4.1 Project Data

When sizing a piston accumulator, independently from the application, it is necessary to precisely define the following operational parameters.

- **Minimum working pressure \( P_1 \)**
  
  The minimum pressure at which the system will still function.

- **Maximum working pressure \( P_2 \)**
  
  To the maximum pressure at which the system will function. The value of \( P_2 \) must always be less than or equal to the maximum working pressure of the accumulator.

- **Volume \( \Delta V \)**
  
  Is the volume accumulated or restored

  \[ \Delta V = V_1 - V_2 \]

  where

  - \( V_1 \) (Volume of gas at \( P_1 \))
  - \( V_2 \) (Volume of gas at \( P_2 \))

- **Minimum temperature of gas \( T_1 \)**
  
  Is the minimum working temperature the gas.

- **Maximum temperature of gas \( T_2 \)**
  
  Is the maximum temperature the gas.

- **Mode and/or field of implementation ADIABATIC or ISOTHERMIC transformation**

  The compression and decompression of nitrogen contained in the accumulator is regulated by the prefect gas laws. If the compression or the decompression is slow (in excess of 3 minutes) such to allow the gas to maintain the temperature close to constant, you will have ISOTHERMIC transformation (Pressure stabilizer, forces balancer, volume compensator, feed in the lubrication circuits) in as much as the change of gas volume follows the law of Bayle Mariotte.

  \[ V_1 \times P_1 = V_2 \times P_2 \]

  In other cases (energy reserve, pulsation compensator, water hammer absorbers etc.) the heat exchange with the ambient is negligible given the speed with which it operates. You therefore have contemporary pressure and temperature variations of the gas, with which you have ADIABATIC transformation, governed by the law:

  \[ V_1^n \times P_1 = V_2^n \times P_2 \]

  Where the coefficient \( n \) takes on values from 1 to 1.4 during the process of compression or decompression (See fig. 11 and fig. 13).

4.2 Pre-charge pressure \( P_0 \)

The definition of the pre-charge pressure of the accumulator has a fundamental importance in order to obtain maximum efficiency in conditions that do not prejudice the longevity of its components. The maximum accumulate or replenishment of liquid we have in theory, with a pre-charge \( P_0 \) equal to the minimum pressure of exertion \( P_1 \). In practice the pre-charge pressure (at the maximum exertion pressure \( T_2 \)) should be at least less than \( 3 \div 5 \) bar of the minimum pressure of exertion, to avoid that the piston strike, the oil side flange and damage the components during replenishment of fluid.

It is advisable that the minimum pre-charge pressure (At the minimum exertion pressure \( T_1 \)) be in excess of friction force and also the weight of the piston itself in a case of horizontal installation or the fluid side in the upright position.

For specific requirements consult our Technical Service Dept. For particular applications, and in the following cases, the recommended pre-charge values are:

\[ P_0 = 0.95 \div 0.97 P_1 \]

The value of \( P_0 \) is referred to the maximum working temperature of the gas, foreseen by the user.

The pre-charge and the control are usually affected at a different temperature that the maximum working temperature \( T_2 \), in which the pre-charge pressure \( P_0 \) at a pre-charge or control \( T_c \) becomes:

\[ P_{pre-charge/control} = \frac{293 + T_c (^ºC)}{273 + 12 (^ºC)} \]

Example for a pre-charge effectuated at 20º C:

\[ P_0 \text{ at 20ºC} = P_0 \times \frac{293}{273 + T_2 (^ºC)} \]

**N.B.** The pre-charge pressure of EPE accumulators supplied directly from the factory, are referred to a temperature of 20º C.

Pulsation compensator and shock absorber:

\[ P_0 = 0.6 \div 0.75 \times P_m \text{ or } P_0 = 0.8 \times P_1 \]

Where:

- \( P_m \) = medium working pressure

Hydraulic line shock damper:

\[ P_0 = 0.6 \div 0.9 \times P_m \]

Where:

- \( P_m \) = medium working pressure of free flow.
4.3 Calculation principles

Compression and expansion of gas inside the accumulator takes place according to the Boyle-Mariotte law regarding the status change in the perfect gases:

\[ P_0 \cdot V_0 = P_1 \cdot V_1 = P_2 \cdot V_2 \]

The PV diagram Fig. 12 shows the “pressure-volume” relationship inside the accumulator.

\[ P_0 \cdot V_0 = P_1 \cdot V_1 = P_2 \cdot V_2 \]

where:

- \( V_0 \) = Nitrogen pre-charge volume at pressure \( P_0 \) (litres).
- \( V_1 \) = Nitrogen volume at pressure \( P_1 \) (litres).
- \( V_2 \) = Nitrogen volume at pressure \( P_2 \) (litres).
- \( \Delta V \) = Volume of discharged or stored liquid (litres).
- \( P_0 \) = Precharge pressure (bar).
- \( P_1 \) = Minimum operating pressure (bar).
- \( P_2 \) = Maximum operating pressure (bar).
- \( n \) = Polytropic exponent.

The curve of volume variation as a function of pressure is dependent on the exponent \( n \), which for nitrogen is contained between the limit values:

- \( n = 1 \) in case compression or expansion of nitrogen takes place so slowly that a complete intercharge of heat is allowed between gas and environment, that is at constant temperature, the condition is isothermal.
- \( n = 1.4 \) when operation is so quick that no interchange of heat can take place, the condition is adiabatic.

In fact, these are theoretical and not practical conditions. It is however possible to state, with reasonable accuracy, that when an accumulator is used as a volume compensator, leakage compensator, the condition is isothermal. In the remaining applications, such as energy accumulator, pulsation damper, emergency power source, dynamic pressure compensator, water hammer absorber, shock absorber, hydraulic spring, etc., it is possible to state, with reasonable accuracy, that the condition is adiabatic.

When is required a more accurate calculation, is possible to use intermediate values of \( n \) as function of \( t \), that is of expansion or compression time, according to diagram (fig. 13):

\[ n = \frac{P_2}{P_1} \]

Note: In all calculations, pressures are expressed as absolute bar (pressure of a fluid or a gas refer to the void) and Temperature as Kelvin degrees (\(^°K = 273 + ^°C\)).

4.4 Volume calculation (isothermal condition)

When \( n = 1 \), the Boyle-Mariotte law becomes

\[ P_0 \cdot V_0 = P_1 \cdot V_1 = P_2 \cdot V_2 \]

so that:

\[ V_1 = V_0 \cdot \frac{P_2}{P_1} \]

and

\[ V_2 = V_1 \cdot \frac{P_2}{P_1} \]

The difference between volume \( V_1 \) (at minimum operating pressure) and \( V_2 \) (at maximum operating pressure) gives the amount of stored liquid (See Section 1.1):

\[ \Delta V = V_1 \cdot V_2 = V_0 \cdot \frac{P_2}{P_1} \cdot \frac{P_1}{P_2} \]

so that:

\[ \Delta V = V_0 \left( \frac{P_2}{P_1} - \frac{P_1}{P_2} \right) \]

Accumulator volume \( V_0 \) will be:

\[ V_0 = \frac{\Delta V}{\left( \frac{P_2}{P_1} - \frac{P_1}{P_2} \right)} \]

which could be also written:

\[ V_0 = \frac{\Delta V}{\left( \frac{1}{P_1} - \frac{1}{P_2} \right)} \]

which shows that accumulator volume increases when \( \Delta V \) is increasing, when \( P_0 \) is decreasing and when the difference between the two operation pressures \( P_1 \) and \( P_2 \) is decreasing.

The values of \( \Delta V \) and \( V_0 \) could be deduced more quickly from the diagrams on pages 12 and 13.
4.4.1 Volume compensator (isothermal)

A typical example of calculation in the isothermal condition is when the accumulator is used as a volume compensator.

Assume a tube with Ø I.D. = 77.7 mm, 120 m long and inside which some oil is flowing at a pressure of 30 bar and a temperature of \( T_1 = 10°C \) and \( T_2 = 45°C \). Permissible change of pressure \( \pm 8\% \).

The volume variation will be:

\[
\Delta V = V_f \left( \frac{T_2 - T_1}{T_2 - T_1} \right) \left[ 1 - \beta \right] = 596 \left( \frac{45 - 10}{45 - 10} \right) (0.00055 - 3 \cdot 0.000012) = 14.2 \text{ It.}
\]

where:

\( \Delta V \) = piping volume (litres),

\( T_2 \) = max. temperature (°C),

\( T_1 \) = min. temperature (°C),

\( \beta \) = cubic expansion coefficient of fluid \( \left( \frac{1}{°C} \right) \),

\( \epsilon \) = linear expansion coefficient of piping \( \left( \frac{1}{°C} \right) \),

\( P_1 \) = min. permissible operating pressure (bar),

\( P_2 \) = max. permissible operating pressure (bar).

where:

\( P_1 = 8\% \) of 30 = 27.6 bar 28.6 (absolute pressure)

\( P_2 = 8\% \) of 30 = 32.4 bar 33.4 (absolute pressure)

\( P_0 = 0.95 \cdot 27.6 = 26.2 \text{ bar 27.2 (absolute pressure)} \)

The permissible change of pressure \( \pm 8\% \) is satisfied.

Problem solution requires the use of an accumulator station with 3 accumulators type \( \text{AP50P250...} \),

or: 1 accumulator and 2 additional bottles 50 litres.

2 accumulators from 80 litres

1 accumulator from 150 litres

4.4.2 Leakage compensator (isothermal)

a) Assume a molding press working at 200 bar which has to be kept closed during the curing time and at constant pressure. Min. permissible pressure 198 bar.

After the mold has been closed, the pump is stopped.

The oil leakages are in the order of 2 cm³/minute.

Curing time is 60 minutes.

\[
\Delta V = Q \cdot t = 0.002 \times 60 = 0.12 \text{ It.}
\]

\( P_1 = 198 \text{ bar 199 (absolute bar)} \)

\( P_0 = 0.95 \cdot 198 = 188 \text{ bar 189 (absolute bar)} \)

\[
V_0 = \frac{\Delta V}{Q} = \frac{12.8}{0.12} = 106.7 \text{ litres}
\]
4.6 Temperature influence

It should be anticipated that the operating temperature will change considerably during the cycle and this variation should be taken into account when the volume is calculated.

If an accumulator is sized to a maximum temperature, then the precharge pressure will be referenced to that temperature. When the temperature drops there will be a comparable reduction of the precharge pressure according to the Gay Lussac law on the relationship between pressures and volumes, as a result, you will get a lower accumulator capacity.

Therefore it will be necessary to have a higher $V_0$ to accumulate or to yield the same amount of liquid $\Delta V$ (see section 4.4).

The relationship between pressures and volumes is:

$$V_{OT} = \frac{V_0 \cdot T_2}{T_1}$$

where:

$T_2 = (°C)+273 = \text{max. working temperature} \ (°K)$.

$T_1 = (°C)+273 = \text{min. working temperature} \ (°K)$.

$V_0 = \text{volume calculated neglecting thermal variation} \ (\text{litres})$

$V_{OT} = \text{increased volume for thermal variation} \ (\text{litres})$

**Example:**

Assume the accumulator volume has to be calculated with the following data:

- Stored volume $\Delta V = 1.7 \text{ Lt. in 2 s}$
- Min. pressure $P_1 = 50 \text{ bar 51 absolute bar}$
- Max. pressure $P_2 = 115 \text{ bar 116 absolute bar}$
- Operating temperature $= +25°C \div +70°C$

The precharge pressure referred to maximal temperature is:

$P_0 = 0.95 \cdot P_1 = 47 \text{ bar 48 absolute bar}$

Volume, calculated in adiabatic conditions, will be:

$$V_r = \frac{\Delta V}{\left[\frac{P_2}{P_1}ight]^{\frac{1}{\gamma}} - \left(\frac{P_0}{P_1}\right)^{\frac{1}{\gamma}}}$$

where:

$\gamma = 1.4$ for air

$\gamma = 1.67$ for nitrogen

$V_r = \text{real volume of accumulator to be used for operating pressures} \ P_1 \text{ and } P_2.$

$\Delta V = \text{real yield obtained from accumulator for the same pressures.}$

$C_1, C_2 = \text{Coefficients to be deduced from diagrams of Figures 14 and 15.}$

4.7 Correction coefficient for high pressure

The formulas refer to ideal gases, but industrial nitrogen used in accumulators does not behave according to ideal gas laws when pressures increase.

It is convenient to keep in mind this characteristic for pressure $P_2 > 200 \text{ bar}$, both for adiabatic as well as for isothermal conditions.
4.8 Emergency energy reserve

Typical occasion when storage is slow (isothermal) and discharge is quick (adiabatic).

Volume will be given by:

\[ V_0 = \left( \frac{P_1}{P_2} \right)^{\frac{n}{n-1}} - \left[ \frac{P_1}{P_2} \right]^n \]

and stored volume by:

\[ V = V_0 \left( \frac{P_2}{P_1} \right)^{\frac{n}{n-1}} - 1 \]

where:

- \( n = 1.4 \) adiabatic coefficient (quick discharge phase)
- \( n = 1 + \frac{1}{1.4} \) polytropic coefficient (slow storage phase)

Value is a function of time and it will be deduced from the diagram in Fig. 13.

In the majority of cases it is possible to suppose \( n_c = 1 \), so that calculation is simplified and result is not affected:

\[ V = V_0 \left( \frac{P_2}{P_1} \right)^{\frac{n}{n-1}} - 1 \]

Example:

An accumulator must discharge 4.6 litres of oil in 3 seconds with a change of pressure from \( P_2 = 280 \text{ bar} \) to \( P_1 = 208 \text{ bar} \).

The loading time is 4 minutes. Define the capacity, keeping in mind that ambient temperature will change from 20°C to 50°C.

\[ V_0 = \frac{\Delta V}{P_2 - P_1} \]

\[ V = V_0 \left( \frac{P_2}{P_1} \right)^{\frac{n}{n-1}} - 1 \]

\[ V = 27.5 \text{ l} nt \]

4.9 Pulsation compensator Q

A typical calculation in adiabatic conditions due to high speed storage and discharge.

The liquid amount \( \Delta V \) to be considered in the calculation is a function of type and capacity of pump:

\[ \Delta V = K \cdot q \]

Value becomes:

\[ V_0 = \frac{K \cdot q}{P_1} \]

where:

- \( q \) = pump displacement (litres)
- \( A \times C \) (piston surface x stroke)
- \( Q \) = flow rate (l/min)
- \( n \) = strokes/min
- \( P \) = average working pressure (bar)
- \( P_0 = P \times X \) (bar)
- \( P_1 = P_0 \) (bar)
- \( \alpha \) = remaining pulsation ± (\%)
- \( K \) = coefficient taking into account the number of piston and if pump is single or double acting.

Example:

Assume a 3-piston pump, single acting, with a flow rate \( Q = 8 \text{ m}^3/\text{h} \) and operating pressure of 20 bar. Calculate the volume necessary to limit the remaining pulsation to \( \alpha = \pm 0.25\% \). Pump R.P.M. 1480 Working temperature 40°C.

\[ P = 200 \text{ bar} \]

\[ q = \frac{6000}{60 \times 1480} = 0.03 \text{ ft} \]

\[ P_0 = (200 - 0.5) = 199.5 \text{ bar} \]

\[ P_1 = (200 + 0.5) = 200.5 \text{ bar} \]

\[ P_2 = (0.1 \times 200) = 140 \text{ bar} \]

\[ X = 0.25 \times 200 \times 0.5 \times 0.5 = 1 \times 0.25 \text{ bar} \]

\[ V_0 = \frac{141 \times 141 \times 141}{200.5 
 200.5 
 200.5} = 1.25 \text{ ft} \]

\[ P_{350 \text{ bar}} = 141 \times \frac{200.5}{310} = 131 \text{ bar rel} \]

The most suitable accumulators is the low pressure type: AP1,5P375...
4.10 Hydraulic line shock damper

A rapid increase in pressure caused by a high acceleration or deceleration in flow is commonly known as water hammer. The overpressure, \( \Delta P \) max, that takes place in piping when a valve is closed is influenced by the length of the piping, the flow rate, the density of the liquid and the valve shut down time. This is given by:

\[
\Delta P \text{ max (bar)} = \frac{2 \gamma L \nu}{t \times 10^4}
\]

The volume of the accumulator required to reduce shock pressure within predetermined limits \( \Delta P \) is obtained with:

\[
V_a = \frac{Q}{2 \gamma L \nu \frac{\Delta P \times 10^4}{t}} \left( \frac{P_1}{(P_1 - P_2)^{\Delta P}} - \frac{P_1}{P_2} \right)
\]

where:
- \( V_a \) = accumulator gas capacity (litres)
- \( Q \) = flow rate in the piping (m³/s)
- \( L \) = total length of piping (m)
- \( \gamma \) = specific gravity of liquid (kg/m³)
- \( \nu \) = flow velocity (m/s)
- \( \Delta P \) = allowable overpressure (bar)
- \( P \) = operating pressure by free flow (absolute bar)
- \( t \) = deceleration time (s) (valve shut down, etc.)

Example:
Assume a water pipe (\( \gamma = 1000 \) Kg/m³) with internal diameter \( d = 80 \) mm, length \( L = 450 \) m, flow rate \( Q = 17 \) m³/h, operating pressure \( P_1 = 15 \) bar, allowable overpressure \( \Delta P = 2 \) bar, valve closure time \( t = 0.8 \) s.

\[
\Delta P \text{ max} = \frac{2 \times 1000 \times 450 \times 0.94}{0.8 \times 10^4} = 10.57 \text{ bar}
\]

The accumulators volume necessary to reduce the \( \Delta P \) max to 2 bar is:

\[
V_a = \frac{17}{2} \left( \frac{2 \times 1000 \times 450 \times 0.94}{0.8 \times 10^4} \right) = 11.65 \text{ litres}
\]

where:
- \( S = \frac{\pi \times 80^2}{4} = 5026.5 \text{ mm}^2\)
- \( V = \frac{17 \times 10^4}{5026.5 \times 0.94} = 3.94 \text{ m/s}\)
- \( P_1 = 15 \times 0.8 = 12 = 13 \text{ abs. bar}\)
- \( P_2 = 10 \text{ abs. bar}\)
- \( P_0 = 15 + 2 = 17 \text{ bar} = 16 \text{ abs. bar}\)

An accumulator of 120 litres, type \( \text{AP120P250} \ldots \)

4.11 Accumulator + additional gas bottles (transfer)

In all cases where a considerable amount of liquid must be obtained with a small difference between \( P_1 \) and \( P_2 \), the resultant volume \( V_a \) is large compared to \( \Delta V \).

In these cases it could be convenient to get the required nitrogen volume by additional bottles. Volume calculation is performed, in function of the application, both in isothermal as well as in adiabatic conditions using the formulas given before always taking temperature into account. To get the maximum of efficiency it is convenient to fix for precharge quite a high value. In cases of energy reserve, volume compensator, hydraulic line shock damper, etc. it is possible to use:

\[
P_0 = 0.97 P_l
\]

Once the required gas volume is calculated, the volume must be allocated between the minimum indispensable portion \( V_{aA} \), which will be contained in the accumulator, and the remaining portion \( V_{aB} \), which represents the volume of additional bottles.

\[
V_{at} = V_{aA} + V_{aB}
\]

where:

\[
V_{aA} = \frac{\Delta V \times (V_{at} - V_{aB})}{0.75}
\]

That means that the sum of volume of required liquid plus volume change due to temperature must be lower than \( \frac{3}{4} \) of accumulator capacity.

The bottle volume is given by the difference

\[
V_{aB} = V_{at} - V_{aA}
\]

Example:
Suppose a \( \Delta V = 30 \) lts. must be obtained in 2 seconds going from a pressure \( P_2 = 180 \) bar to \( P_1 = 160 \) bar. Temperatures: \( \theta_1 = 20°C; \theta_2 = 45°C \)

\[
P_{p0} = 0.97 \times 160 - 135 \text{ bar}
\]

\[
V_a = \frac{\Delta V}{\frac{P_1}{P_2} \left( \frac{P_1}{P_2} - \frac{P_2}{P_1} \right) \frac{\Delta P}{\Delta P} + \frac{\Delta V}{\frac{P_1}{P_2} \left( \frac{P_1}{P_2} - \frac{P_2}{P_1} \right) \frac{\Delta P}{\Delta P}}}
\]

\[
= \frac{30}{\left( \frac{160}{156} \right)^{1.45} \left( \frac{160}{156} \right)} = 362.4 \text{ lts.}
\]

\[
V_{aB} = 362.4 \times \frac{318}{263} = 415 \text{ lts.}
\]

\[
V_{aA} = 30 \times \left( 415 - 362.4 \right) = 83.5 \text{ lts.}
\]

One accumulators \( \text{AP100P250} \ldots \) are used with total \( V_a = 100 \) lts. plus 6 bottles of 50 lts. type \( \text{BB52P360} \ldots \).