University of Bologna

Faculty of Engineering

Mechanical Engineering Department

TYRES INFLATION WITH DE-OXIGENATED AIR

ABSTRACT : CHAPTERS III AND IV

Degree thesis by :
Luca Sabino

Supervisor :
Ph.D. Giovanni Naldi
Ph.D. Piero Pelloni

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CHAPTER III

INFLATION WITH DE-OXYGENATED AIR

3.1 GENERAL NOTIONS

In the previous chapters we demonstrated the importance of correct inflation to ensure the performance specifications for the tyre, such as high contact friction (for effective road holding, good handling and acceleration and short stopping distance), low fuel consumption, low and even wear, etc.

This chapter will show that a tyre inflated with de-oxygenated air loses pressure at half the speed of a tyre inflated with air.

3.2 INFLATION WITH DE-OXYGENATED AIR

To treat the problem analytically, we must make a few simplifying assumptions:

- The de-oxygenated air is assumed to contain only molecular nitrogen (N_2)[1];
- The diffusion of oxygen is assumed to be equal to that of nitrogen (that is, $D_{O_2} \cong D_{N_2}$);
- The casing material is composed of *poly-isoprene*;
- The permeability of the gases (oxygen and nitrogen) in poly-isoprene given in the tables has been measured at 25°C.
- In studying the problem we make use of a simplified geometry (see figure *3.2.1*).

If we define p_{i1} to be the pressure at the casing/interior boundary, p_{i2} that at the casing/atmosphere boundary, P_i the permeability, l the casing thickness and $\dot{n}''$ the flux of gas through the casing per unit of time and surface area, we have:

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[1] As will be shown in chapter IV, de-oxygenated air is indeed very largely composed of nitrogen (approx. 99 % nitrogen, 1 % other gases).

$$\dot{n}'' = P_i \frac{p_{i_1} - p_{i_2}}{l} . \qquad \text{(eq.1)}$$

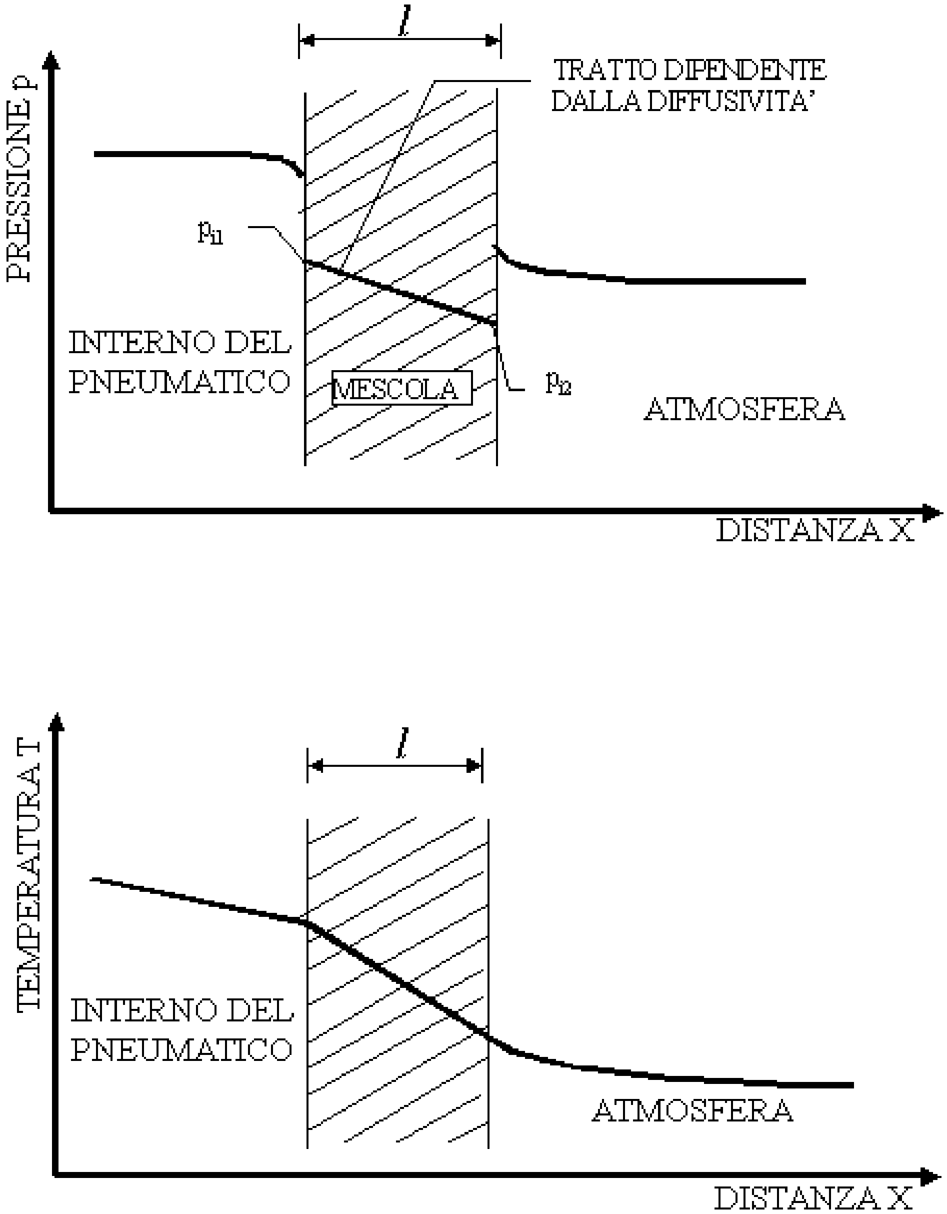

fig.2.1: Pressure p [Pa] and temperature T [°C]

PRESSIONE = PRESSURE
TEMPERATURA = TEMPERATURE
INTERNO DEL PNEUMATICO = TYRE INTERIOR
ATMOSFERA = ATMOSPHERE
MESCOLA = CASING MATERIAL

TRATTO DIPENDENTE DALLA DIFFUSIVITA' = SECTION AFFECTED BY DIFFUSION
DISTANZA = DISTANCE

From the tables, the permeability to oxygen is:

$$P_{O_2} = 4.6 \cdot 10^{-13} \frac{cm^3 (STP) \cdot cm}{cm^2 \cdot s \cdot Pa},$$

where *(STP)* signifies *standard temperature and pressure*, while for nitrogen we have:

$$P_{N_2} = 1.6 \cdot 10^{-13} \frac{cm^3 (STP) \cdot cm}{cm^2 \cdot s \cdot Pa}.$$

If we now call the total internal pressure $p_{tot_{\mathrm{int}}}$, the outer (atmospheric) pressure p_{ext}, and assuming that the tyre is inflated with de-oxygenated air and that the casing thickness is constant and equal to *l* = 1 *cm*, we obtain:

TYRE INTERIOR:	$p_{TOT\ int} = 3\ bar = 3 \cdot 10^5\ Pa$; $N_2 = 100\ \% = 1$;
EXTERIOR (ATMOSPHERE):	$p_{ext} = 1\ bar = 1 \cdot 10^5\ Pa$; $N_2 = 80\ \% = 0.8$; $O_2 = 20\ \% = 0.2$;

$$\Delta p_{N_2} = (3 \cdot 1) - (1 \cdot 0.8) = 2.2 bar = 2.2 \cdot 10^5 Pa$$

and, from (equ.1):

$$\dot{n}''_{N_2} = P_i \frac{\Delta p_{N_2}}{l} = 1.6 \cdot 10^{-13} \frac{2.2 \cdot 10^5}{1} = 3.5 \cdot 10^{-8} \frac{cm^3 (STP)}{cm^2 \cdot s}.$$

In the case of inflation with de-oxygenated air, the deflation due to casing permeability is counteracted by a flux of oxygen into the tyre. To evaluate the value of this flux we calculate Δp_{O_2} and, from (equ.1), we obtain $\dot{n}''_{O_2}$:

$$\Delta p_{O_2} = 0 - 0.2 = -0.2 bar = -0.2 \cdot 10^5 Pa = -2 \cdot 10^4 Pa$$

$$\dot{n}''_{O_2} = P_i \frac{\Delta p_{O_2}}{l} = 4.6 \cdot 10^{-13} \cdot \frac{-2 \cdot 10^4}{1} \cong -1 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}.$$

The flux inward is in any case smaller than the outward flux, and hence the tyre will deflate over time. The total outward flux is given by:

$$\dot{n}''_{tot} = \dot{n}''_{N_2} + \dot{n}''_{O_2} = 3.5 \cdot 10^{-8} - 1 \cdot 10^{-8} = 2.5 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}$$

3.3 INFLATION WITH AIR

If we maintain the assumptions of the previous paragraph (casing material, permeability values,...), we can recalculate the values of $\dot{n}''_{N_2}$ and $\dot{n}''_{O_2}$ in the case in which the tyre is inflated with air:

TYRE INTERIOR:	$p_{TOT\,int} = 3\ bar = 3 \cdot 10^5\ Pa$; $N_2 = 80\ \% = 0.8$; $O_2 = 20\ \% = 0.2$;
EXTERIOR (ATMOSPHERE):	$p_{ext} = 1\ bar = 1 \cdot 10^5\ Pa$; $N_2 = 80\ \% = 0.8$; $O_2 = 20\ \% = 0.2$;

$$\Delta p_{N_2} = (3-1) \cdot 0.8 = 1.6 bar = 1.6 \cdot 10^5 Pa$$

$$\dot{n}''_{N_2} = P_i \frac{\Delta p_{N_2}}{l} = 1.6 \cdot 10^{-13} \frac{1.6 \cdot 10^5}{1} = 2.6 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}$$

$$\Delta p_{O_2} = (3-1) \cdot 0.2 = 0.4 bar = 0.4 \cdot 10^5 Pa = 4 \cdot 10^4 Pa$$

$$\dot{n}''_{O_2} = P_i \frac{\Delta p_{O_2}}{l} = 4.6 \cdot 10^{-13} \cdot \frac{4 \cdot 10^4}{1} = 1.8 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s},$$

and hence the total outward flux in case of inflation with air is given by:

$$\dot{n}''_{tot_{aria}} = \dot{n}''_{N_2} + \dot{n}''_{O_2} = 2.6 \cdot 10^{-8} + 1.8 \cdot 10^{-8} = 4.4 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}.$$

3.4**CONCLUSIONS**

From the above it is evident that a tyre inflated with de-oxygenated air ($\dot{n}''_{tot} = 2.5 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}$) deflates more slowly than one inflated with air ($\dot{n}''_{tot_{aria}} = 4.4 \cdot 10^{-8} \frac{cm^3(STP)}{cm^2 \cdot s}$), in the ratio:

$$\frac{\dot{n}''_{aria}}{\dot{n}''_{N_2}} \cong 2.$$

Let us now calculate the drop in inflation pressure of the tyre in the two cases under consideration (inflation with air and with de-oxygenated air), in a month. This calculation requires us to make further simplifying assumptions in addition to those introduced in paragraph *3.2*:

- During the month in question, we assume that the vehicle is not in use and is stored at a constant ambient temperature of 25°C;
- We consider the gases in question (air and de-oxygenated air) to be *ideal*;
- We will neglect the change in pressure in the tyre's interior over time (that is, the fact that as the tyre deflates its internal pressure drops).

The latter hypothesis is an admissible approximation because, as the result of the calculation will show, the percentage variation in inflation pressure is very low (a few percent).
We will use the simplified geometry[2] of figure *3.4.1*.

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[2] Being a comparison, it is not necessary to calculate the exact tyre size: just define the approximate dimensions and make sure the same are used for both cases.

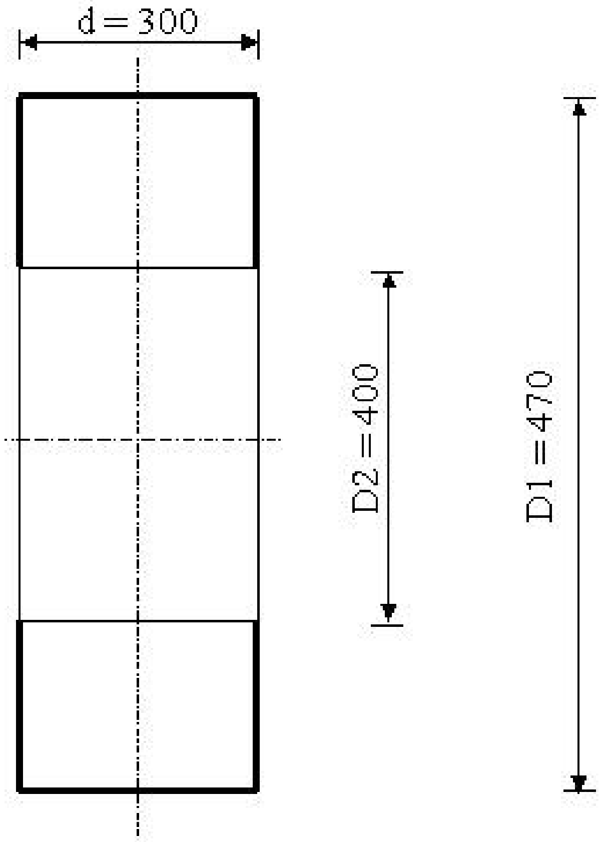

fig.3.4.1: Exchange boundary (heavy line)

The surface $A_{exchange}$ of the tyre through which the gas flows is given by:

$$\begin{aligned} \mathrm{A}_{\mathrm{exchange}} &= 2\cdot\pi\cdot\left[\left(\frac{\mathrm{D}_1}{2}\right)^2-\left(\frac{\mathrm{D}_2}{2}\right)^2\right]+2\cdot\pi\cdot(\mathrm{D}_1\cdot\mathrm{d})= \\ &= 2\cdot\pi\cdot\left[\left(\frac{470}{2}\right)^2-\left(\frac{400}{2}\right)^2\right]+2\cdot\pi\cdot(470\cdot300)= \\ &= 9.8\cdot10^5\,mm^2 = 9.8\cdot10^3\,cm^2 \end{aligned}$$

while the volume V is given by:

$$\begin{aligned} V &= \pi\cdot\left[\left(\frac{D_1}{2}\right)^2-\left(\frac{D_2}{2}\right)^2\right]\cdot d=\pi\cdot\left[\left(\frac{470}{2}\right)^2-\left(\frac{400}{2}\right)^2\right]\cdot300= \\ &= 14.3\cdot10^6\,mm^3 = 14.3\cdot10^{-3}\,m^3. \end{aligned}$$

If we call t_m the number of seconds in a month, that is:

$$t_m = 3600\frac{s}{h}\cdot 24\frac{h}{day}\cdot 30\frac{days}{month} = 2.6\cdot 10^6\frac{s}{month},$$

we can estimate the outward flux of gas in a month.

- **Inflation with air:**

$$\dot{n}''_{tot_{air}} = 4.4\cdot 10^{-8}\frac{cm^3(STP)}{cm^2\cdot s}$$

$$\dot{n}_{tot_{air}} = \dot{n}''_{tot_{air}}\cdot A_{exchange} = 4.4\cdot 10^{-8}\cdot 9.8\cdot 10^3 = 4.3\cdot 10^{-4}\frac{cm^3(STP)}{s}$$

$$n_{month_{air}} = \dot{n}_{tot_{air}}\cdot 2.6\cdot 10^6 = 4.3\cdot 10^{-4}\cdot 2.6\cdot 10^6 = 1118 cm^3(STP)$$

Using the *ideal gas law*:

$$p\cdot V = n\cdot R\cdot T$$

and recalling that the volume of a mole of an ideal gas is given by:

$$Vm = 22.414\ \frac{l}{gmol},$$

It follows that the number of moles of gas initially contained inside the casing is:

$$moles_{air_{init.}} = \frac{p_{init}\cdot V}{R\cdot T}$$

where: $p_{initial} = 3\ bar = 3\cdot 10^5\ Pa$;

$V = 14.3\cdot 10^{-3}\ m^3$;

$R = 8.31451\ \frac{J}{gmol\cdot K}$;

$T = 273.15 + 25 = 298.15\ K$;

These values apply to both cases under consideration.
We therefore obtain:

$$\mathrm{moles}_{\mathrm{air}_{\mathrm{init.}}} = \frac{3\cdot 10^{5}\cdot 14.3\cdot 10^{-3}}{8.314\cdot 298.15} = 1.730\mathrm{gmol}.$$

The number of moles lost from the casing in a month is given by:

$$\mathrm{moles}_{\mathrm{air}_{\mathrm{out}}} = \frac{\mathrm{n}_{\mathrm{month}_{\mathrm{air}}}}{\mathrm{V}_{\mathrm{m}}} = \frac{1118\cdot 10^{-3}}{22.414} = 5\cdot 10^{-2}\mathrm{gmol}.$$

The final pressure p_{fin} is thus:

$$\mathrm{p}_{\mathrm{fin}} = \frac{(\mathrm{moles}_{\mathrm{air}_{\mathrm{init.}}} - \mathrm{moles}_{\mathrm{air}_{\mathrm{fin}}})\cdot \mathrm{R}\cdot \mathrm{T}}{\mathrm{V}} = \frac{(1.730 - 5\cdot 10^{-2})\cdot 8.314\cdot 298.15}{14.3\cdot 10^{-3}} =$$

$$= 2.91\cdot 10^{5}\,Pa.$$

We can therefore assert that *in the case of inflation with air, the internal pressure drops by around* 3% *over a month.*

- **Inflation with de-oxygenated air:**
  We use the same calculation as for the previous case:

$$\dot{n}''_{tot} = 2.5\cdot 10^{-8}\,\frac{cm^{3}(STP)}{cm^{2}\cdot s}$$

$$\dot{\mathrm{n}}_{\mathrm{tot}} = \dot{\mathrm{n}}''_{\mathrm{tot}}\cdot \mathrm{A}_{\mathrm{exchange}} = 2.5\cdot 10^{-8}\cdot 9.8\cdot 10^{3} = 2.4\cdot 10^{-4}\,\frac{\mathrm{cm}^{3}(\mathrm{STP})}{\mathrm{s}}$$

$$\mathrm{n}_{\mathrm{month}} = \dot{\mathrm{n}}_{\mathrm{tot}}\cdot 2.6\cdot 10^{6} = 2.4\cdot 10^{-4}\cdot 2.6\cdot 10^{6} = 624\mathrm{cm}^{3}(\mathrm{STP}).$$

The number of moles lost during the month is thus:

$$\mathrm{moli}_{\mathrm{out}} = \frac{\mathrm{n}_{\mathrm{month}}}{\mathrm{V}_{\mathrm{m}}} = \frac{624\cdot 10^{-3}}{22.414} = 2.8\cdot 10^{-2}\mathrm{gmol}.$$

And hence the final pressure p_{fin} is:

$$\mathrm{p}_{\mathrm{fin}} = \frac{(\mathrm{moli}_{\mathrm{air}_{\mathrm{init}}} - \mathrm{moli}_{\mathrm{out}})\cdot \mathrm{R}\cdot \mathrm{T}}{\mathrm{V}} = \frac{(1.730 - 2.8\cdot 10^{-2})\cdot 8.314\cdot 298.15}{14.3\cdot 10^{-3}} =$$

$$= 2.95 \cdot 10^5 Pa .$$

It follows that *in the case of inflation with de-oxygenated air the drop in inflation pressure is* 1.6% *over the month*.

If we compare the two results, it is evident that a tyre inflated with de-oxygenated air loses pressure at half the speed of a tyre inflated with air. Note that these results are approximated to higher figures, however the purpose of this study is to give a *qualitative* characterisation of the advantages of inflation with de-oxygenated air.

3.5 **OTHER ADVANTAGES OF INFLATION WITH DE-OXYGENATED AIR**

Slower deflation over time of tyres inflated with de-oxygenated air is the most evident, but not the only, advantage offered by this technique. For instance, a further important factor is the deterioration of the casing's lining by the oxygen contained in air (which is currently the most commonly used inflation gas), and it follows that using de-oxygenated air does not have this disadvantage.

All tyres have a service life dependent on a number of factors, including:

- Deterioration of the lining due to oxidation;
- Fabrication defects;
- The quality of the road surface;
- Formation of cracks on the outer surface of the casing due to ozone and normal oxidation.

The most important of these factors, and the one which can be most simply protected against, is the deterioration of the lining due to oxidation. Note that the harmful effects of oxygen on the lining have been known and studied since the 60's, but tyre technology has only taken these studies into account in recent years.

Let us consider Arrhenius Law of chemical reaction:

$$k = A \cdot T^n \cdot e^{-\frac{E}{R_o \cdot T}}$$

where:

- The term

$$A \cdot e^{-\frac{E}{R_o \cdot T}}$$

is the Arrhenius coefficient;

- k is the reaction speed constant;
- T is temperature;
- A is a constant;
- n is a constant;
- E is the activation energy, i.e. the minimum energy of molecular collision required to activate the chemical reaction.

If we consider three substances X, Y and Z, the constant k (in the case of direct reaction) allows us to express the variation in the concentration of Z as a function of the concentrations of X and Y:

$$\frac{d[Z]}{dt} = k \cdot [X] \cdot [Y]$$

where $[X]$, $[Y]$ and $[Z]$ are the concentrations of X, Y and Z respectively. From this we can see that the oxidation affecting the lining depends on the temperature T, the concentration of oxygen in the inflation gas and the time t. Since the state S of deterioration of the tyre has a limit – beyond which the tyre must be replaced – and since, as we have seen:

$$S \propto T,\ t,\ \mathit{concentration}_{O_2}; \qquad S = \mathit{constant}$$

it follows that by reducing the temperature or concentration of the oxygen we increase the life of the tyre. As shown in Chapter II, reducing heat generation inside the casing is extremely difficult and requires changes in the chemical composition of the material; it is very difficult to affect the temperature. It is far simpler to change the oxygen concentration inside the tyre by using de-oxygenated air as the inflation gas.

During the period May 1966 to November 1967, five tests were run in the United States on private car and truck tyres to investigate the phenomenon of oxidation. Each test when run for half of its duration using tyres inflated with air, for the other half with inert gases so as to reduce the concentration of oxygen. A sixth test was run for 36 months (November 1964 to November 1967) on 80 truck tyres to evaluate the effect of oxidation in the inner tube. All six tests clearly demonstrated that using de-oxygenated air as the inflation medium had a positive effect on the life and wear of the tyre. The results demonstrated that if the oxygen concentration inside the tyre is reduced by 6%, the life of the private car tyres was increased by 22 %, and that there was an evident reduction in wear. From this we can calculate that using de-oxygenated (completely oxygen-free) air for inflation would increase average tyre by 25 % in the case of private cars and 40-50% for trucks.

At the time of writing, these tests have been repeated a number of times on a variety of vehicles. We can state that the use of *tubeless* tyres – as compared to the *tubed* tyres in use in the 1960's – make the advantages of using de-oxygenated air even more evident: in this case the average life of private car tyres is increased by 48%, while the life of truck tyres is increased by 26 %.

We must emphasise that if the tyre is inflated with de-oxygenated air, the tyre is subject to reduced deterioration and this results in the possibility of making a larger number of repairs on truck tyres[3]: while using air enables us to make 3 - 4 structural repairs, using de-oxygenated air increases this number to 6 - 7 repairs.

Directive EC/94/95 of the Council dated 21 November 1994 (harmonisation of the legislation of the member states regarding the transport of hazardous goods by road) provides that use of de-oxygenated air for tyre inflation is obligatory for road vehicles transporting hazardous goods, although if the vehicle is transporting the goods only within the national boundaries of the State in which it is licensed, it must comply with the provisions of local legislation.

3.6 THE TYRE MANUFACTURERS' VIEW OF INFLATION WITH DE-OXYGENATED AIR

We quote below the declarations of a number of tyre manufacturers regarding tyre inflation with de-oxygenated air.

"Many manufacturers of industrial and earth moving machines recommend inflation with nitrogen as it reduces the danger of explosion due to excessive external heating, such as:

- *The vehicle catching fire;*
- *Too abrupt braking;*
- *Extended brake application;*

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[3] Since trucks have a very high annual mileage their tyres wear very quickly and, to avoid the high costs associated with replacing the entire set of tyres, it is customary to repair the tread so long as the sidewalls are still in good condition.

- *Welding of the rims with the tyres installed.*

All of these factors can provoke the ignition and burning of the interior of the tyre. An explosion due to tyre combustion is far more powerful than a tyre burst.

Such explosions can cause serious injury and death.

[...] inflation with nitrogen has numerous other advantages:

- *It maintains tyre pressure better;*
- *It reduces aging due to casing oxidation;*
- *It minimises rust formation on the rim."*

Good Year

"Air contains both nitrogen and oxygen. Oxygen diffuses through the casing much faster than nitrogen. A tyre inflated with nitrogen loses pressure at a third of the rate of one inflated with air. Tyres inflated in this way thus require much less frequent checking and also are far less likely to be damaged by insufficient inflation. The use of nitrogen also reduces casing oxidation and the consequent deterioration of the tyre. Nitrogen also reduces rim corrosion and thus makes disassembly easier.

[...] this type of inflation [with nitrogen] is recommended especially for the following applications:

- *Use in explosive atmospheres;*
- *Use on, or in proximity to, incandescent materials (foundries, steelworks, glassworks, etc.);*
- *Use in conditions of electrical sparking hazard (high tension lines and cables);*
- *Use with risk of tyre overheating due to:*
  - *-Intensive use (speed, distance, intensive duty cycles);*
  - *-High transmission of heat from the brakes and engine."*

Michelin

"[...] we give below the main characteristics of nitrogen compared to compressed air and the specific advantages for tyre inflation, as well as some general considerations.

1. ***Nitrogen is oxygen-free**: the absence of oxygen in the tyre reduces the speed at which the casing material ages, with beneficial effects on the condition of the casing itself;*
2. ***Industrial nitrogen is dry**: the gas used for tyre inflation is almost completely dry and free of carbon dioxide. This eliminates or*

minimises the rubber/metal corrosion due to the water vapour in compressed air, and improves the life of the metal belt (and in the case of industrial vehicles, also the life of the casing);

3. ***Nitrogen increases the life of the materials with which it is in contact**: compared to compressed air, the absence of oxygen, CO_2, dust and other impurities protects the valve […];*
4. ***Impermeability**: the casing material […] is more permeable to oxygen than to nitrogen […];*
5. ***Tyre working temperature**: the working temperature of the tyre is not appreciably affected by the use of nitrogen rather than air for inflation;*
6. ***Cost**: the cost of production of nitrogen is generally higher than that of compressed air, although this difference will be reduced as the use of nitrogen becomes more widespread[…];*
7. ***Explosion / fire hazard**: unlike air, nitrogen does not cause the risk of explosion or fire, being inert and non-flammable;*
8. ***Environment:** nitrogen has no negative environmental effects: the air we breath is 80 % nitrogen; (nitrogen) does not contain oil, which is present in compressed air;*
9. ***Tyre mounting/demounting criticalities:** The use of this gas does not incur any particular criticalities inasmuch as it disperses on contact with the air. Nonetheless, it should not be used in small closed areas where it might reduce the normal concentration of oxygen."*

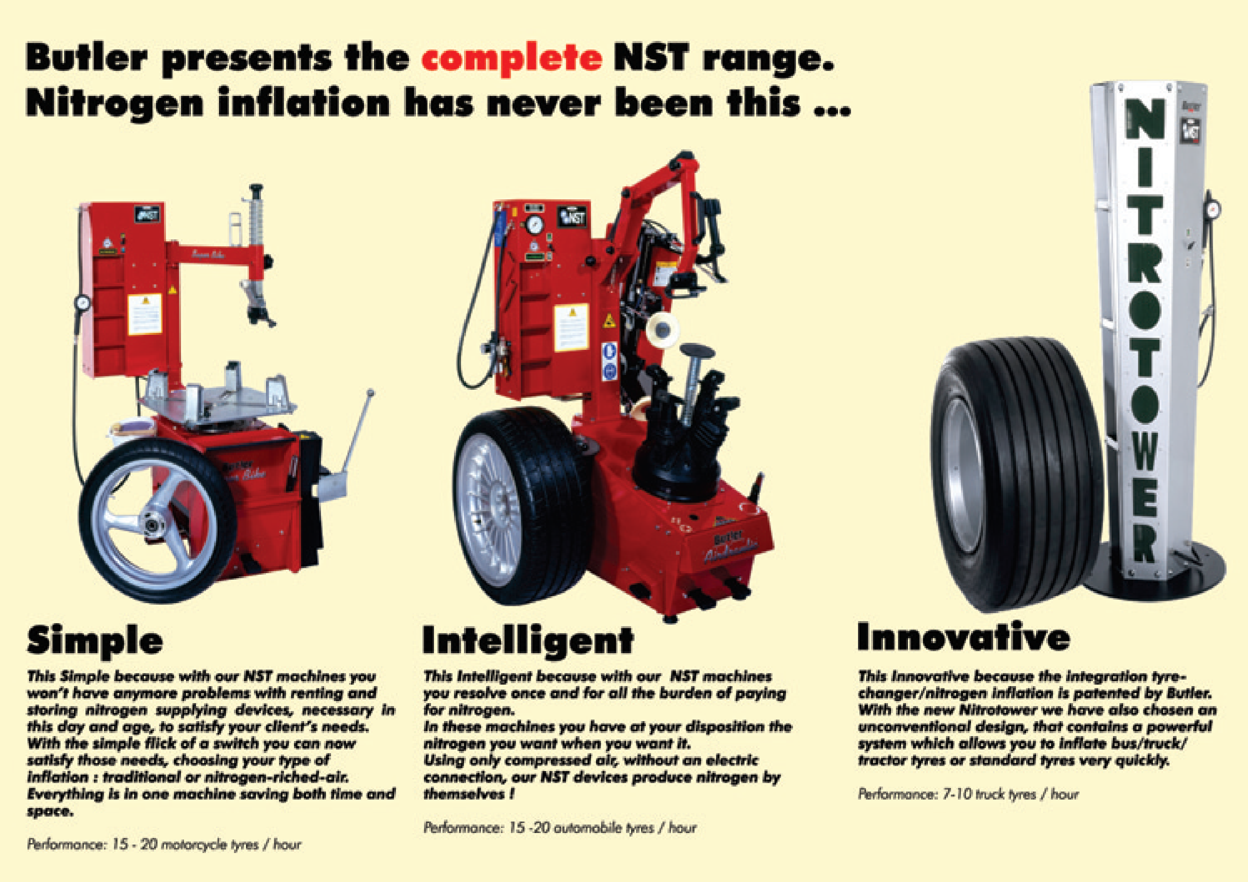
Pirelli

CHAPTER IV

BUTLER NST SYSTEM

4.1 INTRODUCTION

Butler (Rio Saliceto, RE, Italy), a leading producer of tyre equipment, has recently introduced the NST series of nitrogen tyre inflators, which obtain the nitrogen by de-oxygenating the air by means of a membrane. We explain the operation of the inflators, the type of membrane used, and the system's running costs below.



Butler presents the complete NST range.
Nitrogen inflation has never been this ...

Simple

This Simple because with our NST machines you won't have anymore problems with renting and storing nitrogen supplying devices, necessary in this day and age, to satisfy your client's needs. With the simple flick of a switch you can now satisfy those needs, choosing your type of inflation : traditional or nitrogen-riched-air. Everything is in one machine saving both time and space.

Performance: 15 - 20 motorcycle tyres / hour

Intelligent

This Intelligent because with our NST machines you resolve once and for all the burden of paying for nitrogen.
In these machines you have at your disposition the nitrogen you want when you want it.
Using only compressed air, without an electric connection, our NST devices produce nitrogen by themselves !

Performance: 15 -20 automobile tyres / hour

Innovative

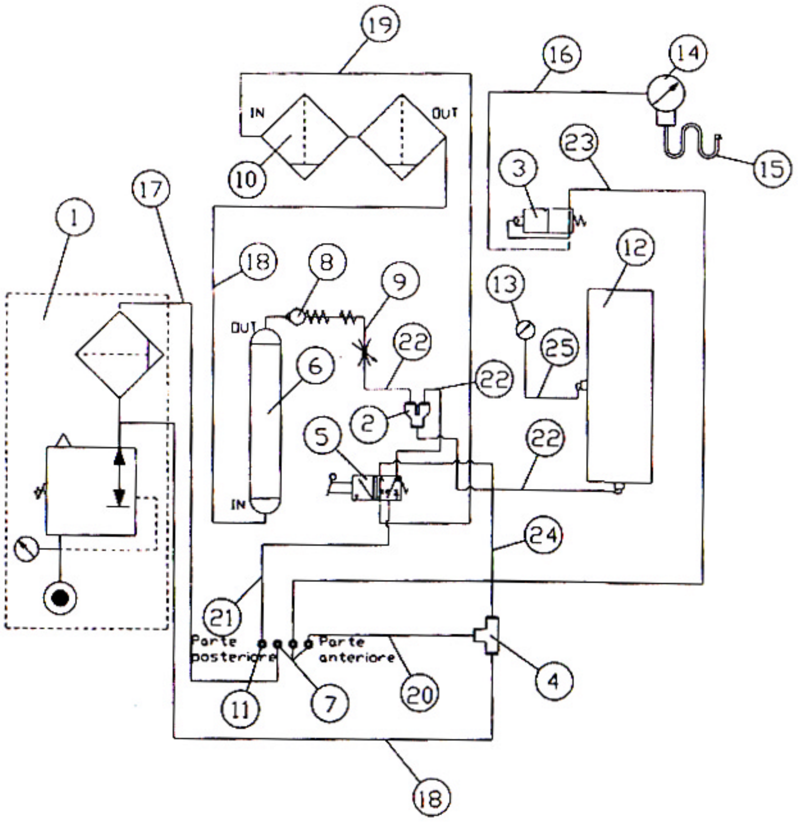
This Innovative because the integration tyre-changer/nitrogen inflation is patented by Butler. With the new Nitrotower we have also chosen an unconventional design, that contains a powerful system which allows you to inflate bus/truck/ tractor tyres or standard tyres very quickly.

Performance: 7-10 truck tyres / hour

4.2 OPERATING PRINCIPLE

With reference to figure 4.2.1, the air enters the FRL unit (1), is delivered to the filter unit (10), passes through the membrane filter (6) – the heart of the system, which actually de-oxygenates the air - and is finally delivered to the tank (12).

Note that the inflator operates like any other inflator, with the single difference that the air is de-oxygenated by the membrane filter, and the filter's control equipment (valves, pressure gauges, etc.).



25-Tube 4x2.7 green
24-Tube 8x6 blue
23-Tube 8x6 red
22-Tube 8x6 green
21-Tube 8x6 green
20-Tube 8x6 blue
19-Tube 8x6 blue
18-Tube 8x6 blue
17-Tube 8x6 black
16-Tube 8x6 red
15-Inflation tube
14-Pressure gauge
13-Pressure gauge
12-Tank
11-Tank fitting
10-Filter unit
09-Flow regulator
08-One-way valve
07-L-shaped through-fitting
06-Membrane filter
05-Valve
04-T-fitting
03-Valve 44 psi
02-V-fitting
01-FRL unit

NST pneumatic circuit

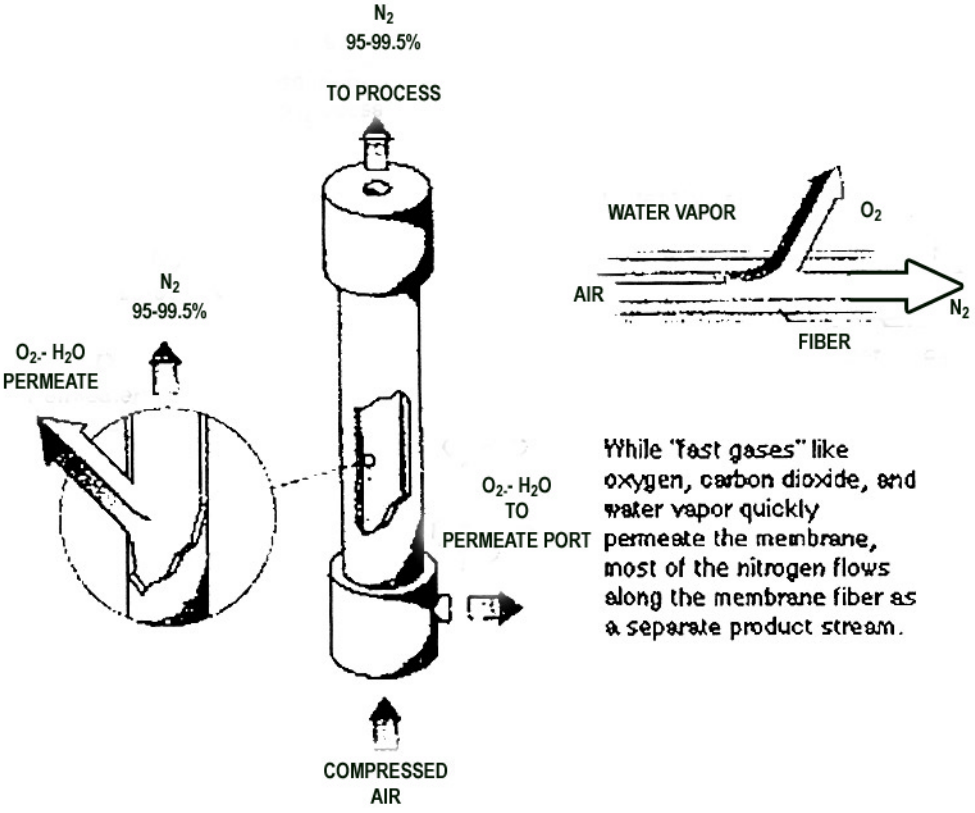
Figure 4.2.1: Functional diagram

4.3 MEMBRANE FILTER

The membrane filter, which de-oxygenates the air, transforms the compressed air (which is delivered by a normal air compressor) into pure commercial nitrogen[1] with dewpoint -58°F (-50°C).

In the functional diagram of figure 4.2.1, the purity of the air entering the membrane filter is assured by the filter unit (10), while the purity of the output nitrogen is ensured by the action of the 0.01 µm.

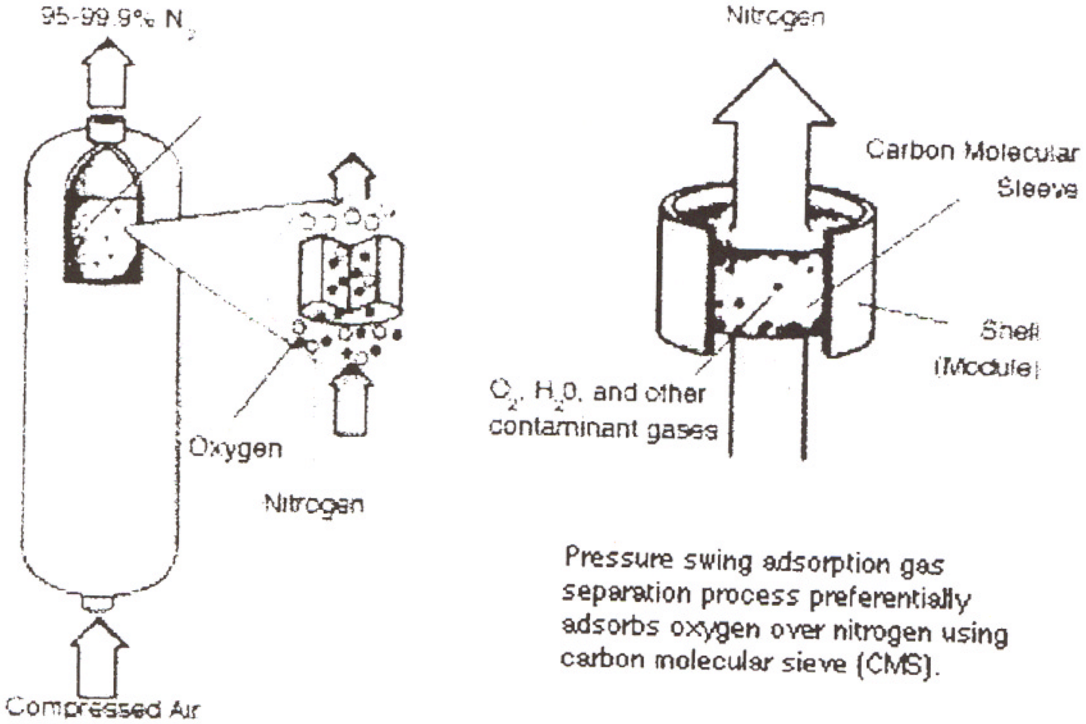
The membrane filter generates nitrogen by separating the air into two parts; one is 95-99.5% nitrogen, which is commercially pure – and the other is oxygen (mainly), carbon dioxide and traces of other gases (see figure 4.3.1).



While "fast gases" like oxygen, carbon dioxide, and water vapor quickly permeate the membrane, most of the nitrogen flows along the membrane fiber as a separate product stream.

Figure 4.3.1: Membrane filter functional diagram

The nitrogen is generated by dividing the air into its component gases (the raw material thus has zero cost) by means of semi-permeable membranes composed of hollow fibres. Each fibre has a perfectly circular cross-section and uniform bore. Since the fibres are extremely small in size, a large number can be contained in a small space, thus enabling us to use a large membrane surface capable of producing a large quantity of nitrogen. The compressed air is introduced into the centre of the fibres via one end of the module (the input) which houses the membrane filter, and flows through its fibres. While the oxygen, water vapour and other trace gases permeate the fibres and are discharged into the atmosphere[2], the nitrogen is trapped inside and exits from the other end of the module (the output) – see figure 4.3.2. Since water vapour is also passed by the filter, the nitrogen produced is very dry, which has the advantage of minimising rust formation mon the rim.



Pressure swing adsorption gas separation process preferentially adsorbs oxygen over nitrogen using carbon molecular sieve (CMS).

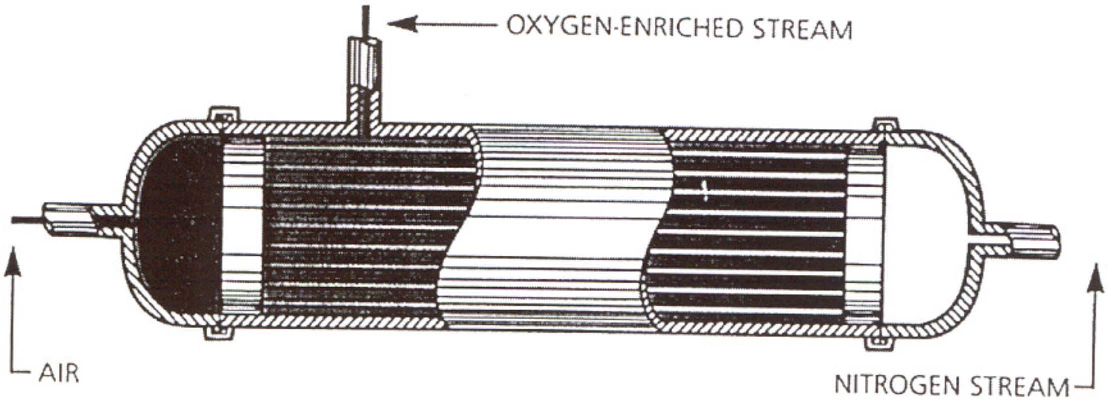


Figure 4.3.2: Fiber functional drawing

4.4 QUALITATIVE COST ANALYSIS

In conclusion, we give below an analysis of the running costs of the nitrogen generator. Note that this is a qualitative analysis, and the costs given below are merely illustrative.

Hours per day	8 (hours/day)
Days per week	5 (days/week)
Weeks per year	48 (weeks/year)
TOTAL HOURS PER YEAR	1920 hours
Hourly nitrogen production	1 (m^3/h)
TOTAL ANNUAL NITROGEN PRODUCTION	1920 (m^3)
Purity of produced nitrogen	95%
Air Factor	2.6
Hourly compressed air consumption	2.6 (N.m^3/h)
ESTIMATED COMPRESSOR POWER	0.2 (kW)
Cost of electrical power	170 (ITL/kWh)
TOTAL ANNUAL COST OF ELECTRICAL POWER	65 (ITL x 1000)
Estimated annual maintenance cost	2.5 (% of proposed price)
TOTAL ANNUAL MAINTENANCE COST	100 (ITL x 1000)
TOTAL ANNUAL RUNNING COST	165 (ITL x 1000)
COST OF NITROGEN PRODUCTION (neglecting amortisation)	**86 (ITL/m^3)**

(Footnotes)

[1] The membrane output is 95-99.5% nitroge

[2] Since these gases are components of air, the fact that they are discharged into the atmosphere has no negative environmental consequencesn