

2.2.1 PRINCIPLE OF OPERATION

Gas compression

In hydropneumatic accumulators, oil or other liquids are maintained under pressure by a pre-compressed gas, usually nitrogen. Therefore, we show some principles on the compression of gases, useful then in the calculation of the accumulators. The fundamental characteristics of a gas are: volume, temperature and pressure.

The law governing these functions is the one on the ideal gases of Boyle and Mariotte, which states that in every condition under which we place a certain amount of gas, the product between its pressure (relative to vacuum) and its volume is constant. The law adds that this remains constant even if the passage from one state to another occurs with equal heat exchange with the external environment.

This means that, for a given quantity of gas, if the volume available is halved, the pressure is twice; the product of the volume for the absolute pressure is constant.

$$P_1 \cdot V_1 = P_2 \cdot V_2 = P_3 \cdot V_3 = \dots = \text{constant}$$

According to the law of Gay-Lussac: at constant volume, in an ideal gas, the absolute pressure and the temperature are directly proportional. Maintaining a constant pressure in an ideal gas, its volume V varies directly with temperature T :

$$V_1:V_2=T_1:T_2$$

And maintaining a constant volume, the pressure varies in proportion to temperature changes:

$$P_1:P_2=T_1:T_2$$

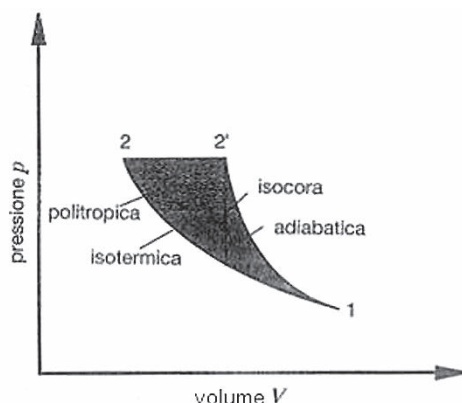
From this it follows that an increase in pressure leads to an increase in temperature and, conversely, a decrease in pressure causes a decrease in temperature. The laws of Boyle and Mariotte and Gay-Lussac are valid exactly only for ideal gases; the nitrogen, being a real gas, is bound to small and influential changes than the laws of the compression of ideal gases. Another crucial factor concerns the change of the aeriform state.

Change in gas state

The state change of the gas may be:

- isochore
- isothermal
- adiabatic
- polytropic

Diagram 2.2a : change of state in the diagram $P - V$



2.2a

Changes in isochore

This change of state is characterized by a constant volume of gas. It occurs when the gas area of the accumulator is pre-charged at low temperature and then subjected to a pressure increase at constant volume due to heat exchange with the environment.

$$\text{Equation of state: } P/T = P_1/T_1 = \text{constant}$$

Isothermal change

This variation, characterized by the constant temperature of the gas, occurs when the charging or discharging of the fluid to / from the accumulator occurs in long times, allowing for the complete heat exchange between the gas and the environment (more than 180 seconds).

$$\text{Equation of state: } P \times V = P_1 \times V_1 = \text{constant}$$

Adiabatic change

The adiabatic change occurs when the discharge and charge of the fluid to / from the accumulator is so fast as to prevent any heat exchange between the gas and the environment (less than 60 seconds).

$$\text{Equation of state: } P \times V^k = P_1 \times V_1^k = \text{constant}$$

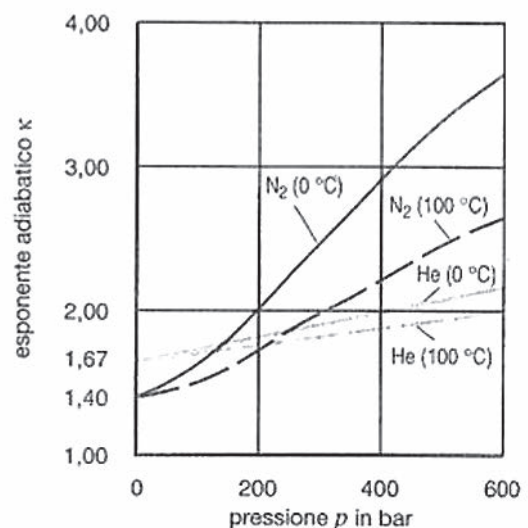
The relationships between temperature and volume and between temperature and pressure are expressed by the thermal equations of state:

$$T \times V^{k-1} = T_1 \times V_1^{k-1}$$

$$T \times P^{(1-k)/k} = T_1 \times P_1^{(1-k)/k}$$

In these equations, "k" is the adiabatic exponent, which for a diatomic gas such as nitrogen under normal conditions, is equal to 1,4.

Diagram 3: evolution of the adiabatic nitrogen exponent depending on the pressure at temperatures of 0°C and 100°C.



2.2b

Polytropic change

The operation of an accumulator never occur under the theoretical assumptions, namely without heat exchange. In practice, there is an intermediate change of state between the isothermal and adiabatic ones, which takes the name of polytropic.

The valid relations are similar to those of the adiabatic change, but it has to substitute the adiabatic change adiabatic exponent with the polytropic exponent N .

2.2.2 SIZING OF THE ACCUMULATOR

With the sizing of the accumulator, we want to establish the geometric capacity according to the pressures within which it works, the amount of fluid that it has to store and return and the time required.

In light of the above, it follows that the equations to be used for the calculation of an accumulator depends on the actual duration of the process of absorption/delivery of the fluid.

As empiric rule for choosing the appropriate equations, apply the following criteria:

- cycle duration < 1 minute: adiabatic change
- cycle duration > 3 minutes: isothermal change
- cycle duration between 1 and 3 minutes: polytrophic change.

The equations to be used for the calculation of the accumulator are shown in Table 3. It should also be noted that the calculation of the accumulator involves some experimental values, which, on one hand, ensure the optimal exploitation of the accumulator volume and, on the other, allow not to endanger the duration. Table 2 shows the experimental values for the various types of accumulators.

Deviations of the real gases

The equations of state shown in the preceding paragraphs apply only if the gas follows the ideal behaviour. In fact, various gases such as nitrogen, differ (especially at other pressures) by the laws of the ideal gas. This behaviour is called "real".

For real gases, relations between the parameters of state (P, T, and V) can be represented only by approximate equations, whose sufficiently precise use is very laborious and long. We prefer, therefore, to take into account the behaviour of the real gases by introducing appropriate correction factors.

In this case, the real volume for an isothermal change of state is expressed by

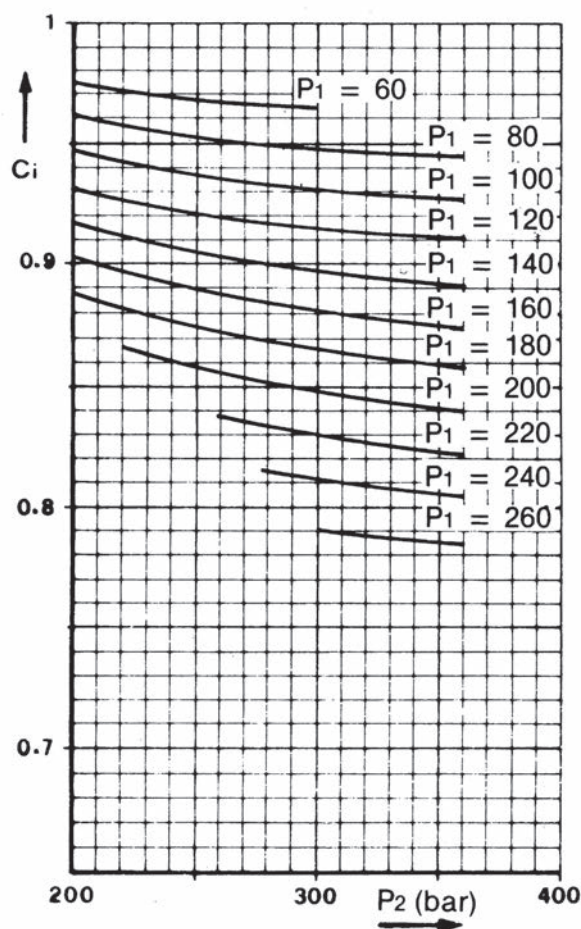
$$V_{0 \text{ real}} = C_i \times V_{0 \text{ ideal}}$$

and for an adiabatic change of state is expressed by

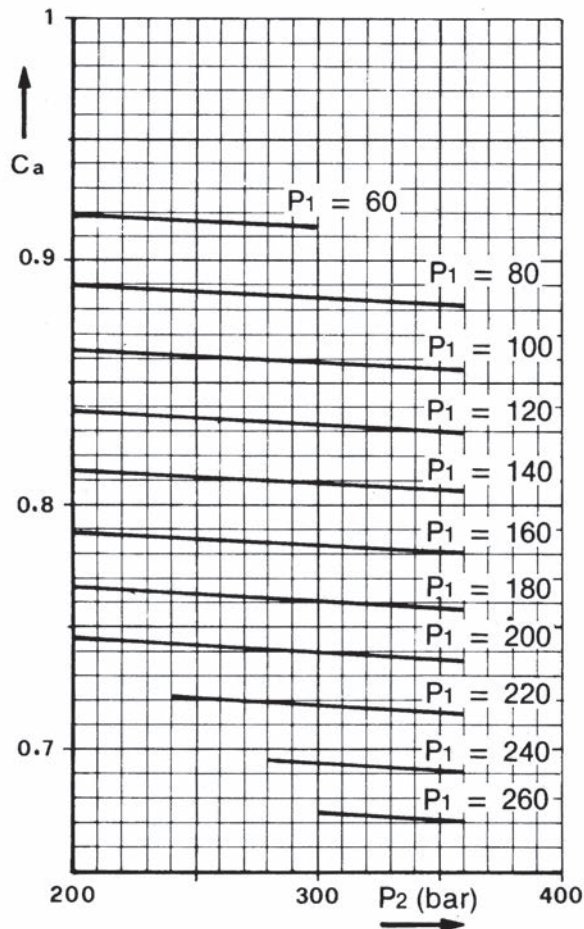
$$V_{0 \text{ real}} = C_a \times V_{0 \text{ ideal}}$$

The correction factors C_i and C_a in the equations can be obtained from the following diagrams

Isothermal correction coefficient C_i



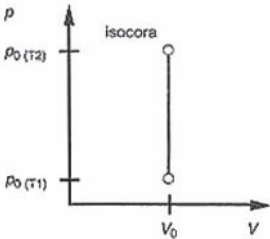
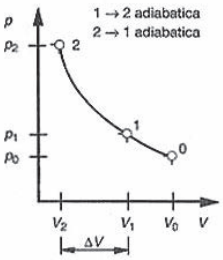
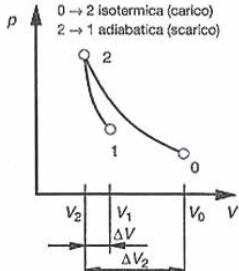
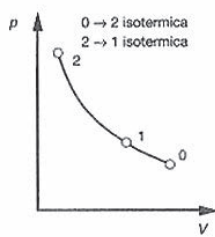
Adiabatic correction coefficient C_a



2.2c

Accumulator	Bladder accumulator High pressure	Bladder accumulator Low pressure	Diaphragm accumulator welded -	Diaphragm accumulator screwed	Piston accumulator with reduced friction
Gas pre-charge pressure P_0 (T_b) (at max. working temperature)	$\leq 0.9 \cdot p_1$ (accumulation of energy) = (0.6-0.9) $\cdot p_m$ (shock absorption)		$\leq 0.9 \cdot p_1$ (accumulation of energy) $0.6 \cdot p_m$ (pulsations damping)		$\leq p_1 - 5$ bar < 2 bar (piston with reduced friction) < 10 bar (normal piston)

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Cycle (state change)	Equation	Notes
	$P_{0(T1)} = P_{0(T2)} \cdot T_{s \text{ min}} / T_{s \text{ max}}$	$P_{0(T1)}$ = pre-charge pressure at minimum temperature $T_{s \text{ min}}$ (degrees Kelvin) $P_{0(T2)}$ = pre-charge pressure at maximum temperature $T_{s \text{ max}}$ (degrees Kelvin) Use Calculation of the pre-charge pressure when the operating temperature is different from the pre-charge temperature.
	$\Delta V = V_0 [(p_0/p_1)^{1/n} - (p_0/p_2)^{1/n}]$ $V_0 = \Delta V / [(p_0/p_1)^{1/n} - (p_0/p_2)^{1/n}]$	$\eta = K = 1.4$ for nitrogen (p_0 at temperature $T_{s \text{ min}}$) Use Accumulation of energy
	$\Delta V_2 = V_0 p_0/p_2 [(p_0/p_1)^n - 1]$ $V_0 = \Delta V \cdot p_2/p_0 / [(p_2/p_1)^{1/n} - 1]$	Use Emergency, safety (p_0 at temperature $T_{s \text{ min}}$)
	$\Delta V = V_0 (p_0/p_1 - p_0/p_2)$ $V_0 = \Delta V / [p_0/p_1 - p_0/p_2]$	Use Leak and volume compensation (p_0 at temperature $T_{s \text{ min}}$)

2.2e

Temperature variation

Temperature variation can seriously affect the pre-charge pressure of an accumulator. As the temperature increases, the pre-charge pressure increases; conversely, decreasing temperature will decrease the pre-charge pressure. In order to assure the accuracy of your accumulator pre-charge pressure, you need to factor in the temperature variation.

The temperature change is determined by the temperature encountered during the pre-charge versus the operating temperature expected in the system.

NOTE: it is important to wait for the thermal exchange caused by pressure shifts to be stabilized in order to check or adjust the pre-filling pressure. As a safety measure, isolate the nitrogen source during the stabilization period.

Equation used

This equation is used for correction of nitrogen filling pressure P_0 in relation to the operating temperature.

$$P_0(T_s) = P_0(T_{20}) \times \frac{T_s + 273}{T_{20} + 273}$$

$P_0(T_s)$ = filling pressure at checking temperature

$P_0(T_{20})$ = nitrogen pressure P_0 at 20°C

NITROGEN FILLING PRESSURE	200	173	183	186	193	200	207	214	221	227	234	241	248	255	261	268
	190	164	171	177	184	190	197	203	210	216	222	229	235	246	248	255
	180	155	162	168	174	180	186	192	198	205	211	217	223	229	235	241
	170	147	153	158	164	170	176	182	187	193	199	205	211	216	222	228
	160	138	144	149	155	160	166	171	176	182	187	193	198	204	209	215
	150	130	135	140	145	150	155	160	165	171	176	181	186	191	196	201
	140	121	126	130	135	140	145	150	154	159	164	169	173	178	183	188
	130	112	117	121	126	130	134	139	143	148	152	157	161	166	170	174
	120	104	108	112	116	120	124	128	132	136	141	145	149	153	157	161
	110	95	99	103	106	110	114	118	121	125	129	133	136	140	144	148
	105	91	94	98	101	105	109	112	116	119	123	127	130	134	137	141
	100	86	90	93	97	100	103	107	110	114	117	120	124	127	131	134
	95	82	85	89	92	95	98	102	105	108	111	115	118	121	124	127
	90	78	81	84	87	90	93	96	99	102	105	108	112	115	118	121
	85	73	76	79	82	85	88	91	94	97	100	102	105	108	111	114
	80	69	72	75	77	80	83	86	88	91	94	96	99	102	105	107
	75	65	67	70	72	75	78	80	83	85	88	90	93	96	98	101
	70	60	63	65	68	70	72	75	77	80	82	84	87	89	92	94
	65	56	58	61	63	65	67	69	72	74	76	78	81	83	85	87
	60	52	54	56	58	60	62	64	66	68	70	72	74	76	78	81
	55	48	49	51	53	55	57	59	61	63	64	66	68	70	72	74
	50	43	45	47	48	50	52	53	55	57	59	60	62	64	65	67
	45	39	40	42	43	45	47	48	50	51	53	54	56	57	59	60
	40	35	36	37	39	40	41	43	44	45	47	48	50	51	52	54
	35	30	31	33	34	35	36	37	39	40	41	42	43	45	46	47
	30	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	25	22	22	23	24	25	26	27	28	29	30	31	32	33	33	34
	20	17	18	19	19	20	21	21	22	23	23	24	25	26	26	27
	15	13	14	14	15	15	16	16	17	17	18	18	19	19	20	20
	10	8.6	9	9.3	9.7	10	10.4	10.8	11.1	11.4	11.8	12.2	12.6	13	13.4	13.8
	5	4.3	4.5	4.7	4.8	5	5.2	5.3	55.5	5.7	5.9	6	6.2	6.4	6.5	6.7
		-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120
REFERENCE TEMPERATURE °C																

2.2f

2.2.3 EMERGENCY ENERGY RESERVE WITH BLADDER ACCUMULATOR

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

Volume will be given by:

$$V_o = \Delta V / (P_o/P_2)^{1/n} \cdot [(P_2/P_1)^{1/n} - 1]$$

And stored volume by:

$$\Delta V = V_o (P_o/P_2)^{1/n} \cdot [(P_2/P_1)^{1/n} - 1]$$

Where:

$n = 1.4$ adiabatic coefficient (quick discharge phase)

$n_e = 1 \div 1.4$ polytropic coefficient (slow storage phase)

$$V_o = \Delta V P_2/P_o / (P_2/P_1)^{0.7143} - 1 ; \quad \Delta V = V_o P_o (P_2/P_o)^{0.7143} - 1/P_2$$

Example:

An accumulator must discharge 4.6 litres of oil in 3 seconds with a change of pressure from $P_2 = 280$ bar to $P_1 = 220$ bar.

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

$$V_o = \Delta V / (P_o/P_2)^{1/1.1} - [(P_2/P_1)^{1/1.4} - 1]$$

$$= 4.6 / (199/281)^{0.09091} \cdot [(281/221)^{0.7143} - 1] = 33.63 \text{ l}$$

$$P_1 = 221 \text{ abs. bar} \quad n_e = 1.1 \text{ (from Fig.2.2a)}$$

$$P_2 = 281 \text{ abs. bar} \quad T_1 = (273+20) = 293 \text{ °K}$$

$$P_o = 0.9 \times 220 = 198 = 199 \text{ bar abs.} \quad T_2 = (273+50) = 323 \text{ °K}$$

Considering the correction coefficient for high pressure and the temperature change, we have:

$$V_{ot} = V_o / C_m \times T_2/T_1 = 33.63/0.777 \times 323/293 = 47.7 \text{ l}$$

Where:

$$C_a = 0.72$$

$$C_i = 0.834$$

$$C_m = C_a + C_i / 2 = 0.777$$

The pre-charge pressure at 20°C will be:

$$P_{o(20^\circ\text{C})} = 199 \times 293/323 = 180.5 \text{ bar} = 179.5 \text{ rel. bar}$$

The accumulator type is **AS55P360**.....

2.2.4 PULSATION COMPENSATOR Q WITH BLADDER ACCUMULATOR

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

The fluid amount ΔV to be considered in the calculation depends on the type and capacity of the pump:

$$\Delta V = K \cdot q$$

Volume becomes:

$$V_o = K \cdot q / (P_o/P_1)^{0.7143} - (P_o/P_2)^{0.7143}$$

Where:

q = pump displacement (litres)

= $A \times C$ (piston surface $\times$ stroke)

= Q/n = flow rate (l/min) / strokes/min.

P = average working pressure (bar)

$P_1 = P - X$ (bar)

$P_2 = P + X$ (bar)

$X = \alpha \cdot P/100$ (bar) deviation from average pressure

α = remaining pulsation $\pm$ (%)

K = coefficient taking into account the number of pistons and if pump is single or double acting.

Pump type	K
1 piston, single acting	0.69
1 piston, double acting	0.29
2 pistons, single acting	0.29
2 pistons, double acting	0.17
3 pistons, single acting	0.12
3 pistons, double acting	0.07
4 pistons, single acting	0.13
4 pistons, double acting	0.07
5 pistons, single acting	0.07
5 pistons, double acting	0.023
6 pistons, double acting	0.07
7 pistons, double acting	0.023

2.2g

Example:

Assume a 3-piston pump, single acting, with a flow rate $Q = 8$ m³/h and operating pressure of 20 bar. Calculate the volume necessary to limit the remaining pulsation to $\alpha = \pm 2.5\%$. Pump RPM 148. Working pressure 40°C.

$$P = 20 \text{ bar} \quad q = 8000/60 \times 148 \times 3 = 0.3 \text{ l}$$

$$P_2 = (20 - 0.5) = 19.5 \text{ bar} \quad K = 0.12$$

$$P_2 = (20 + 0.5) = 20.5 \text{ bar} \quad X = 2.5 \times 20/100 = 0.5 \text{ bar}$$

$$P_o = (0.7 \cdot 20) = 14 \text{ bar}$$

$$V_o = 0.12 \times 0.3 / (15/20.5)^{0.7143} - (15/21.5)^{0.7143} = 1.345 \text{ l}$$

$$P_{o(20^\circ\text{C})} = 15 \times 293/313 = 14 \text{ abs. Bar} = 13 \text{ bar rel.}$$

The most suitable accumulators is the low pressure type: **AS1.5P80**...

2.2.5 HYDRAULIC LINE SHOCK DAMPER WITH BLADDER ACCUMULATOR

A rapid increase in pressure caused by a high acceleration or deceleration in flow is commonly known as water hammer. The overpressure, ΔP max, that takes place in piping, the flow rate, the density of the liquid and the valve shut down time.

This is given by:

$$\Delta P \text{ max (bar)} = 2 Y L v / t \times 10^5$$

The volume of the accumulator, required to reduce shock pressure within predetermined limits ΔP , is obtained by:

$$V_0 = Q/7.2 (2 Y L v / C_0 \times 10^5 - t) / (P_0/P_1)^{0.7143} - (P_0/P_2)^{0.7143}$$

Where:

V_0 = accumulator gas capacity (litres)

Q = flow rate in the piping (m^3/h)

L = total length of piping (m)

Y = specific gravity of the fluid (kg/m^3)

V = $Q/S \times 103/3.6$ = flow velocity (m/s)

$S = \pi d^2 / 4$ = internal pipe section (mm^2)

d = internal pipe diameter (mm)

ΔP = allowable overpressure (bar)

P_1 = operating pressure by free flow (absolute bar)

$P_2 = P + \Delta P$ = max allowable pressure (absolute bar)

t = deceleration time (s) (valve shut down, etc.)

Example:

Assume a water pipe ($Y = 1000 \text{ kg}/\text{m}^3$) with internal diameter $d = 80 \text{ mm}$, length $L = 450 \text{ m}$, flow rate $Q = 17 \text{ m}^3/\text{h}$, operating pressure $P_1 = 5 \text{ bar}$, allowable overpressure $\Delta P = 2 \text{ bar}$, valve closure time $t = 0.8 \text{ s}$.

$$\Delta P \text{ max} = 2 \times 1000 \times 450 \times 0.94 / 0.8 \times 10^5 = 10.57 \text{ bar}$$

The accumulator volume necessary to reduce the ΔP max to 2 bar is:

$$V_0 = 17/7.2 (2 \times 1000 \times 450 \times 0.94 / 2 \times 10^5 - 0.8) / (5.5/6)^{0.7143} - (5.5/8)^{0.7143} = 46.4 \text{ l}$$

Where:

$$S = \pi \times 80^2 / 4 = 5026.5 \text{ mm}^2$$

$$V = 17 \times 103 / 5026.5 \times 3.6 = 0.94 \text{ m/s}$$

$$P_0 = 5 \times 0.9 = 4.5 = 5.5 \text{ abs. bar}$$

$$P_1 = 6 \text{ abs. bar}$$

$$P_2 = 5 + 2 = 7 \text{ bar} = 8 \text{ abs. bar}$$

An accumulator of 55 litres low pressure range will be chosen, type **AS55P30**...

2.2.6 PISTON ACCUMULATOR + ADDITIONAL GAS BOTTLES (TRANSFER)

In all case where a considerable amount of fluid must be obtained with a small difference between P_1 and P_2 , the resultant volume V_0 is large compared to ΔV .

In these cases, it could be convenient to get the required nitrogen volume by additional bottles. Volume calculation is performed, according to the application, both in isothermal as well as in adiabatic conditions, using the formulas given above always taking temperature into account. To get the maximum of efficiency, it is convenient to fix a quite high pre-charge value. In case of **energy reserve**, it is possible to use:

$$P_0 = 0.97 P_1 \quad \text{or} \quad P_0 = P_1 - 5$$

Once the required gas volume is calculated, the volume must be allocated between the minimum indispensable portion V_A , which represents the volume of additional bottles.

$$V_{0T} = V_{0A} + V_{0B}$$

Where:

$$V_{0A} \geq \Delta V + (V_{0T} - V_0) / 0.75$$

This means that the sum of the required fluid volume plus the volume change due to temperature must be **lower than 3/4 of the accumulator capacity**. The bottles volume is given by the difference.

$$V_{0B} = V_{0T} - V_{0A}$$

Example:

Suppose $\Delta V = 30 \text{ l.}$ to be obtained in 2 seconds, from a pressure $P_2 = 180 \text{ bar}$ to $P_1 = 160 \text{ bar}$.

Temperature: $q_1 = 20^\circ\text{C}$; $q_2 = 45^\circ\text{C}$

$$P_{0(45^\circ\text{C})} = 0.97 \times 160 = 155 \text{ bar}$$

$$V_0 = \Delta V / (P_0/P_1)^{0.7143} - (P_2/P_1)^{0.7143} \\ = 30 / (156/161)^{0.7143} - (156/181)^{0.7143} = 382.4 \text{ l}$$

$$V_{0T} = 382.4 \times 318 / 293 = 415 \text{ l}$$

$$V_{0A} = 30 + (415 - 382.4) / 0.75 = 83.5 \text{ l}$$

One accumulator **AP100**... is used with the total $V_0 = 100 \text{ l.}$ plus **6 bottles of 50 l.** type **B52P360**... or 4 additional bottles type **B75P360**... of 75 l.

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