) and constant temperature. If V is indicated in m^3/mole, $L_{i,j}$ will be in J/mole.

Please note that we are working at constant volume, i.e. $V=V_j+V_i=cst$.

The released or absorbed heat of a body is therefore not only used for temperature variations, but also for separating particle when the body transforms from one phase to another. Let's mention water, as an example

- in order to increase the temperature of 1g of ice from $-1\ ^\circ\mathrm{C}$ to $0\ ^\circ\mathrm{C}$, we need 1 calorie.
- the fusion of one gram of ice requires 80 calories, though the temperature doesn't change during the whole process.

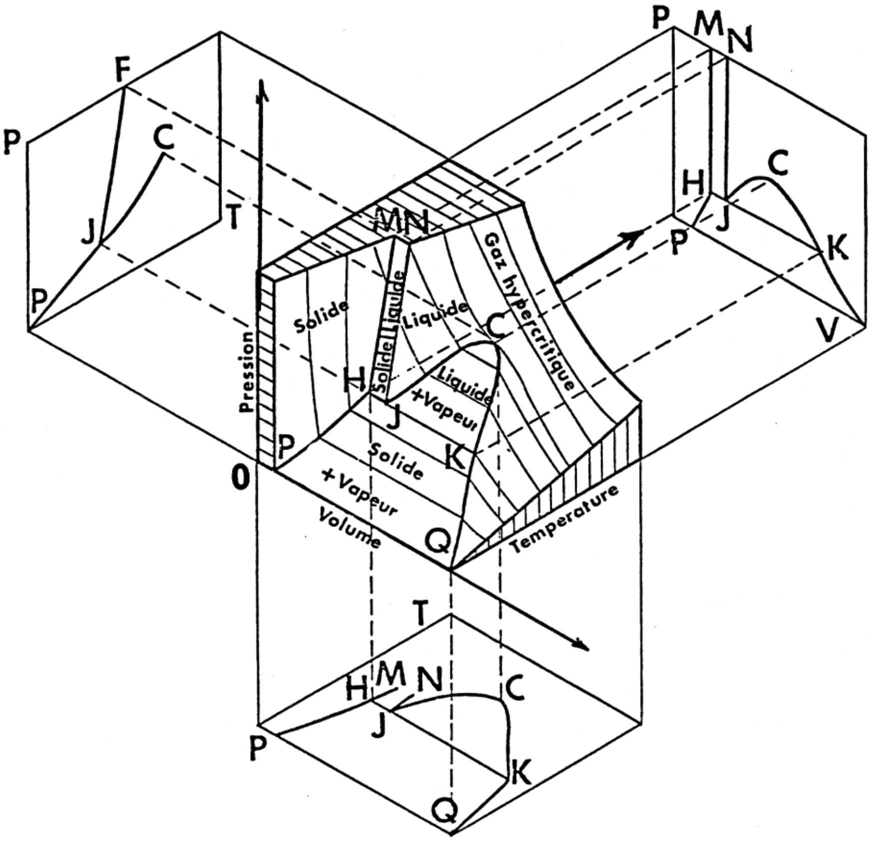


Figure 4: Volume, temperature and pressure space

The three curves of sublimation, vaporization and fusion have one single intersection: the triple point for which the three phases coexist in equilibrium (Fig. 5).

The determination of the triple point can be achieved from the knowledge of at least two of these three curves of phase change. For most materials, the triple point is located at low temperatures and pressures. To determine this, it is then necessary to reduce the pressure and temperature in a sealed container, which can be done simultaneously by means of a vacuum pump. The fundamental question that arises is to know starting what pressure is it possible to have temperatures lower than the triple point. We are therefore faced with the problem of obtaining a pressure $p_{\min}$ low enough to lower the temperature below the triple point.

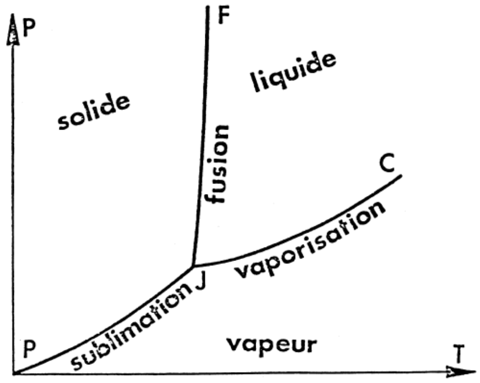


Figure 5: p-T diagram

PUMPING ON A LIQUID PHASE

When immersed in a thermally isolated Dewar, a liquid keeps it's own temperature T. However, if the isolation isn't perfect, there will be a heat exchange of Q' Joules/s with the outside. If, by using a vacuum pump, we reduce the pressure vaporization pressure of the liquid, we will generate an excess of vaporization, which will require a latent heat Q'' every second. The difference $Q''-\mathrm{Q}'$ must come from the liquid, therefore, it is cooled, solidified, and continues to be cooled. The vacuum however, is limited to a minium pressure p_{min}, that depends on the characteristics of the pump. The amount of moles of vapor exchanges with is outside is equal to the number of moles μ of substance sublimated every second by the incoming heat Q:

$$\mu = \frac{Q}{L_S} \tag{2}$$

where L_S is the sublimation heat of the solid. The ideal gas equation can be applied here, and allow us to calculate the corresponding vapor volume V_S:

$$V_S = \mu \frac{RT}{p_{\mathrm{min}}} \tag{3}$$

i.e.: $$p_{\mathrm{min}} = \mu R \frac{T_S}{V_S} \tag{4}$$

In order to calculate the solid's minimal temperature T_{min} when in equilibrium with the vapor pressure p_{min}, we start from the Clausius-Clapeyron equation. The volume of the solid being negligible with respect to the vapor, we can replace: $\Delta V_{i,j}$ with $\frac{RT_{\mathrm{min}}}{p_{\mathrm{min}}}$ whence:

$$\frac{dp}{p} = \frac{L_S}{R}\frac{dT}{T^2} \tag{5}$$

, L_S is supposed independent of temperature.

After integration:

$$\log p + \log C = -\frac{L_S}{RT} \tag{6}$$

In order to determine the integration constant C, let's write equation (6) for two different equilibrium conditions, e.g. T_0 (triple point with pressure p_0) and T_{min} (sublimation temperature at minimum pressure p_{min}):

$$\begin{gathered} -\frac{R}{L_S}\left(\log p_0 + \log \mathrm{C}\right) = \frac{1}{T_0} \\ -\frac{R}{L_S}\left(\log p_{\mathrm{min}} + \log \mathrm{C}\right) = \frac{1}{T_{\mathrm{min}}} \end{gathered} \tag{7}$$

Subtracting the first equation from the second yields:

$$-\frac{R}{L_S}\left(\log p_{\min}+\log p_0\right)=\frac{1}{T_{\min}}-\frac{1}{T_0}$$

which leads to:

$$T_{\min}=\left(\frac{1}{T_0}-\frac{R}{L_S}\log\frac{p_{\min}}{p_0}\right)^{-1} \tag{8}$$

III. EXPERIMENTAL SETUP

III.1. VACUUM CHAMBER.

The elements that make up a vacuum setup are, in addition to the pumps and pressure gauges, the junction pieces, joints, valves, separating units, and traps (fig. 6). The most used materials are metal (aluminum or stainless steel), glass, quartz, ceramic, rubber and plastic.

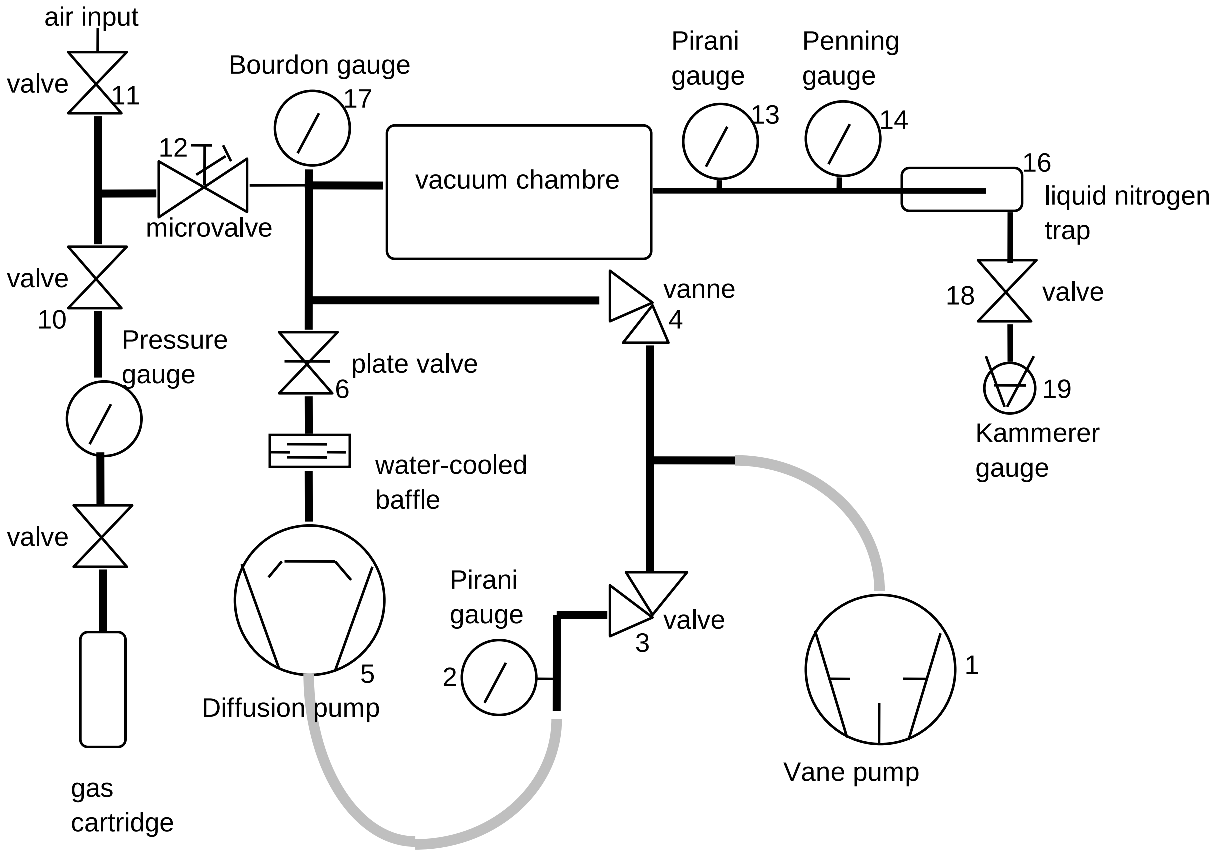


Figure 6: Diagram of the high vacuum setup. The numbering correspond to that on location.

III.2. TRIPLE POINT

Figure 7 shows a diagram of the setup and Figure 8 a photo.

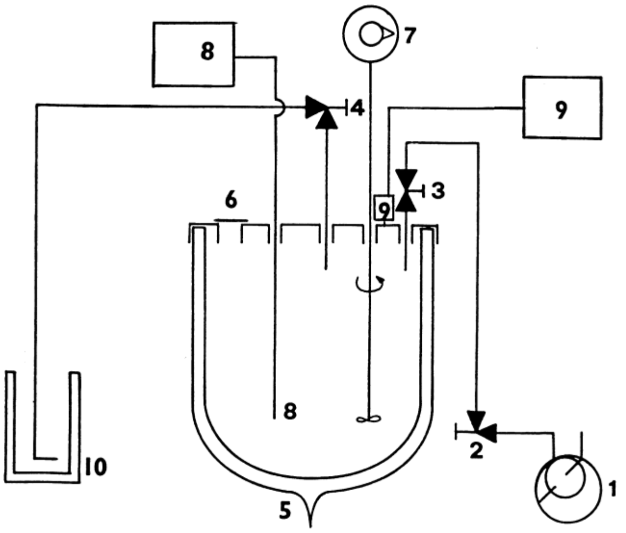


Figure 7: Experimental setup diagram
1: Vane pump
2: Derivation valve
3: Entrance valve in the main Dewar
4: Entrance valve of the cold nitrogen
5: Main Dewar
6: Lid of the main Dewar
7: Control button of the agitator
8: Thermal probe
9: Pressure gauge
10: Dewar containing liquid nitrogen at atmospheric pressure

Measurng temperature and pressure

In order to determine the three curves (sublimation, fusion and vaporization), and their intersection on a (T, p) diagram, we need two main conditions:

1) The indicated values must be instantaneous (no measurement inertia)

2) The two indications must be simultaneous (we need values of T, p at the same moment)

We will use an electronic pressure gauge to measure the and a platinum probe to measure the temperature.

For the values of temperature to be exact, we need a good thermal contact between the probe and the measured body, which isn't the case for solid nitrogen, since it's porous. The probe has been perfected to best satisfy this condition.

Spotting the tripple point

The method consists in performing manipulations that maintain the presence of several phases simultaneously, after a cooling process. By using this method, we will eventually reach the triple point, and stay there long enough to verify that the temperature T_j and corresponding pressure p_j remain constant.

IV. REQUIRED EXPERIMENTS

VACUUM TECHNOLOGY

1) Measure the **primary pumping kinetics** when the vacuum chamber of volume V is emptied. Determine from this the effective throughput S, and the limiting pressure of the vane pump. The vacuum happens very quickly. You may want to film the pressure gauge, and then match the indicated pressure of a given frame to the corresponding time of the video.

2) Measure the **secondary pumping kinetics**, using the diffusion pump. Determine the pumping speed, as well as the limiting pressure of the diffusion pump.

Procedure:

The hot oil of the diffusion pump must never come in contact with that atmosphere at a pressure exceeding 0.01 Torr. Therefore, proceed as follows:

a) Empty out the vacuum chamber until approximately 0.01Torr using the rotary vane pump.
b) Pump out the diffusion pump until it reaches approximately 0.01 Torr.
c) Start the diffusion pump, while making sure to keep the vane pump running “behind” it. The vane pump serves as an outgassing pump for the oil. After approx. 15 min. The diffusion pump reaches its working pressure.
d) If the pressure inside the chamber is less than 0.01Torr, then we can open the plate valve, and the pressure quickly drops from 0.01Torr to $10^{-3}, 10^{-4}$ Torr.

e) Starting at 10^{-2} Torr, turn on the Penning gauge, and write down the pressure as a function of time, until reaching the limiting pressure. Plot the corresponding curve, and determine the corresponding pumping throughput.

Stopping the diffusion pump
Close the plate valve. Turn off the diffusion pump and the Penning gauge.
After MINIMUM 20 minutes, close all the valves leading to the vane pump, before turning it off. Turn off the Pirani gauge, and the main power supply.

Using the microvalve
When the microvalve is correctly closed, the button can turn freely. **NEVER FORCEFULLY TRY TO CLOSE THE VALVE by screwing it passed the free rotation.**

TRIPLE POINT OF NITROGEN

Before doing anything, make sure you have gone through all of the tips below:

- Liquid nitrogen under 1 atm boils at $-195.8\ ^\circ\mathrm{C}$. Any contact will cause sever burns
- Try to avoid gas exchang between the Dewar and the atmosphere, to avoid the formation of frost in the Dewar.
- The optimal fill level of the main Dewar is indicated by the red line.
- Avoid letting the vane pump work on the atmosphere, i.e. with an open valve. The pump heats up.
- <u>When turning off the pump, immediately introduce atmospheric pressure into it, by opening the valve 2</u> (lever pointing right) without letting oil reach the valve.
- Never let the agitator run when the nitrogen is solid.
- When in presence of small crystals in the liquid, reduce the speed of the agitator
- When in presence of liquid only, the maximal speed of the joint should be the graduation “4” on the potentiometer

1) Pump the liquid nitrogen until reaching a partial evaporation, which will cool the rest of the liquid. After a few minutes, we notice that a solid phase appears. Keep pumping until reaching approx. 10 Torr.

2) Close valve (3) (lever pointing up). Stop pumping, and write down the measurements for (T, p), as the nitrogen gets warmer

3) Using these measurements, plot $p = p(T)$ at constant volume, you should get three branches (PJ, FJ, JC). We should notice four different stages during this process:
   - simultaneous increase of T and p (sublimation curve)
   - constant T and p (triple point)
   - approximate constant value of T and increase in p (fusion curve)

   To obtain the vaporization curve, stop pumping just before formation of a solid phase and trace the increase of T and p.

4) Repeat steps 1 through 3 at least once.

5) Solidify the nitrogen (down to approx. 10 Torr), and close the valve (3). After having filled the Dewar (10) with liquid nitrogen, let nitrogen into the system using the valve (4). What phenomenon can you observe? How can you explain this?

6) Knowing the parameter of the pump, use equation (8) to calculate the minimal temperature that can be reached.

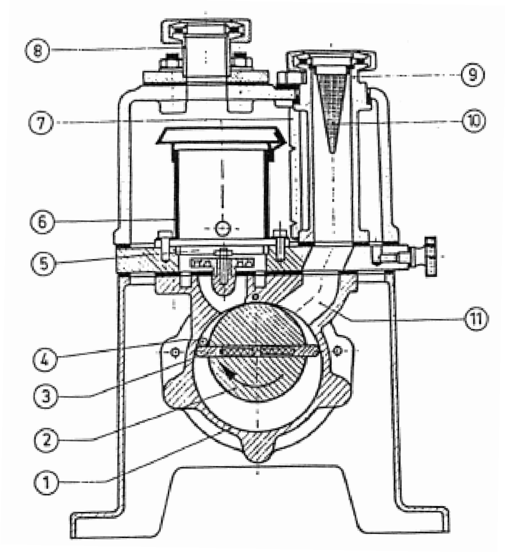
Fig. 8 : Image of the experimental setup.

ANNEX

VACUUM PUMPS

Rotary vane pumps

A vane pump (fig. 9) consists of a hollow cylinder (1) in which an uncentered rotor (2) containing vanes (3) is rotated. The vanes are constantly pressed against the cylinder walls, thus sucking air from one side of the pump (11) and pushing it through the exhaust valve (5) on the other side. The rotor is off center, so that the volume of gas trapped by two vanes is variable. This allows the air to be compressed when arriving towards valve, which ensures that there will always be enough pressure to lift it. Many parts of the system are covered in oil. The oil simultaneously acts as a lubricant and covers up the remaining gaps.



1. Cylindrical pumping body
2. Uncentered rotor
3. Vanes
4. Gas Ballast entry
5. Oil covered exhaust valve
6. Oil deflectors
7. Oil gauge
8. Exhaust tubing
9. Entrance tubing
10. Impurity trap
11. Suction canal

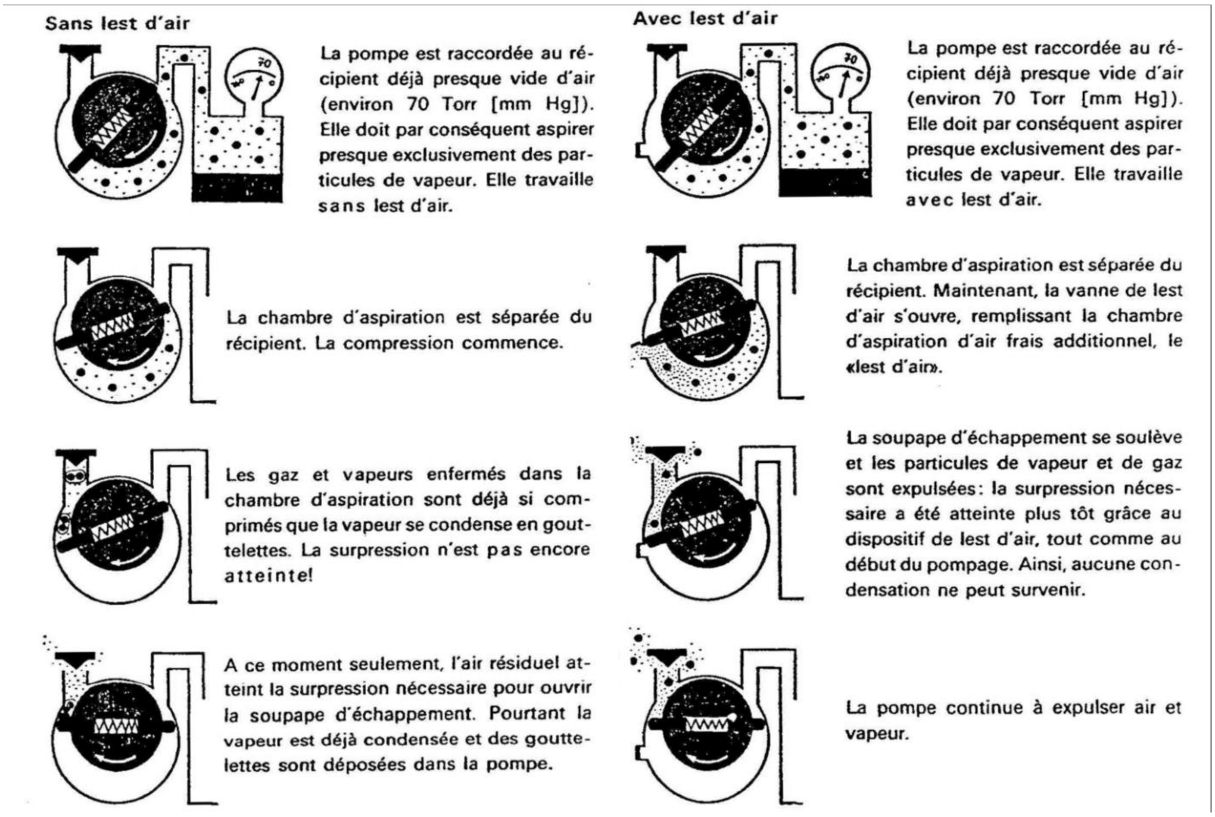
Figure 9: Sectional view of a rotary vane pump

Gas Ballast

The gas ballast allows for vane pumps to not only pump gas, but also large quantities of condensable vapor. When a vane pump is used at low pressures, of the order of 10^{-2} Torr, the compression rate reaches $\sim 10^5$ (i.e. $760/10^{-2}$). If the pump absorbs vapor, it could be compressed passed its saturation pressure. For instance, if the pump is at $70\ ^\circ\mathrm{C}$ and absorbs water vapor, the vapor can only be compressed up to 250 Torr (saturation pressure of water at $70\ ^\circ\mathrm{C}$). If we continue compressing the water vapor, it will condense into droplets, without increasing the pressure. The exhaust valve doesn't open, and the water stays in the system, where it will create an emulsion with the oil, and deteriorate its lubricating properties.

The gas ballast stops water vapor from condensing (fig. 10). Before the compression starts, a well dosed amount of air is injected into the suction chamber, in order to lower the compression rate (up to $10/1$). The vapor that get sucked into the system can now be compressed with the extra gas, and will open the exhaust valve before condensing.

When starting the pumping process, the gas ballast must always be open. The small layer of water that almost always covers the walls of a vacuum chamber evaporate progressively when starting the pumping. It is only once this vapor has been completely eliminated (after 1 to 2 min), that we can close the gas ballast in order to reach the desired low pressures.



Sans lest d'air

La pompe est raccordée au récipient déjà presque vide d'air (environ 70 Torr [mm Hg]). Elle doit par conséquent aspirer presque exclusivement des particules de vapeur. Elle travaille sans lest d'air.

La chambre d'aspiration est séparée du récipient. La compression commence.

Les gaz et vapeurs enfermés dans la chambre d'aspiration sont déjà si comprimés que la vapeur se condense en gouttelettes. La surpression n'est pas encore atteinte!

A ce moment seulement, l'air résiduel atteint la surpression nécessaire pour ouvrir la soupape d'échappement. Pourtant la vapeur est déjà condensée et des gouttelettes sont déposées dans la pompe.

Avec lest d'air

La pompe est raccordée au récipient déjà presque vide d'air (environ 70 Torr [mm Hg]). Elle doit par conséquent aspirer presque exclusivement des particules de vapeur. Elle travaille avec lest d'air.

La chambre d'aspiration est séparée du récipient. Maintenant, la vanne de lest d'air s'ouvre, remplissant la chambre d'aspiration d'air frais additionnel, le «lest d'air».

La soupape d'échappement se soulève et les particules de vapeur et de gaz sont expulsées: la surpression nécessaire a été atteinte plus tôt grâce au dispositif de lest d'air, tout comme au début du pompage. Ainsi, aucune condensation ne peut survenir.

La pompe continue à expulser air et vapeur.

Figure 10 : Pumping cycle with and without gas ballast

Fluid pumps

Fluid pumps are all based on the same principle: the gas to be evacuated is transported from a low pressure region to a higher pressure region using a high pressure jet of steam (oil, mercury, water, …). The steam never leaves the pump, since it is condensed as soon as is hits the cooled walls of the pump.

Gaede was the first to notice that a relatively low gas pressure could be sucked into a jet of steam at a much higher pressure, so that the gas molecules were transported from a low pressure area to a higher pressure area. This seemingly paradoxical phenomenon is due to the fact that the steam is first completely gas-free, so that the gases diffuse from an area where there is a gas of high partial pressure (container) to an area where the partial pressure of the gas is lower (the steam). You can consider the steam as a semi-permeable membrane (similar to the osmosis phenomenon), through which the gas can diffuse to enter but not to leave, the partial pressure of the gas is therefore much higher on one side of the jet than on the other.

Diffusion pumps ($<10^3$ Torr)

Diffusion pumps (fig. 11) are made of a pumping body (1), in which the bottom can be heated, and the sides cooled, and an internal body with several stories (generally three) (2). The motor fluid kept in the heating tank (5), is heated and vaporized electrically. The vapor rises in the column (4) and leaves through the nozzle (3) at a supersonic speed. The fluid then condenses on the water cooled walls, and drips back into the heating tank. The pumped gas is absorbed by the oil, and leaves through the exhaust tube.

For oil diffusion pumps, it is necessary to outgas and fractionate the oil before letting it back into the heating tank (5).

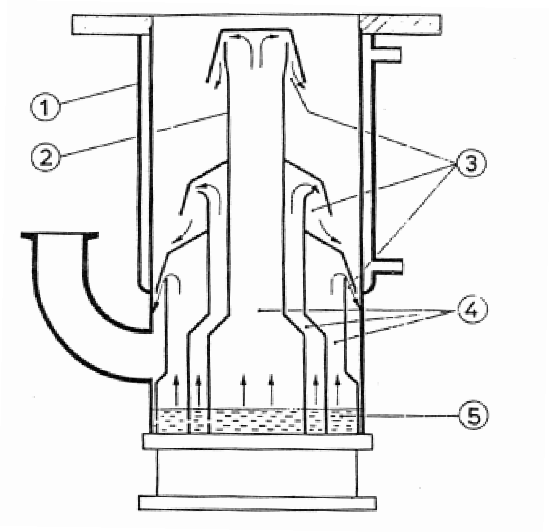


Figure 11: Diffusion pump diagram.(1) Pumping body, (2) Internal body, (3) Nozzles, (4) Steam rising tube, (5) Heating tank.

Outgassing: The condensed motor fluid drips along the walls is brought under the heat tank, at a temperature of approximately $130\ ^\circ\mathrm{C}$, at which point the more volatile molecules are absorbed by the *primary pump*. The less volatile molecules however, remain in the fluid.

Fractionating oil: After being outgassed, the motor fluid is made up of elements varying in weight. The fractionating equipment makes sure the elements easiest to evaporate are brought to the first nozzle, close to the primary vacuum, and the elements hardest to evaporate are brought to the third nozzle, close to the molecular vacuum.

Stopping oil molecules: Most of the time, we place a cold trap between the diffusion pump and the vacuum chamber, to stop the oil molecules from leaving the pump.

PRESSURE GAUGES: MEASURING PRESSURE

To this day, the region of measurable pressures ranges from 760 Torr to 10^{-13}Torr, over 16 decimal points. In order to measure pressures in such a large region, we use instruments called pressure gauges. Since no physical object is capable of measuring pressures over this whole range, we resorted to designing a whole family of pressure gauges that are used for measuring pressures in different ranges, each of which spreads over a few decimal points.

Mechanical pressure gauges: the mechanical energy is either supplied by the gas whose pressure we wish to determine (e.g. membrane gauge, U-pressure gauge) or by and external source of work (compression gauges, e.g. Kammerer gauge).

Electrical pressure gauges: The electrical energy is either transformed into heat, on which we then base our measure (e.g. thermal conductivity gauge, Pirani gauge) or used to ionize the gas (e.g. ionization gauge, Penning Gauge)

Bourdon gauge

The pressure gauge is mainly made of a curved tube, closed off at one end, whose other end is connected chamber whose pressure we would like to determine (fig. 12).

As the pressure P reduces with respect to the atmospheric pressure P_{atm}, the radius of the tube decreases (easy to prove). This motion is then amplified and calibrated by connecting the tube to a needle. Since the tube deforms elastically, the scale is linear.

The measured pressure varies with the atmospheric pressure, but does not depend on the type of gas contained in the chamber.

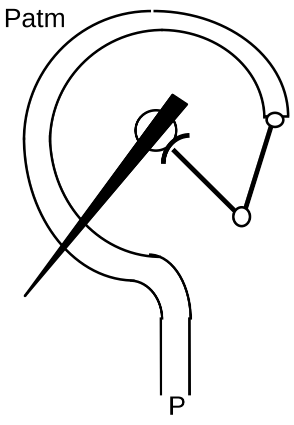


Figure 12: Bourdon gauge

Pirani gauge

This gauge uses the thermal exchange between a hot wire and the gas (fig. 13). The heat exchange depends on the pressure, but also on the type of gas. The temperature of the wire is determined according to its resistance. The wire is connected to a compensating voltage via a Wheatstone bridge. This is a simple and solid gauge when the required precision isn't too high. The main disadvantages of the Pirani gauge are that it must be recalibrated for each gas, and is only useful for a limited range of pressure ($10^1 - 10^{-3}$ Torr).

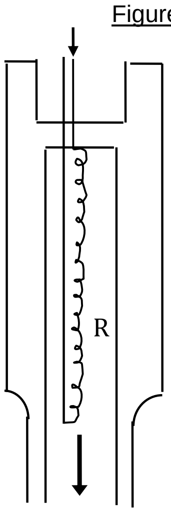


Figure 13 : Pirani gauge

Penning gauge

This gauge uses the ionization of the gas between two electrode (fig. 14) to determine the pressure. The current that travels through the discharge gauge varies as a function of the pressure. In this gauge, the path of the electrons is increased using a permanent magnetic field, which extends the range of measureable pressure

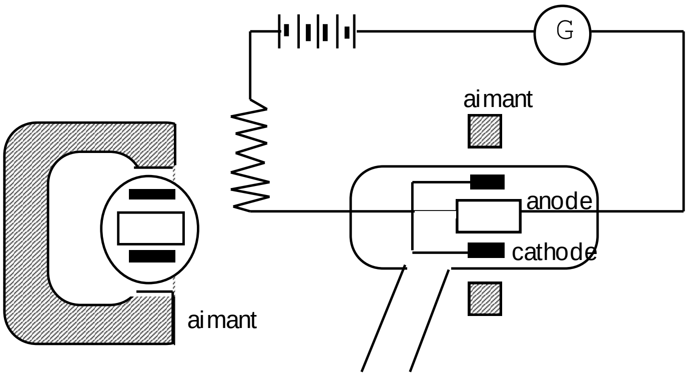


Figure 14 : Penning gauge

The usable pressure range of the Penning gauge is $10^{-2} - 10^{-7}$ Torr. These instruments are robust, insensitive to air and vibrations, but is pretty imprecise when the cathode is cold. The precision doesn't exceed 20 %. This gauge needs to be recalibrated for each gas.