Chapter 13

FLUID CONTAMINATION

The fluid of oil hydraulic systems is inevitably contaminated with solid, liquid and gaseous particles from the external environment or developed in the fluid itself during operating and rest phases. Such a contamination can be accidental and inevitable, due to negligence or it can be the result of poor maintenance and lack of additional components. These particles are very polluting and they cause fluid alteration and circuit corrosion, with the ensuing system inefficiency and even system failure.

Contamination control ('contamination' is the technical word referring to the inclusion of particles in oil hydraulic fluids) plays a fundamental role in designing advanced oil hydraulic systems that cannot sustain a particle with a diameter of just a few micron. Many authoritative studies involving laboratory and machine tests showed that 70% of oil hydraulic failures are due to fluid contamination. As a matter of fact, the use of appropriate filters, as well as correct maintenance is vital to ensure a long working life of systems; failing them, machines are bound to be short-lived, even if they are designed properly and provided with high-quality components, well-dimensioned tanks, suitable relief valves, smooth hoses with an adequate bore and a fluid with appropriate additives.

The percentage mentioned above can seem exorbitant compared to the general causes of deterioration of a mechanism. Oil hydraulic systems are always lubricated abundantly since the fluid flows through every pressurised component and the drain lubricates non-pressurised components; mobile parts and parts subjected to friction are designed so as to last longer than the machine, provided they are adequately lubricated, or at least to sustain a specific amount of operating time before needing replacing. The fluid itself guarantees heat dissipation under normal working conditions, while extreme working conditions can easily be envisaged and suitable measures can thus be taken in advance. As a result, the real cause of deterioration can be nothing other than a fluid contaminated with foreign particles that has devastating effects on components.

For this reason, the techniques of contamination prevention and contaminated filter cleanup are crucial and indispensable in any circuit. Fluid decontamination entails first a careful analysis of the contamination causes and second the adoption of measures that neutralise its consequences. Particles are removed by various types of filters that block impurities thus preventing them from reaching the tank, the pipes and the different components.

The inclusion of filters in every hydraulic system is the only method to reduce fluid contamination to an acceptable level. The care level of filtration depends on the type of system and its components. Fluids cannot be decontaminated totally (by the way, no new fluid is pure), but at such a level that mobile parts can sustain. Nonetheless, it is crucial to do everything possible to avoid further contamination.

CONTAMINATION AND RELATED EFFECTS

In order to choose the right decontamination system, it is important to be aware not only of the technical parameters of the circuit (pressure/flow, environmental features, type of process, type of fluid, maintenance cycles), but also of the causes of contamination and the physical composition of the contaminating substances.

Sources of contamination

As said above, particles can be in the solid, liquid and gaseous state. Solid contaminants are certainly the main cause of deterioration; gaseous particles undermine system performances and promote the development of other solid contaminating substances. The ingress of foreign liquids leads to viscosity alterations and changes into vapour and ice.

A system can be subjected to an **initial** contamination due to the introduction of an inadequate fluid. The fluid can be a poor-quality type or have been stored in dirty tanks or tanks with traces of liquid substances such as water, diesel, petrol or solvents; another major cause of contamination can be a poor cleaning of the internal parts of the system (e.g., presence of dust or assembly residues).

It is clear that the prevention of initial contamination does not require expensive resources: a scrupulous examination of the fluid and the new machine (especially its tank, cylinders, manifold single blocks and piping) are enough.

Progressive contamination is much more complicated. The expression 'progressive contamination' refers to all those contaminations that occur during the working life of a machine. Progressive contamination can be caused by the wear and deterioration of seals and metal parts, oxidation or other chemical phenomena and poor maintenance. The following paragraphs focus mainly on poor maintenance.

Genesis and nature of the contaminant

The presence of **solid particles** in a contaminated hydraulic fluid is generally due to the following causes:

- ✓ *Manufacturing and assembly of components*: traces of shavings, soldering waste, fusion sand, corpuscles of cast iron, aluminium and other metals, rubber, fibres can be found on components although manufacturers strive to provide clean components. Unfortunately, during storage the lubricating oils attract much dust that enters components.

- ✓ *Working machine operation*: during operating cycles, the friction between components generates metal and seal particles that settle in the tank. Furthermore, the parts that are in contact with the external environment (such as cylinder rods, drive shafts, valve control rods, albeit equipped with rod wipers) are inevitably contaminated by dust and other substances found in the air. If tank air breathers are not protected with appropriate filters, they allow the ingress of dust.
- ✓ *Maintenance operations*: inaccurate replacement, disassembly and assembly of components, fluid replenishment and substitution entail the contamination with abrasives substances.

Gaseous contaminants result from the phenomenon described in Chapter 2 (Hydraulic fluids properties, Vapour pressure). In one litre of hydraulic mineral oil there are about 80 cm^3 of air (8-10%). In case of high pressure, the suction of more air from the tank leads to a considerable reduction in system performance (at atmospheric pressure, the amount of changes according to the kind of fluid; water content is about 3-4% in water-glycol emulsions, 5-6% in water-oil emulsions, 7-9% in synthetic fluids). The fluid contaminated with gas flows back into the tank and it is sucked again. This phenomenon is evident if there is foam in the tank, which means there is air in the oil film. Before taking complex measures, it is important to make sure first that all the pipes connected to the tank, apart from drains, are placed under the fluid level.

The presence of foreign **liquids** can results from either the condensation of the steam found in the atmosphere (hence found on the free surface of the fluid or the initial contamination previously described.

Therefore, ordinary contamination is the consequence of a many different chemical and mechanical phenomena that should not occur ideally but that are inevitable even in advanced systems.

What follows is a list of the most important processes that cause fluid contamination and hence system damage:

- ✓ **Abrasion** – Particles already found in the fluid penetrate the gap between two opposite mobile surfaces (for example a directional valve spool/ body, the opposite teeth of a gear pump or motor, the piston/cylinder of a piston pump or motor, the poppet/seat of a non-return valve), thus abrading their surfaces. The ensuing particles are a source of contamination.
- ✓ **Erosion** – Particles already found in the fluid are pushed against a solid part (metal, elastomers) at a high speed, abrade its surface and produce more contaminants, like in the previous case. As pressure rises, even the smallest particles foster the erosion process.
- ✓ **Adherence** – The contact of two metal parts causes adherence because of molecular attraction; for this reason, some particles can stick together or to any surface.

- ✓ **Mechanical stress** – Tearing can occur in highly stressed components; the ensuing particles contaminate the fluid.
- ✓ **Cavitation and air inclusion** – the presence of gas can cause or promote cavitation phenomena (see chapters 2 and 3).
- ✓ **Corrosion** – Water and other chemical substances attack sensitive materials. Rust due to oxidation increases the number of abrasive particles.
- ✓ **Microbial reproduction** – The presence of water promotes the large-scale reproduction of the few microorganisms found in the mineral fluid. Fluid properties are thus undermined and highly corrosive phenomena occur.

In addition, there is a problem about additives. As a matter of fact, in order to have some specific characteristics (antirust, wear-resistance, Pour point depressant, antifoam properties– see Chapter 2), they contain particles of zinc, silicone, phosphorus, boron, sulphur and chlorine or particles of magnesium, barium, calcium and so on. Furthermore, in some special cases of nuclear radiation exposition, the fluid undergoes changes that can wear washers, thus increasing contamination.

Effects on the system

Contaminants affect all oil hydraulic fluid purposes:

- ✓ *Energy transmission* – The presence of gas affects compressibility while water reduces viscosity; they are both a source of cavitation.
- ✓ *Lubrication* – Solid particles abrade materials, resulting in damage on the opposite surfaces. Foreign liquids reduce the lubricating properties of the fluid.
- ✓ *Sealing* – The abrasion and corrosion of metal surfaces and elastomers reduce their thickness, leading to leakages.
- ✓ *Degradation of fluid properties* – The presence of foreign bodies, liquids and gases modifies the quality of the fluid. This causes early ageing and degradation of the fluid properties.

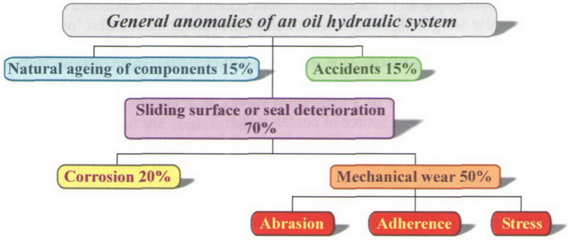


Figure 13.1

Studies carried out in Europe and in the USA confirm that degradation, the collapse or the malfunctioning of oil hydraulic systems depend mainly on contamination control quality (Figure 13.1).

Particle size definition

The size of contaminating particles is measured in microns, the abbreviation of micrometre [µm], which means one millionth of a metre. The size is defined by calculating the longest chord of the particle.

Equivalances of microns, inches and mesh		
microns	*inches*	*mesh*
297	0.0117	50
210	0.0083	70
149	**0.0059**	**100**
105	0.0041	140
74	0.0029	200
53	0.0021	270
44	0.0017	325
10	0.00039	1250
5	0.000019	2500

The table above shows the size of the most common particles. Besides microns, particle sizes are measures in inches or **mesh** in Anglo-Saxon countries.

Particle size:		
micron	*from*	*to*
Grain of salt	80	200
Sea sand	100	2000
Calcareous dust	10	1000
Powder coal	5	500
Ø human hair	40	150
Coal dust	1	100
Cement dust	3	100
Talc powder	5	60
Bacteria	3	30
Paint pigments	0.1	7
Tabacco smoke	0.01	1
Minimum size men can see: 40 micron		

Critical tolerance

Each component of an oil hydraulic system has a minimum or critical tolerance between sliding or sealing parts. Beyond this critical tolerance, solid particles cause the effects described so far.

For instance, assuming the tolerance between the spool and the body of a directional valve equals 40 micron, smaller particles can pass through the clearance without causing any damage while larger particles cause the degradation of its components. If we consider this parameter only, the circuit end would need a filter at in order to extract all the foreign bodies that are larger than 40 micron. Actually, the situation is much more complicated because it is important to take the whole circuit into account as its components have different critical tolerances; in addition, filters cannot work properly throughout their whole working life. Furthermore, most components are affected by their function: in an axial piston pump, the critical tolerance between the pistons and the cylinders is not the same as that of the body and the distribution plate.

As a result, tolerance must take the orthogonal movements of axial sliding parts into account. Assume a distributor has a maximum tolerance of 40 micrometres: if two particles (40 and 30 micrometres) entered respectively the upper and lower space between the spool and the body, they would amount to 70 micrometres overall, i.e. an unacceptable level.

What is more, pressure affects the filtering quality (high pressure fosters the passage of large particles between sliding parts) and metal or elastic seals are subjected to abrasion and corrosion. Although rod wipers prevent the inclusion of particles from the external environment, some tiny particles still enter causing the degradation of rod wipers.

What follows are few general examples of the critical tolerance of some oil hydraulic components.

Critical tolerances of some oil hydraulic components

Component	*Area*	*micron*
(Compensated) gear pumps	body	1 - 2
	teeth/body	2 - 100
Vane pumps	vane/stator	0.5 - 1
	vane/rotor	5 - 15
Piston Pumps	piston/cylinder	5 - 30
	hydrostatic power steering	1 - 10
	port face	0.5 - 2
Directional Valves	spool/body	2 - 20
Servo- valves	nozzle	18 -60
	poppet/seat	2 -20
	holes	150 - 400
	Ports	1 - 5
Actuators	in general	50 - 250

Critical tolerances and filtration degree of components can be calculated only approximately: the same component can have different critical tolerances according to its manufacturing quality. In other words, decontamination is strictly related to the characteristics of the device. The use of filters depends on the quality of the component and decontamination as recommended by manufacturers is affected by the product quality. On average, pumps require a 10-25 micron filters, whereas valves need 20-25 micron filters, except proportional valves that demand 10 micron filters; servo-valves require a filters with meshes equalling about 6 micron.

Typical failures

There are three kinds of failures causes by contaminated fluids:

- ✓ *Irreparable failure* (called catastrophic failure): particles that enter the gap between mobile parts compromise their functioning (piston failure, blocked slider, poppet/seat damage).
- ✓ *Transitory failure*: some particles enter components undermining their operation temporarily; during the opposite movement, the pressurised fluid cleans the seats dragging the contaminants (particles create a clearance between the spool and the seat, blocks the complete shifting of the spool, etc.). It is difficult to identify the main cause of this kind of failure since it causes the abnormal operation of the whole system.
- ✓ *Progressive deterioration*: it is due to not only the natural deterioration of components, but also to the continuous micro-erosion (the high-speed pressurised fluid throws particles against the walls) and abrasion produced by particles that cause more and more damage over time. A poor control of filters leads to irreparable failure.

Erosion can be considered less catastrophic then abrasion if it is kept under control. As a matter of fact, an excellent filtration of the particles having a larger size than the minimum clearance of devices do not lead to an increase in contaminants; the inevitable tiny particles found in the fluid cause a relatively negligible erosion that can be considered as natural degradation.

Instead, designers and maintenance workers must take abrasion seriously into account. The damage caused by particles carried by the fluid can be irrelevant or substantial according to their size. Particles cause the erosion of servo-valves and bearings. Contaminants that are larger than sliding clearance are blocked upstream: this can lead to a restriction of the inlet hole with an ensuing flow reduction; however, this occurs rarely if filters work properly. The main threat is posed by those particles having a size close to the critical tolerance: two slightly smaller particles can easily merge while two slightly larger particles can be pushed into the pressurised fluid; in both cases abrasion causes many problems as well as the development of new contaminants. (Figure 13.2)

Every device deteriorates if contaminants in the fluid undermine its surfaces. The most delicate part of vane pumps is the gap between the mobile vane and the stator. By abrading the stator and smoothing the tip of the vane, contaminants seriously compromise the sealing between the suction and delivery chambers (Figure 13.3). An appropriate filtration also avoids damage to the less exposed parts of the vane and the rotor.

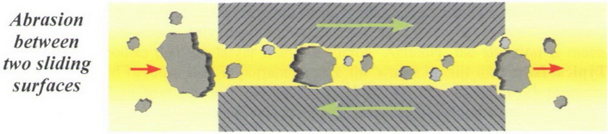


Figure 13.2

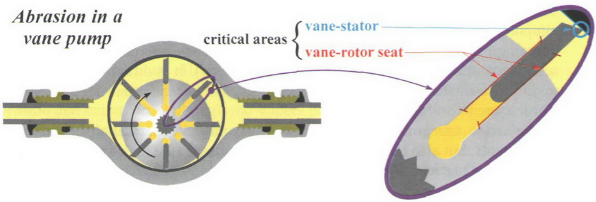


Figure 13.3

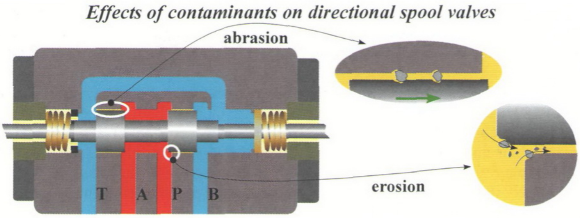


Figure 13.4

In directional valves contaminants cause abrasion on the surfaces of the spool and obviously of the body; high-speed particles pushed by the fluid damage the surfaces and smooth the angles of active parts of the spool and the holes of the valve body. (Figure 13.4)

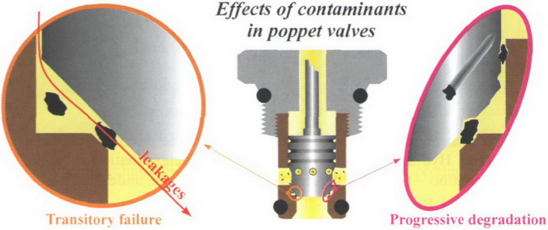


Figure 13.5

Particles can enter the gap between the seat and the spool of any directional valve or control valve, thus entailing leakages; in many cases, particles are pushed back during the reverse movement but the damaged surfaces undergo deformation over time, undermining their performances (Figure 13.5).

ANALYTICAL METHODOLOGIES

The choice of the filtration system for a certain circuit is strictly related to the analysis of the circulating fluid. Analysis methods used to identify the contamination degree are established by some standards and they are fundamentally based on the calculation of the number of contaminating particles found in a specific amount of fluid. According to the method chosen, this implies taking samples of the liquid in one or more specific areas of the circuit. The sample is then examined in a laboratory.

The scrupulosity and the repetitiveness of the analysis is strictly related to some factors inherent to the systems, like it complexity, its technological quality, its operating time, its pressures and flow rates, its working temperatures and the environmental conditions.

International fluid analysis standards

Over the last 30 years the analytical complexity and different methods chosen have led to the creation of a set of standards that set the appropriate system to identify the fluid contamination degree. Some of them are now outdated because they would lead to unreliable systems; consequently, these outdated standards are thus replaced by other standards bases on modern methodologies. ISO standards about hydraulic fluid contamination are part of other general or specific standards such as those establishing testing powders features or components testing in fluid power. The following list provides a good documentation that can be considered as the main point of reference.

- ISO 3938 Hydraulic Fluid Power – Contamination Analysis – Method for reporting analysis data
- ISO 4021 Hydraulic Fluid Power – Particles contamination analysis – Extraction of fluid samples from lines of an operating system
- ISO 4406 Hydraulic Fluid Power – Fluids – Solid contaminant code
- ISO 4407 Hydraulic fluid power – Fluids – Determination of solid particle contamination – Counting method using a microscope under transmitted
- ISO 12103/1 Road vehicles – Test dust for filter evaluation – Part 1: Arizona test dust.
- ISO 11218 Aerospace – Cleanliness Classification for Hydraulic Fluids.
- ISO 11171 Hydraulic Fluid Power – Calibration of automatic particle counters for liquids.
- ISO/TR 16386 Impact of changes in ISO fluid power particle counting-contamination control and filter test standards
- NAS (National Aircraft Standard) 1638 Cleanliness Requirements of Parts Used in Hydraulic Systems.
- SAE AS 4059 Aerospace Fluid Power – Cleanliness Classification for Hydraulic Fluids.
- SAE ARP 598 – Aerospace Microscopic Sizing and Counting of Particulate Contamination for Fluid Power Systems.
- NIST (National Institute of Standards and Technology) – Standard Reference Material 2806 – Medium Test Dust (MTD) in Hydraulic Fluid (1997).

Beside these, there are other standards on filters features and their working life, which are covered in the next paragraph.

Testing powders

Comparisons among contaminating and non-contaminating fluids, the calibration of tools for contaminant measurement, the definition of filters performances and tests must be carried out with a specific testing powder containing a specific amount of particles having a specific size.

Testing powders under ISO 12103

ISO standard	*Type*	*General information*
ISO 12103 – A1	ISO UFT (ultrafine test dust)	PTI(*) 0-10 mm test dust
ISO 12103 – A2	ISO FTD (fine test dust)	PTI fine test dust SAE fine test dust
ISO 12103 – A3	ISO MTD (medium test dust)	PTI 5-80 mm test dust SAE 5-80 mm test dust
ISO 12103 – A4	ISO CTD (coarse test dust)	PTI coarse test dust SAE coarse test dust

(*) PTI (Powder Technology Inc.) stands for the company that produces the powder.

The first testing powder is from Arizona (USA) and it is made of ground silica granules ranging from 0 to 100 μm. It was marketed in the 1960s and it is known as ACFTD (Air Cleaner Fine Dust Trust). ACFTD was the standard for components trials and calibrations for 20 years under ISO 4402, 9632, 4572. As in the early 1990s the US company which had the patent stopped producing it, the SAE and the ISO started procedures for a substitute product. The resulting ISO 12103 led to the standardization of a product divided into four different powders (see the table above).

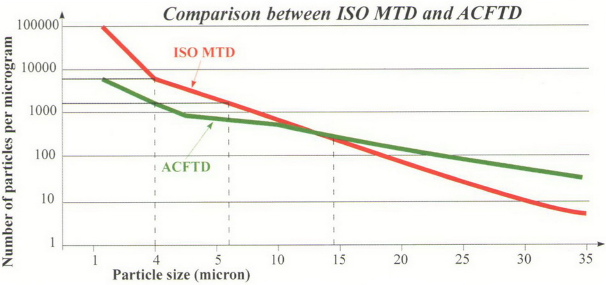


Figure 13.6

Powders normally used in Fluid Power are the ISO MTD (A3) and the ISO FTD (A2). The difference, albeit limited, between the new powders and ACTFD forced the ISO to update ISO 4402 procedure, which was thus replaced with the ISO 11171; ISO/TR 16386 explores the consequences of these changes.

ISO 4402 established the definition of particles according to their maximum chord (that is the circumference of its longest projection). Nowadays all the particles whose surface is equivalent to their bidimensional projection are considered as irregular particles by counting devices; consequently, tools do not consider their chord but their diameter. Compared to the previous one, this system shows a discrepancy: 1 μm of ACFTD under ISO 4402 corresponds to 4.2 μm of MTD under ISO 11171.
Therefore, the new definition in micrometres is followed by the letter 'c' in brackets, for example 6 μm(c) and 14 μm(c).

Contamination level codification

ISO 4406, which was issued in 1987 and modified several times until 1999, sets the procedure for hydraulic fluids contamination level codification. Particle counting enables to determine the exact quantity of contaminants per millilitre of fluid. Since the quantity is usually very high and their minimum deviation is irrelevant, a single numerical code refers to a number of particles having similar size ranging from a minimum to a maximum level (example: Code ISO 21 = from 10000 to 20000 particles contained in 1 millilitre of the fluid).

Given the importance of particle size, the final codification includes 3 codes (there were 2 codes instead before).

The first numerical code refers to the number of particles per millilitre of fluid that are larger than 4 μm(c).

The second numerical code stands for the number of particles larger than 6 μm.

The third numerical code considers the number of particles larger than 14 μm.

For instance, 21/17/13 identifies a contamination of:

- ✓ From 10000 to 20000 particles larger than 4 μm(c)
- ✓ From 640 to 1300 particles larger than 6 μm(c)
- ✓ From 40 to 80 particles larger than 14 μm(c)

The following chart shows numerical codes in respect to the amount of contaminants.

ISO 4406 – Scalar numbers and their code		
Particles per millilitre of fluid		ISO code
More than	Up to	
80000	160000	24
40000	80000	23
20000	40000	22
10000	20000	21
5000	10000	20
2500	5000	19
1300	2500	18
640	1300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1
0.005	0.01	0
0.0025	0.005	0.9

NAS 1636 is often used as an alternative to ISO 4406. NAS 1636 was created for the aerospace industry but now it is used in oil hydraulics as well. NAS standards identify a series of classes from 00 to 12 that indicate the maximum particle quantity per 100 millilitres calculated on a differential base, in a certain size range.

The following chart shows data referring to NAS 1638, but this was replaced by the 4059 standard in order to conform with ISO 11171.

NAS 1638 – maximum levels of contamination – Sample of 100 ml														
Size	*Classes*													
	00	0	1	2	3	4	5	6	7	8	9	10	11	12
5-15µm	125	250	500	1000	2000	4000	8000	16K	32K	64K	128K	256K	512K	1.024M
15-25µm	22	44	89	178	356	712	1425	2.85K	5.7K	11.4K	22.8K	45.K	91.2K	182.4K
25-50µm	4	8	16	32	63	126	253	506	1012	2025	4050	8.1K	16.2K	32.4K
50-100µm	1	2	3	6	11	22	45	90	180	350	720	1.44K	2.88K	5.76K
< 100µm	0	0	1	1	2	4	8	16	32	64	128	256	512	1024

$K=10^3$; $M=10^6$

Particle counting

What has been said so far highlights the fact that contaminant definition cannot be the result of empirical methods; it is instead the result of reliable, uniform and accurate techniques. Another important factor is the proportion between the quantity of the fluid and its contaminants: in other words, the result refers to the quantity of contaminants found in a certain volume of liquid. The oldest method is based on the counting of numerical particle by means of an **optical microscope**. The fluid is taken from the tank or from the port M (M: take-off port, see Chapter 8, Directional Valves) of a valve; it is then filtered through a porous membrane; the examination of this membrane at the microscope and its comparison with the sample membrane determines its contamination class.

Particle counting can also be performed through **gravimetrical analysis**. The sampled fluid flows between two membranes whose weight has been previously defined; after the filtration, the difference between the gross weight and the tare indicates the quantity of particles. This is the simplest method of gravimetrical analysis.

Spectrographic analysis consists in a comparison between a sample fluid and a sample taken from the machine: the spectrum of the latter, calculated with an infrared rays device (spectrometer), is compared with the former in order to identify solid and chemical contaminants.

Unlike optical microscopes, **scanning electron microscopes** (SEM) are capable of identifying also chemical contaminants.

The **ferrography** technique is suitable when contaminants have a ferrous origin (they are mainly due to erosion): particles are separated with a magnet, then their size is calculated with a microscope. This method can be used when all components are of steel mix origin only; particles from elastomers, anti-extrusion seals etc... are not identified.

Nowadays, the simplest, quicker and cheapest (except for the initial costs) method is based on **optoelectronic sensors**, which calculate the number and size of particles flowing in a testing pipe via some electronic mechanisms. We are now going to analyse the special procedures employed in this important method.

Laser diode optical sensors

Optoelectronic sensors are used not only in oil hydraulics but also in semiconductor manufacturing, pharmacology and drinking water analysis. These devices (Figure 13.7), also known as **automatic particle counters**, are made up of two essential parts:

Optical sensor – it identifies contaminant particle size and quantity.

Counter – the signals identified by the optical sensor are processed and printed or showed on a display.

Automatic particle counter

Figure 13.7

A bottle sampler can be connected to the counter. Bottle samplers compare the sampled fluid with the ideal contamination-free fluid, thus identifying the class of contamination (Figure 13.8).

Bottle sampler-counter combination

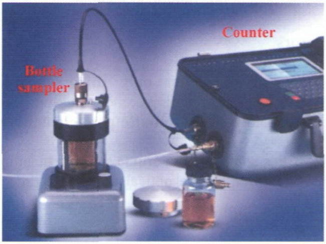


Figure 13.8

Automatic counters can be used in a laboratory or directly connected to the machine through a small pipe. Results are shown on a display or printed (every model is equipped with a display and a mini-printer). They can respond to the versions established by ISO 4406 or NAS 1638. With specific software they can be transformed into diagrams displayed on a Pc (Figure 13.9).

A rapid comparison between particle quantity upstream and downstream of the filter can be performed with a specific optoelectronic device called *Twin laser system.*

Automatic particle counter

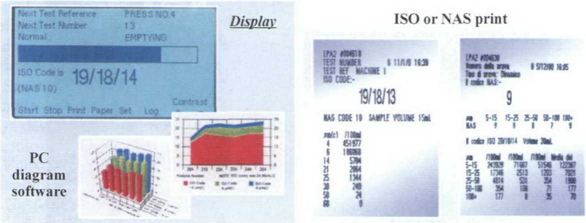


Figure 13.9

The device for particle counting consists of an emitter, more precisely a laser optical sensor, and a photodetector that sends signals to the counting unit. The technique for the identification of particles that are larger than a micrometre is based on the principle of light extinction between the emitter and the photodetector

(Figure 13.10); the pipe in which fluid flows is placed between them. A light scattering emitter/photodetector is needed in case of measurements below 1 micron. Whenever a particle enters the gap between the laser diode and the photodetector, the light extinction produces an electric signal proportional to the particle size in the photodetector. Signals are sent to the counting device and processed according to the calibration previously performed with the sample fluid, whose particle distribution is known.

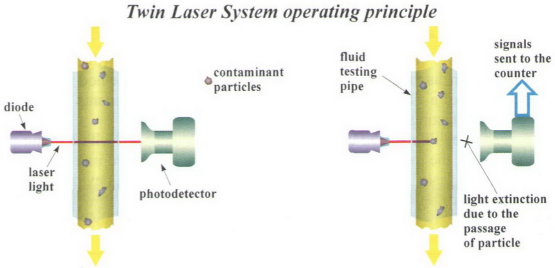


Figure 13.10

FILTRATION TECHNIQUE

Filtration devices too have to meet all the requirements of the following standards:

- ISO 2941 Hydraulic fluid power – Filter elements – Verification of collapse/burst resistance
- ISO 2942 Hydraulic fluid power – Filter elements – Verification of fabrication integrity and determination of the first bubble point.
- ISO 3723 Hydraulic fluid power – Filter elements – Methods for end load test
- ISO 3724 Hydraulic fluid power – Filter elements – Verification of flow fatigue characteristics
- ISO 3968 Hydraulic fluid power – Filters – Evaluation of differential pressures versus flow characteristics
- ISO 16889 Hydraulic fluid power – Filters – Multi-pass method for evaluating filtration performance of a filter element.
- ISO 11170 Hydraulic fluid power – Filter elements – Sequence of tests for verifying performance characteristics.

Filtration devices consist of the following parts:

- ✓ Filter – generic filtration component made up of internal, external and auxiliary components and placed on the machine or near it; it is often wrongly called 'filter element'.
- ✓ Filter body – it contains all the components (filter element, by-pass valve, magnet) and it is equipped with inlet/outlet ports for its connection to the pipe.
- ✓ Filter element – it is found inside the body and its task it to stop contaminants.

Multi-pass test

The efficiency of a filtration element is defined by ISO 16889 (that replaces ISO 4572). It is known as 'multi-pass test' or 'Beta Ratio'. This method identifies the retaining capacity of a filter by calculating the quantity of contaminants upstream and downstream of the testing filter.

This test has to be effectuated on an appropriate bench equipped with a motor pump and a testing filter; the motor pump and the filter must be connected in a closed circuit (Figure 13.11). A laser system type automatic particle counting device is arranged upstream and downstream of the filter and they display all the information about the exact size and quantity of particles on the terminal; testing powders with specific size are added to the fluid.

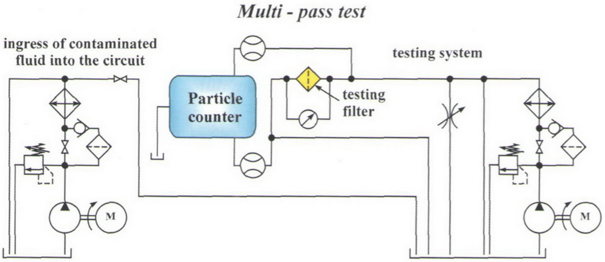


Figure 13.11

The resulting Beta Ratio ($\beta_{x\mu}$) about particles having a specific size ($x\mu$) is calculated according to particles quantity before and after the filter

$$\beta_{x\mu} = \frac{\text{Number of particles larger than X micron before the filter}}{\text{Number of particles larger than X micron after the filter}}$$

For example, if the multi-pass test of a specific filter identifies the presence of 4000 contaminating units equalling 9.8 μm(c) upstream of the filter and 20 elements of the same size after the filter, its retaining capacity of particles of 9.8 micrometres has $\beta_{9.8(c)} \geq 200$.

The Beta Ratio can be calculated in percentage with the following formula:

$$E_{x\mu} = \frac{\beta_{x\mu} - 1}{\beta_{x\mu}} \cdot 100$$

For example, $\beta_{9.8(c)} \geq 200$ can be converted into a percentage as follows:

$$E_{9.8\,(c)} = \frac{200 - 1}{200} \cdot 100 = 99.5\%$$

The following table shows the relations between Beta Ratio and its respective percentages.

Beta Ratio ($\beta_{x\mu}$)	Filter efficiency ($E_{x\mu}$) %
1	0%
1.5	33%
2	50%
5	80%
10	90%
20	95%
50	98%
75	98.7%
100	99%
200	99.5%
1000	99.9%
5000	99.98%
10000	99.99%

Key features of filters

Filters of oil hydraulic systems have to meet requirements that are fundamental for the correct operation of the machine. These requirements are:

- ✓ Quick reduction in fluid initial contamination and the impurities that can be found in the system.
- ✓ Steady curbing in progressive contamination over a long time according to the system features.
- ✓ A by-pass valve that operates upon filter clogging is often needed.

- ✓ Optical or electromechanical indicator in case of clogging (placed on the filter body).
- ✓ Filter elements must sustain nominal pressures, overpressures or mechanical stress; they must also be long-lived and retain the particles blocked.
- ✓ Filter size must be compatible with the circuit maximum flow.
- ✓ Low pressure drop (differential pressure between inlet and outlet) .
- ✓ Uniform filtration despite reasonable temperature/viscosity changes.
- ✓ Compatibility with the fluid.
- ✓ Compact size and limited weight.
- ✓ The design must promote easy maintenance (replacement or cleanup of the filter element).
- ✓ Filtration capacity must be suitable for the circuit components.
- ✓ Low initial and maintenance cost.

Filter selection criteria

The type of filters and their arrangement in a system entail some reflections related not only to what was stated above but also to the whole functionality, costs, operating and security conditions.

Designers must choose inlet filters or outlet/tank filters according to the components, installation/maintenance costs and minimal efficiency. As a matter of fact, filtration devices differ considerably as far as inlet/outlet pressure is concerned.

The *contamination sensibility of components* determines the size of meshes inside filter elements. Technical catalogues usually recommend the ISO codes in terms of the maximum acceptable fluid cleanliness for each component. Clearly, if a single filter decontaminates several devices, the filtration degree must correspond to the features of the most delicate unit.

The solidity of the filter body and the filter element depend on the *working pressure* and the kind of *cycle* (soft, medium, heavy type); the choice is thus affected by the following pressure range:

0 – 70 bar; 70 – 150 bar; 150 – 250 bar; 250 – 350 bar; more than 350 bar

Environmental conditions are very important in the choice of the filter element since they play an important role in fluid contamination. Protected places such as laboratories are considered as places enjoying *good* environmental conditions; industrial sites and lifts have *fairly good* conditions, whereas the maritime and mobile industries experience *difficult* conditions and foundries are subjected to *very bad* environmental conditions.

Filter quality is strictly related to working hours. Manufacturers divide productions into different groups according to them: up to 1000 working hours, 5000 working hours, 10000 working hours, more than 10000 working hours.

Maximum tolerable contamination of oil hydraulic components (general data). Contamination classes under ISO 4406			
	P max = 70 bar	***P max = 130 bar***	***P max = 200 bar***
Gear pumps	20/18/15	19/17/15	----
Vane pump- fixed displacement	20/18/15	19/17/14	18/16/13
Vane pumps- variable displacement	18/16/14	17/15/13	----
Piston pumps- fixed displacement	19/17/15	18/16/14	17/15/13
Piston pumps- variable displacement	18/16/14	17/15/13	16/14/12
Directional solenoid valves	----	20/18/15	19/17/14
Pressure control valves	----	19/17/14	19/17/14
Flow control valves	----	19/17/14	19/17/14
Non- return valves	----	20/18/15	20/18/15
Proportional directional solenoid valves	----	17/15/12	15/13/11
Pressure control proportional valves	16/14/12	15/13/11	----
Servo-valves	----	16/14/11	15/13/10
Cartridge valves	----	18/16/13	17/15/12
Hydraulic remote control valves	18/16/13	----	----
Cylinders	20/18/15	20/18/15	20/18/15
Vane motors	20/18/15	19/17/14	18/16/13
Axial piston motors	19/17/14	18/16/13	17/15/12
Radial piston motors	20/18/14	19/17/13	18/16/13
Orbital motors	21/19/17	20/18/15	19/17/14
Closed circuit (hydrostatic drive)	----	17/15/13	16/14/12

The scrupulous consideration of these parameters has clearly a major impact also from the *economic* point of view, especially if the system has many filters. The use of filters whose performances are higher than those actually required is absolutely useless: apart from considerable costs, the initial differential pressures are likely to be higher than expected and they also occupy more space and weigh more. Security is another fundamental aspect: filters plays a key role in every system whose failure can pose a serious threat (for instance, if the cylinder of the breaking system of a vehicle is clogged and there are no by-pass valves, the vehicles takes more time to break).

Filter element

Particle retaining can be performed through *surface or in-depth* filtration. In surface filtration, impurities with a larger size than mashes pile up on the side penetrated by the fluid while in-depth filtration particles are blocked in the filter element (Figure 13.12).

Surface filter elements (Figure 13.13) are made up of a rolled metal square mesh ending with two shaped discs. It is possible to perform filtrations up to 25 μm.

Piling-up of particles in filter elements

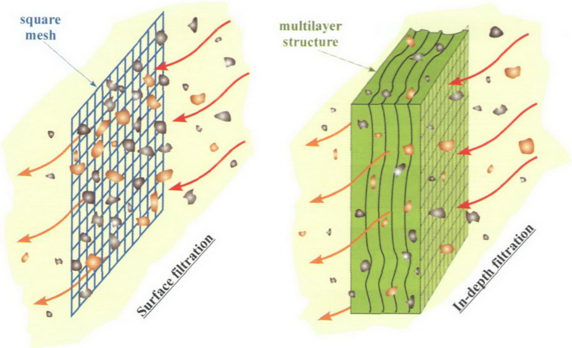


Figure 13.12

Metal mesh of a surface filter element

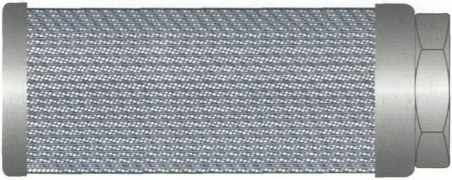


Figure 13.13

Other surface filter elements consist of a specific triangular or notched thread wound around a riddled cylinder (Figure 13.14). Manufacturers state this technique ensures a minimum filtration of 25 μm. The thread can be made of bronze, brass, stainless steel or other rustproof and corrosion-resistant metal materials. It is important to underline that many manufacturers prefer to avoid this in oil hydraulics.

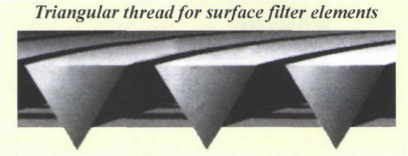


Figure 13.14

Particles are kept in the filter element in **in-depth** filters, whose blind holes are made of fibrous and porous materials. Only very tiny particles remain in the fluid. Figure 13.15 shows the general operating principle of these components.

In-depth filters are made of random-oriented fibres. The fluid releases its contaminants while it flows through tangled ways. As felt is now obsolete, it is replaced by paper with cellulose fibres, nylon and other synthetics fibres. The whole downstream face of the elements or both faces are supported by metal grills. In order to exploit the filter surface as much as possible and to guarantee the maximum axial solidity, the paper – or any other fibrous material – is folded and rolled in a cylindrical shape (Figure 13.16). Once the filter is clogged, it must be replaced since its depuration is not possible.

In-depth filter element operating principle

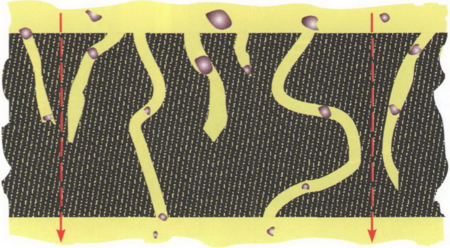


Figure 13.15

Fibrous or surface filter cartridges (Figure 13.17) for inlets or outlets (see later on) are solidly arranged inside the bucket of the filter body.

Zoom in on an in-depth filter element made of a fibrous material

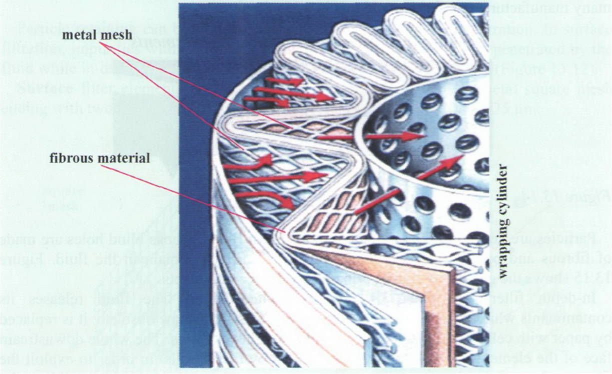


Figure 13.16

Cartridge filters

Figure 13.17

In filter elements made of *sintered* metal, which is an agglomerate of bronze microspheres (they can also be made of stainless steel, titanium or nickel), the fluid flowing in the tiny gaps between the microspheres releases its solid impurities. Even though they can sustain very high pressures and temperatures, they are not suitable for systems subjected to considerable vibrations because they are rather rigid.

In versions with microspheres reduced to the minimum, solid decontamination up to 2 μm is possible. Sintered elements are rarely used as generic filters; instead, they are widely used as microfilters in order to protect different components (manual pumps, load sensing and proportional valves, compensator, etc.); in these cases, these elements act as a hollow cylinder inside the component.

By-pass valve

Pressure losses between the inlet and outlet of the filter cause a differential pressure that rises as clogging increases. In order to avoid useless pressure losses, a non-return valve (its poppet faces the inlet port) placed inside the head of the filter is operated when the maximum differential pressure is exceeded (Figure13.18).

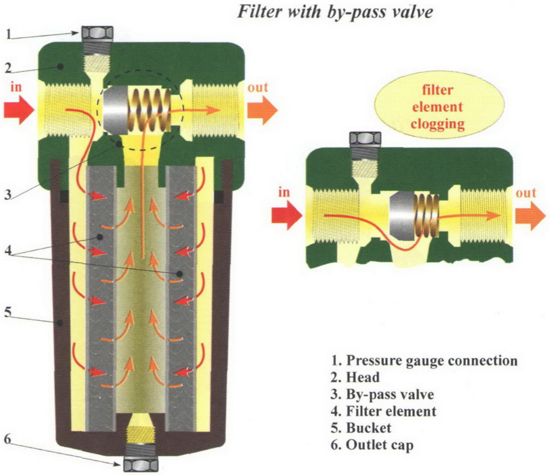


Figure 13.18

Clogging gauge

Filters are not always equipped with a by-pass valve; even if there is one, it is difficult to make sure whether it is clogged. The need for filter element replacement – or depuration in some cases - is indicated by a clogging gauge placed on the head of the filter (Figure 13.19).

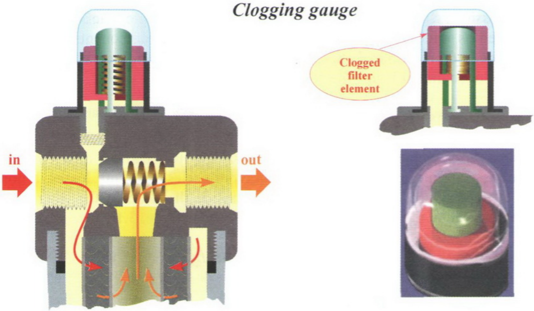


Figure 13.19

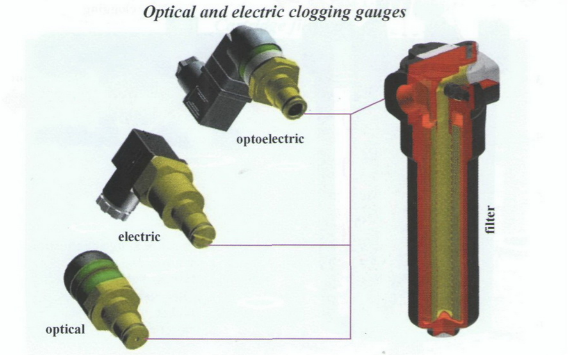


Figure 13.20

The clogging gauge, often called **service indicator** or **efficiency indicator**, displays the accumulation level. It has two indicators of different colours (usually red and green): the predominance of the red one means that the maximum differential pressure has been exceeded while green predominance indicates the accumulation level.

The electrical version allows the remote signalling of clogging; the opposing spring of the optical indicator or simply the pressure switch closes a contact connected to a light indicator, a siren or any other signalling device and connects the contact to a solenoid valve with shut-off function: the whole system thus is isolated or supply is blocked in series with the solenoid starter of the prime mover.

Figure 13.20 shows an electric connector with an optical gauge.

Magnetic separation

In order to avoid an early filter clogging it is possible to place a magnetic column that attracts and keeps ferromagnetic particles and reduces the filter cartridge clogging (Figure 13.21).

This device is useless with high-speed flows and very tiny particles; furthermore, it is necessary to make sure that even slow flows are not subjected to abrupt speed surges in order to avoid that particles enters the fluid again. Magnetic bars, columns or parallelepipeds can also be permanently installed in the tank.

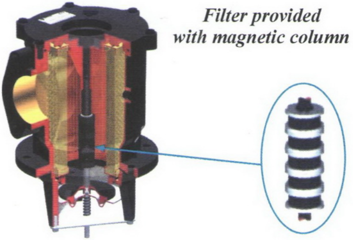


Figure 13.21

Duplex

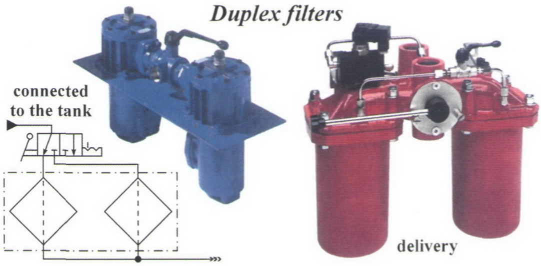


Figure 13.22

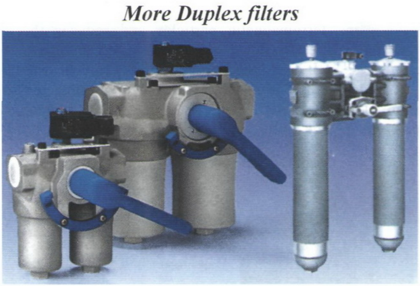


Figure 13.23

The inclusion of a second parallel filter with the same features as the first filter allows the replacement of the clogged filter without stopping the machine. The two filters have to be introduced alternatively through a ball hand switch 3/2 (Figures 13.22 and 13.23).

Spin-on

Spin-on have the same structure as the diesel motor filters used in civil and industrial vehicles. They are widely used in mobile applications and sometimes also in stationary applications.

Spin-on have the same features as other oil hydraulic filters but they sustain maximum flows of 350 l/min and maximum pressures of 12 bar. The head is assembled 'in line' (the hydraulic connection to the pipes affects also the assembly of the element); it can have a by-pass valve and optoelectric indicators. The filter element (surface or fibrous in- depth type) cannot be cleaned since it cannot be separated from the bucket (Figure 13.24).

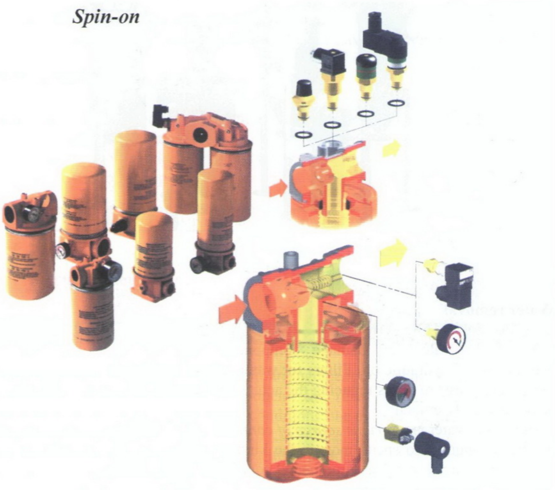


Figure 13.24

As they can be replaced easily, their costs are cut and their maintenance is easy, especially in mobile machine, because the bucket and the filter are only spinned on the head (hence, the word 'spin-on'); an elastomer placed on the flat part of the mobile unit ensures sealing.

Self-cleaning filters

These filters, provided with surface filter element and body, are equipped with a manual or automatic cleaning device. This device consists of a wiping mechanism that can be operated from the outside without stopping the machine (Figure13.25).

The substances wiped settle to the bottom of the bucket and are periodically removed by workers.

Figure 13.25

Water removal

No doubt water can damage components seriously and cause the chemical degradation of hydraulic oil. Filters for water cannot be added in most systems because they entail pressure drops reducing the actual power, even though their decontaminating action is clearly crucial.

However, water is a *serious source of contamination*. Water removal methods depend on the willingness to spend money, the kind of system and the quantity of water; the latter is influenced by the environmental conditions of the system.

Unless the system experiences technical accidents in which water ingress is temporary but devastating (pipe bursts or poor sealing in oil-water heat exchangers, open tank filling port, hydro-pressure cleaning of the machine), water steadily enters the system in the form of humidity. Air humidity enters the tank through its air bleeds, which stop solid particles but cannot block the micro-drops in the air. Because of environmental or system temperature changes, humidity condensates and mixes with the fluid. Furthermore, humidity that settles on the cylinder rod during extraction can penetrate through worn seals.

The most common water removal methods are based on gravity or centrifugal separation, absorption (particles are trapped in the interstices), adsorption (some materials, such as silica, accumulate water on their surface), or coalescence (micro-drops are gathered together by the filter element and thus fall to the bottom of the bucket).

The method based on cooling devices is very efficient. Their coil contains a cooling fluid at a temperature of about 0 °C; cooling devices promote the achievement of the dew point of the vapour contained in the air and the resulting drops fall to the bottom of the box so that the condensation separator in series to it removes them. Apart from absorption (coalescence filters are instead used in pneumatic transmissions as they guarantee brilliant results), the other methods require additional components, which add to the high costs of a per se complicated system.

Consequently, this problem cannot be underestimated; most stationary applications (at least those placed indoor and not subjected to the direct action of water) have a low-risk factor but it is a major problem for self-propelled or naval machines.

FILTER PLACEMENT

Filter placement depends on the component features. We have already discussed the possibility of introducing an inlet, outlet or tank filter; the circuit can have just one filter, for example a suction filter, or many filters. Filter arrangement affects pressure drops, as shown in the following table.

Filters - Pressure drops (differential pressure)		
	Δp min	Δp max
Suction filters	0.02 bar	0.1 bar
Low-medium-high pressure filters	1 bar	1.5 bar
Return filters	0.3 bar	0.5 bar

The following conditions usually affect their arrangement on machines:

- ✓ In order to protect a specific component, the filter must be placed directly upstream of it (delivery); under these conditions, the system is equipped with one or more additional filters.
- ✓ Contamination control requires two filters in medium/simple applications: a suction filter connected to the pump inlet port and a return filter connected to the tank directly or indirectly. Simple systems are often equipped with only one suction or return filter for economic reasons, but this technique is not recommended more often than not.
- ✓ Contamination control can also be performed with an external recycling system with an auxiliary pump (off- line filtration); it is advisable to equip the main pump with a suction filter.
- ✓ Contamination control requires also filter ports placed in the tank for fluid replenishment or filling. The ports for air bleed must be protected by filters that prevent the ingress of the contaminants found in the air.

We are now going to describe the three positions in which filters can be mounted. It is important to underline that most systems require many filters that have to be placed according to specific needs.

Suction filters

In oil hydraulic systems, the suction filter plays a vital role even if it has large meshes because it prevents the ingress of large particles from the tank into the circuit.

Generic scheme of a suction filter

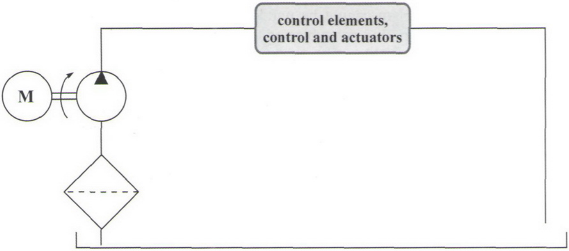


Figure 13.26

Body and cut-away view of a suction filter

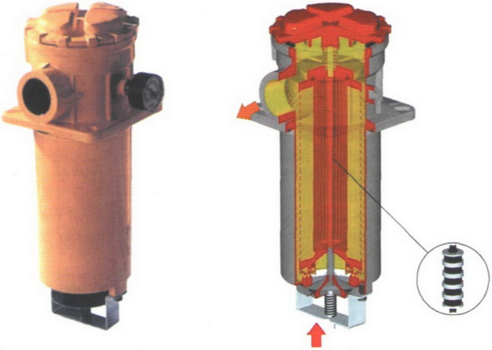


Figure 13.27

Examples of a suction filters

Figure 13.28

Suction filters (Figure 13.27) are equipped with elements having a low degree of filtration that ranges from 60 to 250 μm (remember that it reaches 10 μm in the suction process in hydrostatic transmissions). As a matter of fact, a large mesh is needed so as to avoid cavitation problems in the pump: the maximum acceptable pressure drops must not produce a differential pressure that is higher than 0.1 bar. For this reason, in machines subjected to low temperature starts, the high viscosity of the fluid must not cause further pressure drops. Otherwise, the filter cartridge must be replaced with another cartridge with lower decontaminant power. This operation has to be carried out after checking the pump and filter installation features in their catalogues.

A slight change in suction pressure undermines the functioning of some pumps. Under these circumstances, it is advisable to avoid this kind of filtration.

It was common practice in the past to connect the filter to the inlet tube end at the bottom of the tank. As EN 982 has banned it, the filter is now placed between the pump and the inlet tube with flanges.

It is advisable to mount the filter so that it can be replaced without emptying the tank; however, if this is the case, some of the filter impurities are likely to fall to the bottom of the tank during this operation. If it is supported on a wall flange, the filter can be bulky but the easy extraction of the cartridge reduces maintenance operations considerably.

Low – Medium – High pressure filters

A pressure filter can be placed in order to protect the whole system, a part of the system or just a component that needs a high level of decontamination (Figure 13.29).

Generic diagrams for low-medium-high pressure filters

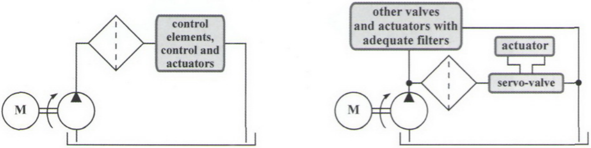


Figure 13.29

In pressure filters, filter elements have small mashes since higher pressure drops over the filter are tolerated (see previous table); their body must sustain high nominal pressures and this leads to an increase in costs.

Components for low-medium-high pressures are available on the market and they are standardized as follows: p max 15, 35, 60, 110, 250, 320, more than 400 bar, maximum flows over 1000 l/min and maximum filtration degree equal to 3 micron.

Pressure filters are placed immediately downstream of the pump in some systems in order to protect components from damage caused by the pump itself; in any case, the pump is the main element responsible for contaminating particle production.

Cut-away view and body of a low-medium-high pressure filter

Figure 13.30

Since filters cannot be arranged in the suction position because of the suction features of many pumps, another use of pressure filters consists in placing them before the element that generates the hydraulic power. It is advisable to use suction filters with large meshes plus another filter for the removal of the particles produced by the actuator or by control components.

In machines equipped with electroproportional systems, servo-valves, Load sensing or control lines, the filter is generally placed downstream of the control component that needs protection. Under these circumstances, it is clearly advisable to choose an element whose filtration degree equals the filtration degree of the component that needs protection, and whose maximum flow is equivalent to the maximum flows found upstream of the component.

Examples of a
low-medium-high pressure filters

Figure 13.31

Return filters

The filtration of the return line is the most common technique in small/medium-sized oil hydraulic systems without high-level controls. However, the return filter is related to the need for a single return pipe connected to the tank and a suction filter (it is even possible to equip each pipe with its own filter if there are many return lines) (Figure 13.32).

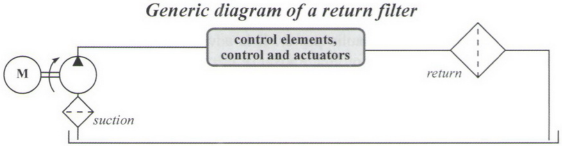


Figure 13.32

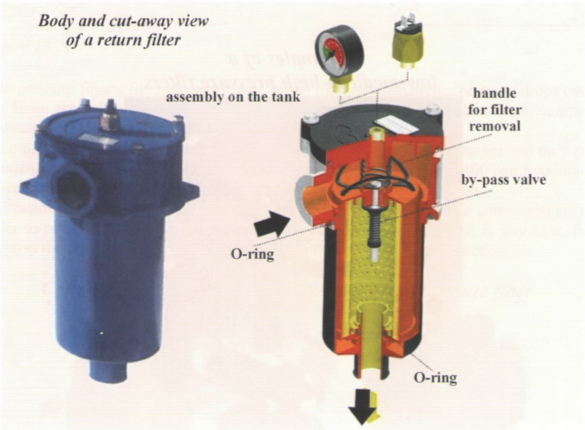


Figure 13.33

The filtration degree usually ranges between 25 and 125 μm, although return elements ranging from 3 to 250 micron with flows ranging from 10 to 1500 l/min are available as well. The maximum tolerable pressure of the component must be in line with the maximum tolerable pressure of the system; return filters that can sustain pressures ranging from 3 to 25 bar are available on the market (Figure 13.33). These filters are not suitable for the closed circuits of oil hydraulic motors (hydrostatic transmission, hoists) since the return branch turns into a pressure branch in the reverse direction; the auxiliary pump of such systems can be protected through a return filter instead.

In order to define the size of the filter that has to be placed on the return line, it is important to consider that the actual return flow is often much higher than the flow delivered by the pump because of the presence of accumulators, fast discharge valves and many differential cylinders in the circuit.

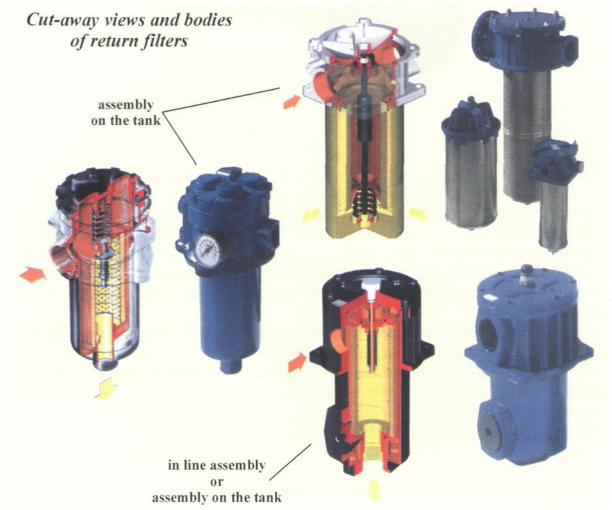
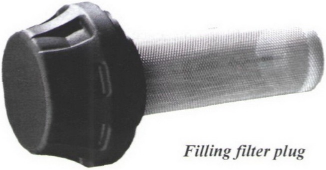


Figure 13.34

Most return filters are assembled with the body placed on the external side and the bucket fastened on the internal side of the tank cover with a pipe that ends under the level of the fluid (Figure 13.34). Some slip-in types are provided with an additional plug for the fluid replenishment or filling.

Filter plugs

Apart from preventing the accidental ingress of contaminants, filter plugs avoid the initial contamination (see first paragraph) caused by solid particles. The fastening plug (Figure 13.35) of the port is equipped with a large mesh basket grill that block contaminant ingress.



Filling filter plug

Figure 13.35

Breathers

When the machine is operating, the space over the fluid level is subjected to volume changes caused by the expulsion of fluid by the accumulators or movements of differential cylinders. The holes of air compensation, which are indispensable in order to avoid vacuums or higher pressures than atmospheric pressure, are on the upper wall of the tank and must be protected by filters capable to block all the impurities found in the air.

Filter elements consist of simple steel wool, other porous materials that can be held in a specific body or directly included in the plug or bended paper that has to be replaced upon clogging, like air filters for compressors or combustion engines, which are available in spin-on or cartridge versions (Figure 13.36). The choice of filter elements depends on the decontamination degree of the system. A system requiring a scrupulous depuration needs high-quality air filtration too.

Filter plugs and breathers

Figure 13.36

Off-line filtration

Off-line filtration or **recycling** filtration consists in the use of one or more separated filters that are completely independent from the operating system; the fluid is conveyed to the filter through a direct connection to the main pump or, in most systems, through an independent motor pump (Figure 13.37).

Generic diagrams of off-line filters

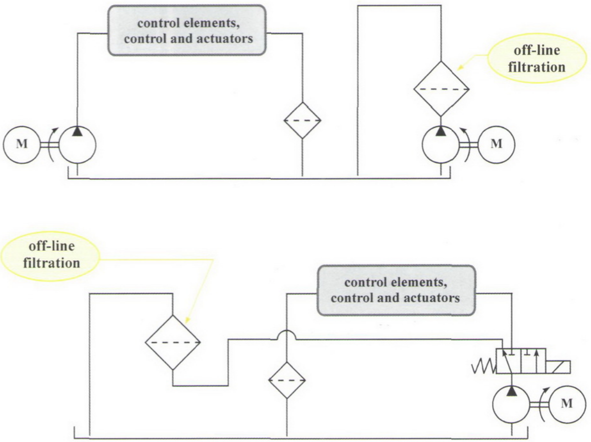


Figure 13.37

Flow accounts for 10-20% of the overall volume of the tank in recycling filtration and it can be divided into the following groups:

1) *Additional filtration in the system already equipped with filters*: the system itself cannot ensure the protection of the elements, which must not be subjected to pressure filters and return filters. Off-line filtration guarantees constant cleaning since it works even when the system is off (if equipped with an independent motor pump). Filter elements can be replaced even when the machine is working; since the machine is independent from the circuit, it is not affected by fluid hammers, stress and pressure drops that occur while the machine is working.

2) *Fluid replenishment*: this is the most efficient method to prevent initial contamination.

3) *Cyclic or occasional decontamination of the fluid*: the fluid is entirely decontaminated, if possible when the machine is not working. Special units deliver good results in terms of elimination of water and dissolved gases (Figure 13.39).

Off-line filtration small mobile unit

Figure 13.38

Large off-line mobile unit for solid, liquid and gaseous decontamination

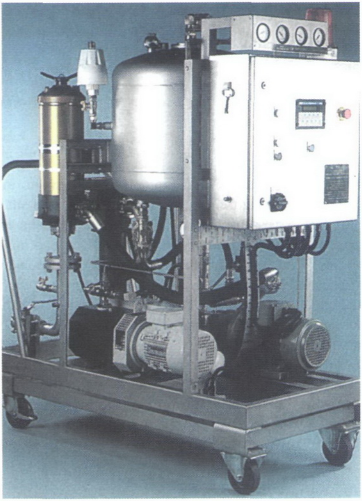


Figure 13.39

Chapter 14

ACCUMULATORS

Accumulators are an important element of a system in most obsolete and modern technologies from the energy point of view. As a matter of fact, by 'accumulator' we mean a device that absorbs energy from a specific source and releases it when it is needed. While the philosophic debate on whether the Voltaic battery is an accumulator or not is still ongoing (electric energy results from a chemical reaction but it is released right away), no doubt the battery of a vehicle, a mobile phone, an emergency light, a laptop and other devices is an accumulator that transforms the electric energy they receive from other sources into chemical potential, which is turned back into electricity when needed. Many other technologies are based on this same principle, like the tank of a pneumatic compressor, steam boilers and springs (they release their mechanical energy immediately or progressively, as shown in many oil hydraulic applications and in old clocks, whose gears were set into motion by a manually-loaded spring).

Examples of oil hydraulic accumulators

Figure 14.1

As far as oil hydraulic is concerned, the definition of an accumulator above needs broadening: the general task of an oil hydraulic accumulator is *to store a certain amount of energy*, that is a certain volume of fluid according to the container capacity at a specific pressure, *so as to release it during a specific phase of the operating cycle*. In order to highlight the role and the importance of accumulators better, it is worth considering the origins of the hydraulic accumulation process, which is still widely applied, albeit with some technological changes, in applications concerning industrial and drinkable water distribution. Pumps, above all piston versions, are subjected to pulsating flow (see Chapter 4) depending on the number of pistons: phases of positive flows (delivery) alternate with 0-flow phases (suction) if there is only one piston.

In the 19^{th} century, the water from wells already equipped with single-acting piston pumps gushed on alternately (the same phenomenon occurs in present hydraulic manual pumps, like screw jacks). In order to solve this problem, 'wind' pumps first appeared (as shown in Western films) and motor pumps later on (old motor pumps are displayed in any wine museum or among old fire-fighting devices) were equipped with an expansion box, the progenitor of the accumulator. As the 'suction-discharge pump' (this is how it was called) is operated, during the delivery phase the fluid partially occupies chamber P and compresses the air held inside. At the dead point of the piston, i.e. throughout the suction process, the air in chamber P can expand back, ensuring water thrust in the delivery pipe (Figure 14.2)

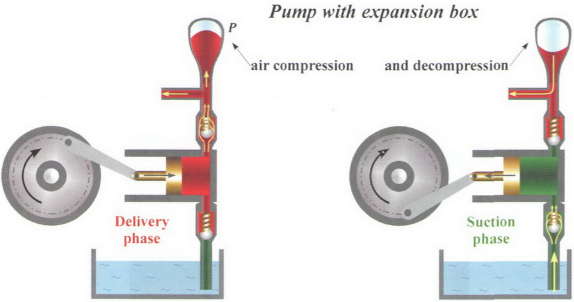


Figure 14.2

All modern oil hydraulic accumulators are based on this operating principle, even if they are more complex and equipped with additional devices. The oil hydraulic fluid that needs releasing at some specific point of the process is conveyed through a pipe from the delivery line into metal containers designed so as to sustain the nominal and peak pressures of the system.

Accumulators differ in fluid release. First of all, it is important to make a distinction between **constant pressure** accumulators (the fluid flows out of the accumulator at a uniform pressure throughout the phase) and **variable pressure** accumulators (pressure decreases as the fluid flows out). Accumulators differ also in their external source, which can be a spring, a weight or a compressed gas. Compressed gas accumulators can be further divided into two groups: accumulators with and without a separator between the hydraulic fluid and the gas.

What follows is a list of the ISO standards about accumulators:

- ISO 5596 Hydraulic Fluid Power – Gas-loaded accumulators with separator – Ranges of pressures and volumes and characteristic quantities.
- ISO 10945 Hydraulic Fluid Power – Gas-loaded accumulators – Dimensions of gas ports.
- ISO 10946 Hydraulic Fluid Power – Gas-loaded accumulators with separator – Selection of preferred hydraulic ports.

Like all pressurised containers, accumulators that exceed a specific nominal volume must have a test certificate in accordance with the standards of the country where they are installed. Furthermore, they must be checked periodically. The nominal volume, the maximum pressure and the pre-load pressure must be stated in a plate on the accumulator. Accumulators must comply with the Pressure Equipment Directive (Chapter 17).

ACCUMULATORS FOR CASUAL USE

Besides gas loaded accumulator with separator (see later on), different types of constant pressure and variable pressure accumulators are used in mobile and stationary hydraulic systems. Although they are rather unpopular (unlike the versions provided with separator), they are employed in long-life systems that are constantly operating, they are essential in some modern systems, like those demanding a constant pressure.

Weight loaded accumulators

Weight loaded accumulators are the only accumulators that are loaded and unloaded at a constant pressure (Figure 14.3). The piston equipped with seals that slide within the piston simply stores the fluid while the unloading thrust results from the mass of weights plus the piston, minus the friction due to seals. Like in any cylinder, the outlet pressure depends on the ratio of force to the surface F/S and it is affected by seal resistance. The loading force must be at least equal to the unloading force because if the nominal pressure of the circuit (relief valve pressure setting) is less than the pressure needed to lift the weights, the piston of the accumulator rests on the inlet port of the fluid.

The loading time determines the volume accumulated. For example, assuming a pump delivers 30 l/min and an accumulator has an effective volume of 15 l, it takes 30 seconds to fill it completely (friction is not taken into account); if the accumulator shut-off valve is open for 15 seconds only, 7.5 l of fluid are stored at the nominal pressure.

Weight loaded accumulators are used in oil hydraulics only if unloading demands a constant pressure. Otherwise their use is not recommended because of their large size, heavy weight, slow responses of the weight (this causes abrupt fluid hammers during loading), the need to arrange them in a vertical position and to prevent recoils.

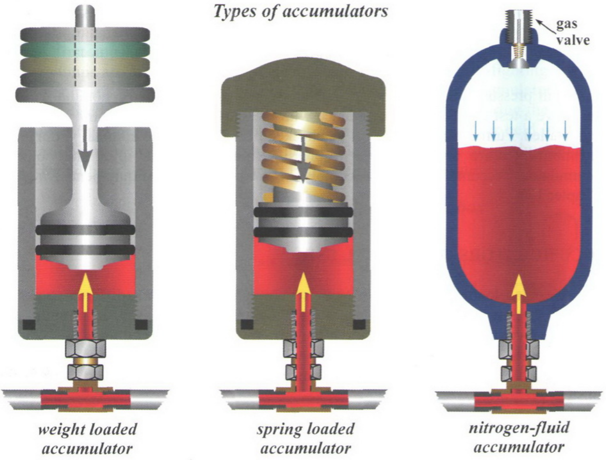


Figure 14.3

Spring loaded accumulators

Spring loaded accumulators are similar to weight loaded versions, but the weight is replaced by a spiral spring (Figure 14.3). Contrary to what is generally believed, they are variable pressure accumulators since the spring cannot deliver a constant energy as its stroke is subjected to elastic rules. Spring loaded accumulators are used to compensate for volume changes with an almost constant pressure (that is the reason why people consider them constant pressure accumulators) and they are small-sized because high pressures and flow rates would demand that the spring be held in expensive and bulky containers.

Nitrogen – fluid accumulators

Their operating principle is the same as the expansion box principle described at the beginning of this chapter: the fluid pushed inside the tank by the pump compresses the gas, but in this case it is already preset at a precise pressure (Figure 14.3). There are versions with one unit or more banks made up of an accumulation element that already holds some fluid and that is connected to other cylinders storing the pressurised inert gas (generally nitrogen). Banks allow the storage of large volumes, up to 4000 litres, but the lack of the separating diaphragm increases the risk of fluid and inert gas mixing. These accumulators are not much used in oil hydraulics although they ensure constant pressure unloading. They are used in some large oil hydraulic applications when the transmission fluid is water.

GAS-LOADED ACCUMULATORS WITH SEPARATOR

Gas loaded accumulators with separator are certainly less bulky and lighter than the previous ones. They are also more efficient and they avoid the risk of fluid and inert gas mixing. Furthermore, they sustain vibrations and can be arranged in any position. There are three types of such accumulators (piston accumulators, bladder accumulators and diaphragm accumulators), which differ in the component that separates the oil hydraulic fluid and the gas. The rest of this chapter focuses only on these types of accumulators.

Why nitrogen?

The gas used in gas loaded accumulators is generally nitrogen (N_2). Actually, the compression of the atmospheric air would avoid the rental of a cylinder and ease the task of maintenance men and installers, who could easily load the accumulator with a compressor delivering high pressures, replenish the gas leaked over time and set new parameters.

Nevertheless, nitrogen is employed for its inert properties: as a matter of fact, it is a non-flammable gas that does not cause corrosion; in addition, it is not expensive and it is available in super-pressurised cylinders provided by competent companies that must comply with high security standards. The high-pressure and high-temperature air-oil combination can trigger the spontaneous combustion that is the typical principle applied to diesel engines; under these circumstances, the explosion, which would occur close to the gas precharge valve (this is the most delicate area of the cylinder) would throw the valve itself and other fragments into the surrounding environment. Furthermore nitrogen reduces the ageing of elastic elements (seals and bladders).

Compressed air can be used instead of nitrogen in water systems or at a pressure below 15 bar. It is important to underline that the use of oxygen or other non-inert gases is absolutely forbidden, even at low pressures or in emergency situations.

Piston accumulators

The structure of piston accumulators is similar to the structure of an actuator cylinder: they have a body, a piston, end caps, static and dynamic seals. However, they are not provided with rods and the gas side of the piston is hollow in order to store a large quantity of nitrogen (Figure 14.4).

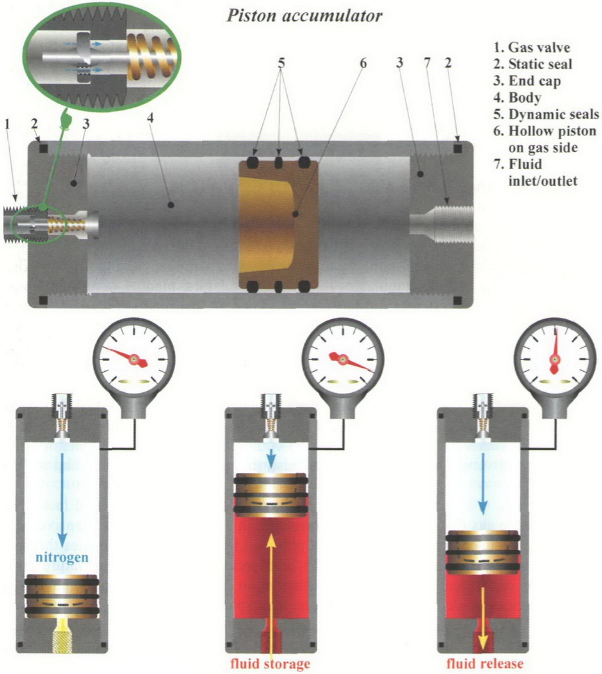
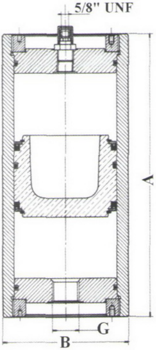


Figure 14.4

Piston accumulator size



Piston Ø mm	Working pressure (bar)	Oil volume in litres	A mm	B mm	Oil-gas connection	Weight kg
100	250	1	365	120	G 1"	16
100	250	2	493	120	G 1"	19
100	250	3	620	120	G 1"	22
100	250	4	747	120	G 1"	26
100	250	5	874	120	G 1"	29
100	250	6	1000	120	G 1"	33
100	250	10	1511	120	G 1"	47
100	**375**	**1**	**397**	**130**	**G 1"**	**23**
100	**375**	**2**	**525**	**130**	**G 1"**	**29**
100	**375**	**3**	**652**	**130**	**G 1"**	**34**
100	**375**	**4**	**780**	**130**	**G 1"**	**40**
100	**375**	**5**	**906**	**130**	**G 1"**	**45**
100	**375**	**6**	**1032**	**130**	**G 1"**	**50**
100	**375**	**10**	**1543**	**130**	**G 1"**	**72**
180	250	10	705	216	G 1½	90
180	250	15	900	216	G 1½	109
180	250	20	1100	216	G 1½	126
180	250	25	1275	216	G 1½	142
180	250	30	1490	216	G 1½	160
180	250	40	1885	216	G 1½	195
180	250	50	2277	216	G 1½	230
180	250	60	2670	216	G 1½	264
180	250	80	3455	216	G 1½	333
180	**375**	**10**	**753**	**216**	**G 1½**	**100**
180	**375**	**15**	**950**	**216**	**G 1½**	**118**
180	**375**	**20**	**1146**	**216**	**G 1½**	**135**
180	**375**	**25**	**1323**	**216**	**G 1½**	**151**
180	**375**	**30**	**1540**	**216**	**G 1½**	**170**
180	**375**	**40**	**1932**	**216**	**G 1½**	**204**
180	**375**	**50**	**2325**	**216**	**G 1½**	**239**
180	**375**	**60**	**2718**	**216**	**G 1½**	**273**
180	**375**	**80**	**3500**	**216**	**G 1½**	**342**
250	250	30	1042	294	G 1½	230
250	250	40	1245	294	G 1½	260
250	250	50	1450	294	G 1½	290
250	250	60	1653	294	G 1½	320
250	250	80	2060	294	G 1½	380
250	250	100	2468	294	G 1½	440
250	250	120	2875	294	G 1½	500
250	250	150	3485	294	G 1½	590
250	**350**	**30**	**1092**	**294**	**G 1½**	**247**
250	**350**	**40**	**1295**	**294**	**G 1½**	**277**
250	**350**	**50**	**1500**	**294**	**G 1½**	**307**
250	**350**	**60**	**1700**	**294**	**G 1½**	**337**
250	**350**	**80**	**2110**	**294**	**G 1½**	**397**
250	**350**	**100**	**2518**	**294**	**G 1½**	**457**
250	**350**	**120**	**2925**	**294**	**G 1½**	**517**
250	**350**	**150**	**3535**	**294**	**G 1½**	**607**
350	250	100	1660	400	on demand	605
350	250	150	2180	400		725
350	250	200	2700	400		845
350	250	250	3220	400		965
350	250	300	3740	400		1085
350	250	400	4780	400		1325
350	**350**	**100**	**1750**	**413**	on demand	**785**
350	**350**	**150**	**2270**	**413**		**940**
350	**350**	**200**	**2790**	**413**		**1095**
350	**350**	**250**	**3310**	**413**		**1250**
350	**350**	**300**	**3830**	**413**		**1405**
350	**350**	**400**	**4870**	**413**		**1710**

Figure 14.5

Compared to bladder accumulators and diaphragm accumulators, piston accumulators offer some advantages: the piston allows the exploitation of the whole inner volume; in the other kinds of accumulators, the bladder of the diaphragm can be damaged and the hydraulic fluid can easily mix with nitrogen; this risk is very limited in piston accumulators (the piston usually has three dynamic seals in order to ensure good sealing). Furthermore, piston accumulators can be used with any hydraulic fluid (compatibility involves seals only) and their maintenance is simple. Nonetheless, piston accumulators have many drawbacks as well: their response time is limited by seal friction and piston mass inertia, like in weight loaded accumulators.

The gas precharge valve and the fluid inlet/outlet ports are respectively on the front and rear end caps. The introduction of nitrogen through the precharge valve pressurises the upper chamber at a specific pressure (see the following paragraph) and pushes the piston against the end cap of the port opposite to the precharge valve; when the hydraulic circuit is activated (the pressure must exceed the nitrogen pressure), the pressurised fluid pushes the piston again against the precharge end cap, thus compressing the nitrogen. When the nitrogen pressure is equal to the fluid pressure, the piston stops; as the hydraulic pressure decreases, if the pressure in the circuit is less than precharge pressure, the accumulator releases the whole volume of the fluid or a part of it until the pressure of the gas and the pressure of the circuit are perfectly balanced.

Piston accumulators with additional nitrogen cylinders

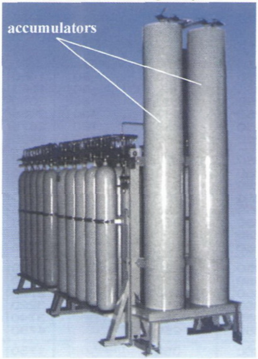


Figure 14.6

In most versions, the end caps and the body are made of carbon steel; the internal part of the body is lapped, while the piston is made of a light alloy. Seals have to be chosen according to the fluid (the seals supplied are usually compatible with mineral oil). Piston accumulators are generally used in systems having a pressure of 200-250 bar and can be assembled in every position; their capacities range from 1 to 400 dm^3. Figure 14.5 shows different types of piston accumulators (with different pressures and accumulation capacities) available on the market.

Systems experiencing considerable flows and little changes between the minimal and maximal cumulative pressure (see following paragraphs) need the connection of the piston accumulator to a set of additional pressurised nitrogen cylinders in order to allow the return of the fluid to the circuit (Figure 14.6).

Bladder accumulators

Bladder accumulators are the most popular accumulators in oil hydraulics along with diaphragm accumulators. Bladder accumulators are light-weight and small-sized and they have no response inertia. They are fundamentally made up of a body, a bladder for gas-fluid separation, a precharge valve and an anti-extrusion valve (Figure 14.7).

Cut-away view of a bladder accumulator

Figure 14.7

The standard size of bladder accumulators depends on the maximum quantity of nitrogen they can store, which ranges between 0.2 and 50 dm^3.

Their cylindrical *body* is made of carbon steel; it is a single block obtained through hot forging (Figure 14.8) and it can sustain very high pressures without being damaged.

Hot forging of an accumulator body

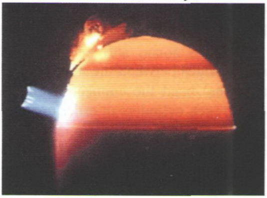


Figure 14.8

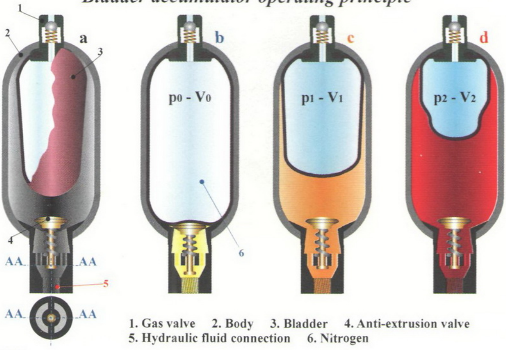
Its expansions, caused by high pressures and abrupt temperature changes, do not undermine its performance. However, this does not apply to some versions designed for low-pressure systems: a cap is soldered to their cylindrical body and sometimes they are lined with nickel, zinc or even totally made of stainless steel.

The elastic *bladder*, which is responsible for pressurised nitrogen storage and fluid-nitrogen separation, is generally made of nitrile rubber, whereas versions made of butyl rubber, neoprene rubbers and other materials are available for some special applications. The best structures consist of a single body as it is more robust and prevents leakages between the hydraulic fluid and the gas.

Nitrogen is conveyed into the bladder through the precharge gas *valve*, also known as 'inflating valve'; this is a free flow non-return valve that transfers the gas from the cylinder to the bladder and vice versa.

Gas valves can be vulcanised to the bladder (in case of gas valve anomaly, the bladder too has to be replaced) or simply fixed with a nut; in this case, the valve can be replaced without replacing the bladder. The cap, usually knurled, protects the valve from external contamination. Each 'transfer' and 'fluid separator' application needs the inclusion of a valve with a special design.

Bladder accumulator operating principle



1. Gas valve 2. Body 3. Bladder 4. Anti-extrusion valve 5. Hydraulic fluid connection 6. Nitrogen

Figure 14.9

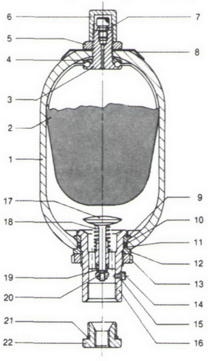
Figure 14.9 shows the process of hydraulic fluid storage and release in a bladder accumulator. The device is generally equipped (a) with a bladder pre-charged with nitrogen at a minimum pressure of about 3-10 bar (in order to avoid the presence of air during nitrogen loading). The precharge (b) of nitrogen causes the inevitable expansion of the bladder (V_0), which now rests on the anti-extrusion valve. In this case, the pressure of the gas is indicated with p_0, and in this phase, it is higher than the pressure of the hydraulic fluid.

When the pressure in the plant exceeds the pre-charge pressure p_0, the fluid overcomes the contrast power of the bladder and by flowing inside the accumulator it compresses the nitrogen with a consequent reduction of the volume in the bladder. The hydraulic pressure that is now equal to the nitrogen pressure is referred to as p_1 and the volume of the bladder as V_1.
As hydraulic pressure increases (d), the gas reduces its volume proportionally; the maximum working pressure p_2 reduces the bladder at the lowest volume V_2.

Anti-extrusion valve

Anti-extrusion valves are employed in accumulators whose pressures are higher than 15 bar. Their particular shape avoids the tearing of the pressurised bladder during hydraulic inactivity periods; the fluid, whose pressure is equivalent to or less than p_1, presses on the valve, overcomes its opposing force and flows into the accumulator.

Cut-away view of a high-pressure bladder accumulator (up to 300 bar)



1. Body
2. Bladder
3. Gas valve
4. Washer
5. Nut for gas valve fastening
6. Protection cap
7. Inflating valve
8. Plate
9. Banking ring
10. Seal
11. Anti-extrusion ring
12. Shoulder ring
13. Fluid valve lochnut
14. Air bleed screw
15. Seal for the bleed screw
16. Valve body
17. Poppet
18. Spring
19. Braking bush
20. Nut
21. Adaptor seal
22. Adaptor

Figure 14.10

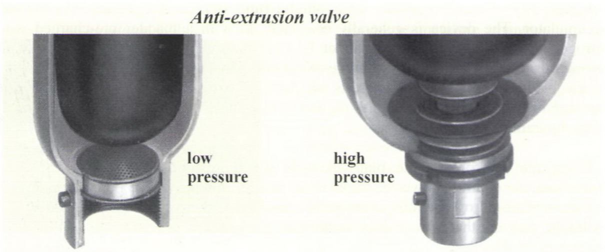
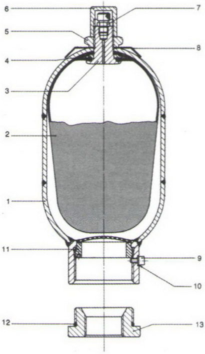


Figure 14.11

In low-pressure accumulators, the anti-extrusion valve is replaced by a simple perforated plate (Figures 14.11 and 14.12).

Cut-away view of a low-pressure bladder accumulator (70 bar max)



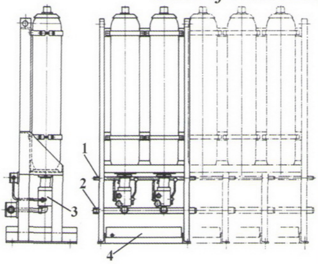
1. Body
2. Bladder
3. Gas valve body
4. Washer
5. Gas valve fastening nut
6. Protection cap
7. Inflating valve
8. Plate
9. Bleed screw
10. Bleed screw seal
11. Anti-extrusion plate with stop ring
12. Adaptor seal
13. Adaptor

Figure 14.12

Banks of accumulators

As most commercial types do not exceed maximum volumes of 50 litres per accumulator, systems requiring higher volumes can be equipped with a bank of accumulators that bring together different elements; a delivery manifold connects the hydraulic fluid ports and each element has its own independent gas valve.

Bank of bladder accumulators



1. Outlet manifold
2. Delivery manifold
3. Safety block
4. Basin

Figure 14.13

Examples of bladder accumulators

Figure 14.14

Delivery manifolds are equipped with an outlet port, which is essential when they must be emptied for maintenance or disassembly reasons.

A set of accumulators (made up of at least 2 accumulators and up to 12) can be arranged in single or double line according to the number of elements and the space available (Figure 14.13).

Like in piston accumulators, if there are considerable flows and minimal differences between p_1 and p_2, a set of additional nitrogen cylinders can be connected to the accumulator.

Diaphragm accumulators

Diaphragm accumulators (Figures 14.15, 14.16, 14.17, 14.18) differ from bladder accumulator in the shape of the gas-fluid separator. Furthermore, their body must be divided into two parts in order to enable the introduction of the diaphragm. The volume of these devices ranges from 0.1 to 10 dm^3 and they sustain pressures up to 350 bar.

Diaphragm accumulators

Figure 14.15

Cut-away view of a diaphragm accumulator

Figure 14.16

Their *body*, which is divided into two sections, has the same features as that of bladder accumulators. It is generally made of carbon steel, stainless steel or even PVC if pressures do not exceed 10 bar.

These sections are connected by means of a thread on their ends.
Their U-shaped *elastic diaphragm* ends with a border between the two shoulders of the male and female parts: when tightened, they guarantee excellent sealing and stability of the separator.

Materials change according to the fluid and they range from nitrile rubber, neoprene, natural rubber, etc. A *vulcanised disc* placed on the bottom of the diaphragm prevents its extrusion; these elements are often unequipped with the anti-extrusion valve. Nitrogen storage and release is ensured by the gas precharge valve, which is tightened at the tip of the upper body like bladder accumulators, but it does not touch the diaphragm. Storage and release develop as described above ($p_0 - V_o$, $p_1 - V_1$, $p_2 - V_2$).

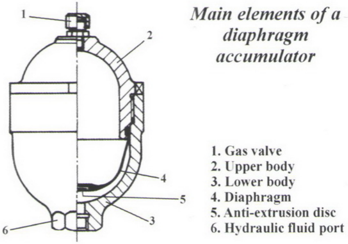


Figure 14.17

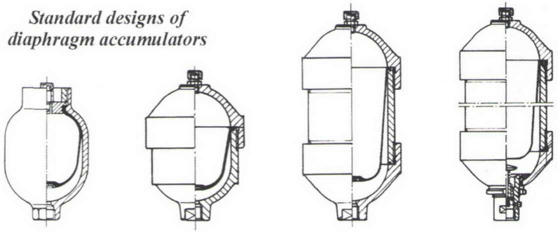


Figure 14.18

USES

The use of one or more accumulators in oil hydraulic systems reduces costs since much energy is saved and fewer components are needed. Accumulators are widely used in the stationary applications as well as mobile applications. It is important to underline that the unloading relief valve for accumulator described in Chapter 10 is indispensable in the vast majority of circuits equipped with an accumulation device.

A check is always mounted between the pump and its delivery pipe for two reasons: first, it prevents the fluid released by the accumulator from entering pump and secondly it prevents the accumulator from unloading when the pump is on stand-by.

Energy accumulation

If an accumulator is installed in a circuit that works with requires *different flows phases*, a low displacement pump can be used. As a matter of fact, if the accumulator conveys some fluid to the actuator, the pump clearly does not have to deliver the same quantity of fluid. Consequently, the power of the first engine (p • Q) is less than the product of the pressure by the maximum flow required. The pressure level, which is different for each actuator, must not mislead; provided storage times allow it, the accumulator releases the fluid stored at the pressure set on the relief valve, which is equal to the maximum pressure needed by the element that has the strongest force in respect to the piston diameter.
Assume a working cycle is divided into three phases (Figure 14.19) and each working cycle requires the same maximum pressure.

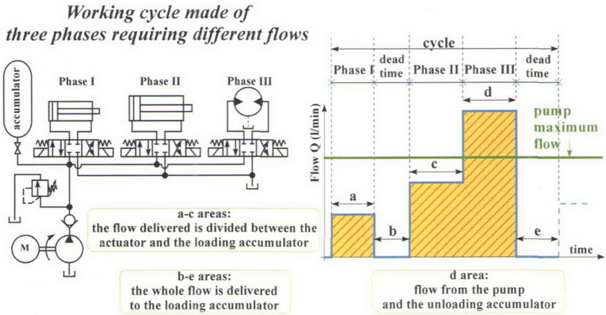


Figure 14.19

Throughout each cycle, actuators work exclusively during their phase. During phases I and II, cylinders need a flow that is less that the flow the pump can deliver and the remaining fluid is pushed into the accumulator; between the first and the second phase, actuators are in the end-of-stroke position (flow equals zero even at the maximum pressure) and the whole flow of the pump is conveyed to the accumulator. The oil hydraulic motor involved in the third phase needs a certain amount of oil delivered by the maximum flow of the pump on the one hand and by the flow formerly stored and now released by the accumulator on the other in order to develop a certain speed. Even during inertia periods between cycles ('e' area), the whole flow of the pump is conveyed to the accumulator.

Despite a considerable displacement reduction, it is clear that the flow of the pump is always higher than the maximum flow needed by actuators that do not require the help of the accumulator (Figure 14.19); this is essential if it is not possible to store enough fluid during dead times.

Assume the motor of the third phase must be supplied with a flow of 40 litres; a certain amount of the fluid must be accumulated in the device during the other phases of the cycle in order to be released with the flow from the pump. If the capacity of the actuator of the first phase is equal to 5 litres and the rod stroke lasts 0.25 minutes, the capacity of the actuator of the second phase is equal to 10 litres and the rod stroke equals 0.5 minutes; the pump maximum flow is equivalent to the flow needed by actuators of the first and second phases, that is to say 20 l/min (5/0.25 and 10/0.5). χ litres can be conveyed into the accumulator in a span of time that corresponds to the addition of b and e areas, since in a and c areas storage is hindered by the maximum flow delivered by cylinders. If the dead point of b is 0.1 minute and the dead point of e equals 0.5 minutes, the accumulator inlet is 12 litres (0.6 • 20 l/min). Considering the third phase data above (constant rotation of the engine lasting 1 minute, with a displacement that requires 40 l/min), as the pump delivers 20 l/min, it requires 20 litres more instead of 12 litres. The pump must be dimensioned so as to make up for those missing 8 litres but the flow is not equal to 28 l/min since it must be calculated according to the fluid excess in phases I and II. As the higher pump flow would involve an increase of the output speed on rods, flow control valves must be added to the cylinders. The same storage/release principle, aiming at cutting costs and energy savings, is used to make up for drops or in order to keep a device at a specific constant pressure.

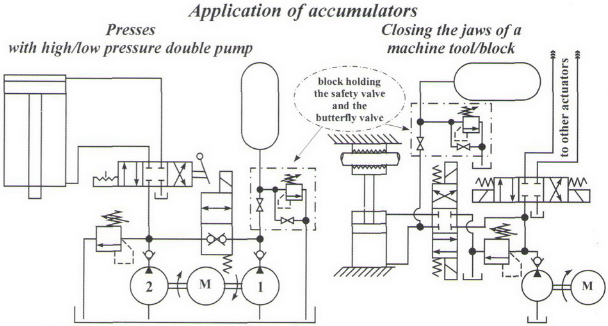


Figure 14.20

In presses equipped with a low/high pressure double pump (Chapter 5, Control and further in-depth analysis, and Chapter 10, Pressure control and adjustment valves), the inclusion of an accumulator reduces quick advance phases (Figure 14.20): during the pressing performed by pump 2, pump 1 loads the accumulator so that it can release the flow during the quick upward stroke or in the early downward stroke.

Accumulators firmly hold the workpiece in the vice in machine tools. As jaws are positioned, the pump can focus on other elements and the accumulator guarantees tightening.

Two butterfly valves (generally they are manually-operated ball valves or monostable solenoid valves 2/2) are found in manifolds that contain the unloading relief valve for accumulator, often called safety valve. By closing the first one (placed near the accumulator), the system works even if the accumulator is by-passed; the second valve instead puts the safety valve in the by-pass position: the accumulator is emptied and component replacement and maintenance can be performed. Almost all accumulators are equipped with this device.

The inclusion of an accumulator in circuits that are not working and that require the stability of actuators will make up for *leakages*; if the closed centre valves stay in a neutral position for a long time, the introduction of fluid by the accumulator makes up for fluid leakages between the spool and the body. This method consists in an automatic control through a two-threshold pressure gauge that intervenes at the minimum and maximum pressure (Figure 14.26). For example, in order to hold a suspended load, the pressure gauge is set at the minimum pressure acceptable by the accumulator and at the maximum pressure acceptable by the pump: if the pump is off, the accumulator that sustains the load releases the fluid due to leakages till the minimum acceptable pressure is reached; in the meanwhile, the pressure gauge operates the pump that fills the accumulator again. When the maximum pressure is reached, the upper threshold of the pressure switch by passes the pump.

Pulsation dampening

We are now going to consider an issue mentioned at the beginning of this chapter and described in Chapter 4 (Fixed or variable displacement pumps): the problem of the pulsating flow of pumps.

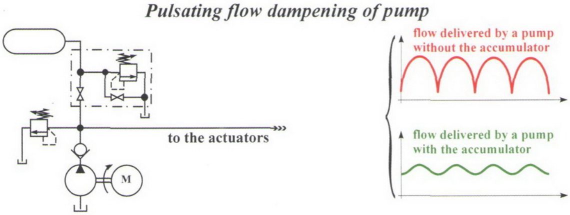


Figure 14.21

As shown in Figure 14.21, the accumulator is placed immediately downstream of the check valve and the relief valve. In order to dampen pulsations as much as possible, the accumulator must be directly connected and close to the pump.

Likewise, it is possible to avoid hydraulic counterblows caused by solenoid valves: the accumulator is directly connected to the port P of the valve. Another application of accumulators on solenoid valves has already been discussed in Chapter 8 (Servo-controlling valves with by-pass centre).

Fluid hammer absorption

Oscillations due to fluid hammer or hydraulic oscillations in general (Chapter 16) cause serious damage to the system. Shock waves can be dampened by diverting it to the accumulator. While designing systems, it is obviously difficult to define the exact collocation of the accumulator in the circuit; the exact place where the accumulator needs arranging can be identified only when the machine is operating.

Spring action

Accumulators improve mechanical spring performances in systems requiring dampening. Forces from the hydraulic circuit are dampened in the accumulator by the pre-charged nitrogen. A very simple application is the replacement of a mechanical *counterweight*, that is to say a strong spring or a chain that supports a particular element or a rope or chain sliding on a pulley and ending with a heavy weight. For instance, in order to keep a vertical slide of a machine tool, it must be equipped with a spring attached to the opposite surface. Its connection to a cylinder improves the support precision and reduces the spaces needed for mechanical systems (Figure 14.22).

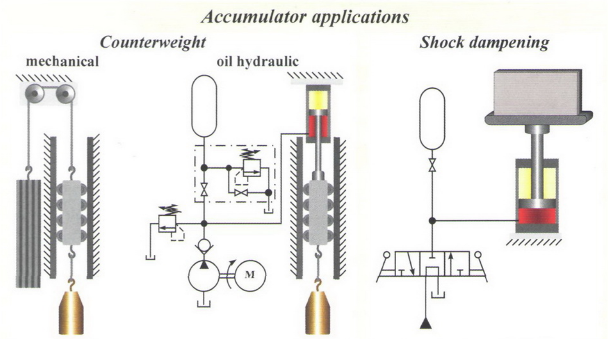


Figure 14.22

Accumulators *dampen the shocks* caused by the load as well. The goods on loading and unloading platforms (for instance those of self-propelled machines) may shift abruptly by accident or due to negligence; as a result, the support cylinder would be subjected to a dangerous counterpressure. Snowploughs are affected by road conditions the drivers cannot see; dangerous overpressures develops whenever a bump, a stone or a pothole make the plough bump since this transmits this movement to the related cylinder.

The cables of cable cars and chairlifts are subjected to expansion due to the variations in temperature and cabin weight; the *tension* cylinders in stations guarantee rope tension thanks to the inclusion of accumulators.

Suspension for vehicles

Accumulators replace the spring or leaf spring suspension system in many self-propelled vehicles and some trucks. The circuit, without the pump, is made up of a cylinder with the chamber opposite to the wheel shaft connected to the accumulator. Restrictors enable dampening adjustment (Figure 14.23). The wheel transmits the shocks to the piston of the cylinder; the counterbalance of pre-charged nitrogen mitigates the oscillation of the vehicle.

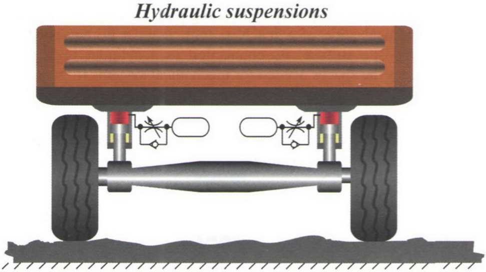


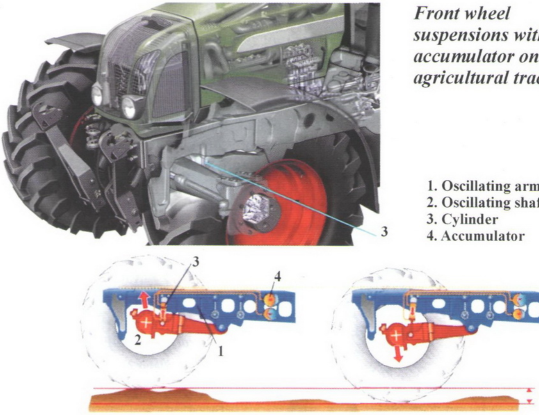
Figure 14.23

It is employed in many applications, like medium/powerful agricultural tractors.

Suspension is ensured by means of a cylinder with an accumulator on both front wheels. As Figure 14.24 shows, both chambers of the double-acting cylinder, placed between the oscillating shaft and the chassis, are connected to their accumulator; upward jolts drive the oil into the accumulator. As the vehicle is confronted with a pothole, the sudden lack of support is made up for by the gas in the accumulator: by pushing the fluid into the cylinder, it drives the wheel closer to the roadway surface.

Consider that in these vehicles the suspension of back rear wheels is not possible because of the indispensable transmission rigidity between engine/gearbox and shaft; as a result, the cabin is instead provided with mechanical springs. In order to avoid the shocks caused by the trailer (plough, sprayers, etc.) of modern farming tractors, rear 'third point' cylinders are dampened by an accumulator that is controlled by a proportional solenoid valve.

Front wheel suspensions with accumulator on an agricultural tractor



1. Oscillating arm
2. Oscillating shaft
3. Cylinder
4. Accumulator

Figure 14.24

Fail-safe devices

Accumulators play a crucial role when the cycle experiences sudden stops (power supply failure, malfunctioning pump, etc.) and the machine has to be in the rest position for logistic and safety reasons. The diagram of Figure 14.25 shows a simple method that can be adopted in order to solve this problem: the accumulator can bring actuators to the rest position even if there is no supply to the prime mover and the solenoid valves.

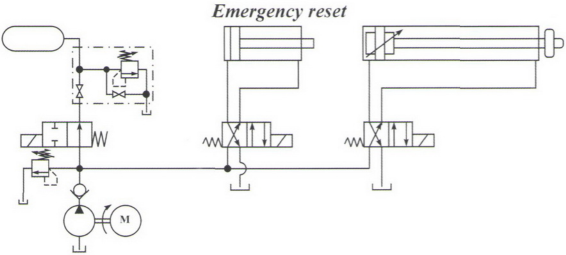


Figure 14.25

Transfer function

The word 'transfer' is not derived from English, but Latin ('transferre' = to bring/to carry). It refers to the transfer of a certain pressure/force but in this case in the opposite direction: the accumulator transfers the hydraulic power generated by the pump upstream through the separator and it uses it for different purposes. Transmission fluids can be both liquids, whether the same or different type (oil/oil, oil/water), or hydraulic fluid and gas (oil/nitrogen, oil/air).

The transfer function is very useful in *fatigue tests* aiming at verifying the resistance to pressure of specific components; two fundamental fatigue tests are shown in Figure 14.26.

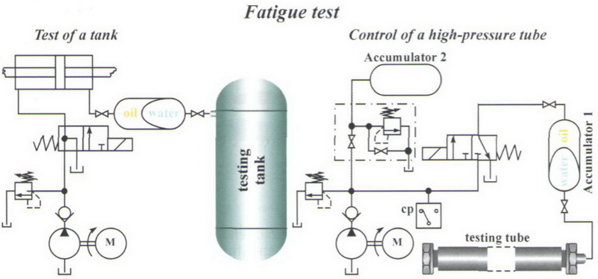


Figure 14.26

The tank on the left must undergo a cycle of overpressures. The oil flows from the pump to the cylinder (the rod is not used) and from the body opposite to this cylinder to the accumulator; in order to avoid the presence of residues between the bladder and the testing tank, the hydraulic fluid is replaced by water. A timed electromechanical circuit defines the total number and time of impulses that have to be sent to the tank.

The system on the right requires a less complex control circuit but it needs two accumulators. The first accumulator plays the transfer role with the separation oil/water; at a certain pressure, the two-threshold pressure gauge (cp), interrupts the supply to the prime mover and consequently the second accumulator supplies the fluid in order to make up for leakages until the pump operation is restored.

Gas cylinders are supplied with a maximum pressure of 200 bar and the precharge conditions of the accumulator to be installed in a specific circuit sometimes require higher pressurisation. The transfer function allows the increase in the precharge pressure supplied by standard gas cylinders. Figure 14.27 clarifies this concept: assuming cylinders pressure is equal to 200 bar, the non-return valve α is open as long as the hydraulic pressure is lower; when the standard gas pressure is exceeded, α closes preventing overpressures in the mother cylinders. The gas contained in the bladder of the accumulator is compressed at a pressure higher than 200 bar and it can be transferred to the accumulators that will work at higher precharge pressures by opening the 2/2 solenoid valve.

Precharge pressure exceeding gas cylinder standard level

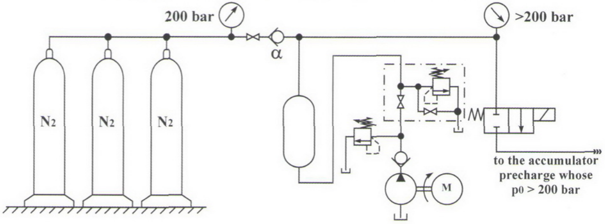


Figure 14.27

Banks of accumulators and additional gas cylinders

We have already mentioned the use of a set of nitrogen cylinders (see piston and bladder accumulators) in systems subjected to substantial flow rates and little changes of the minimum and maximum cumulative pressure. In order to supply large quantities of fluid to the circuit, much gas is needed. Figure 14.28 shows a system made up of four bladder accumulators (systems with considerable flows require a set of accumulators since the maximum capacity of each accumulator is 50 litres) connected to nitrogen cylinders.

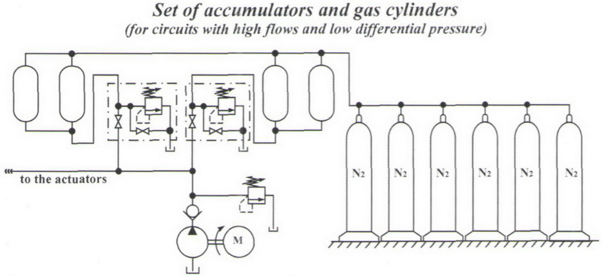


Figure 14.28

DIMENSIONING

The examples and calculations in this paragraph refer to bladder accumulators (Figure 14.29), but they apply also to piston and diaphragm accumulators. Many factors have to be taken into account in the dimensioning of an accumulator: the structure of the element, precharge and working pressures, volumes (V) and temperature limits.

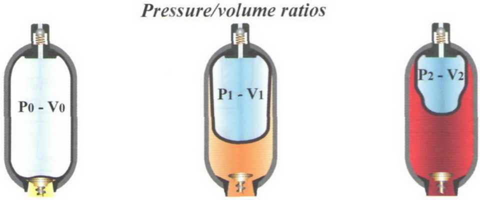


Figure 14.29

What follows are accumulator conditions:

$p_0 - V_0$ refers to pre-charge conditions. Hydraulic pressure is low; the bladder in the accumulator is expanded.

$p_1 - V_1$ refers to the minimum working pressure of the hydraulic system. The pressure of the fluid is a slightly higher than the pre-charge pressure. The fluid enters the accumulator and reduces the volume of the bladder; this reduction compresses the gas and its pressure is equal to the pressure of the hydraulic fluid.

$p_2 - V_2$ refers to the conditions of maximum pressure the hydraulic circuit can sustain. The bladder has reached its maximum contraction increasing the gas pressure, which is equal to the pressure of the hydraulic fluid though.

Pressures

In order to preserve the efficiency of accumulators and to exploit it fully, it is advisable to make sure that the p_2/p_0 ratio does not exceed 4 as far as bladder accumulators are concerned.

This ratio applies to bladder accumulators; p_2/p_0 must not exceed 8 in diaphragm accumulators, whereas there is no specific limit for piston accumulators. The pre-charge pressure p_0 should equal the minimum working pressure p_1. Actually, in order to avoid that the anti-extrusion valve closes each cycle, it is advisable to use a pre-charge having the maximum following value:

$$p_0 = 0.9 \cdot p_1$$

If the former $p_2/p_o = 4$ is taken into account, the previous definitions can be completed as follows:

$$p_0 \min \geq 0.25 \cdot p_2 \qquad p_0 \max \leq 0.9 \cdot p_1$$

This method, which applies to systems based on energy accumulation, spring action, etc., requires the correction of the element of multiplication in the following applications:

Pulsation dampening: $p_0 = 0.6 \div 0.75 \cdot p_m$ (average working pressure)

Fluid hammer absorption with elastic separator: $p_0 = 0.6 \div 0.9 \cdot p_m$ (free flow average pressure)

Fluid hammer absorption with piston separator: $p_0 = p_1 - (2 \div 5 \text{ bar})$

Accumulator with additional cylinders: $p_0 = 0.95 \div 0.97 \cdot p_1$

Since, temperature is measure in Kelvin degrees (°C+273) under the International System of Units (SI) and the pre-charge p_0 is often performed at temperatures Tx other than the environmental temperature (conventionally 20 °C), the pre-charge pressure at 20 °C is:

$$p_0\ 20\ °C = p_0 \cdot \frac{20\ °C + 273}{Tx + 273}$$

Physical correlations

Gas behaviour, depending on pressure, volume and temperature, is related to the physical laws explored in Chapter 1 (Elements of Hydrostatics, Compression of a perfect gas). As absolute pressure (relative p + 1 bar) has to be determined, the law of Boyle and Mariotte comes into play:

$$p \cdot V = \text{constant}\ (p_0 \cdot V_0 = p_1 \cdot V_1 = \ldots)$$

In order to calculate the exact volume of the accumulator, it is important to note that nitrogen as a real gas does not exactly respect the compression laws of perfect gases. Another important factor is its (stage) behaviour changes due to temperature variations) depending on the kind of application.

When the device is working (the fluid is being stored or released), the gas and the environment exchange energy: if their temperatures are different, they tend to become more similar. When compression and expansion take quite a long time (more than 3 minutes), the gas exchanges heat with the environment in a uniform way and its temperature varies slightly. This process is often called **isothermal transformation**. On the contrary, in rapid processes (less than 3 minutes), there is poor heat exchange and the gas temperature increases; this process is called **adiabatic transformation**.

Figure 14.30 (on the left) shows the pressure-volume accumulator curve.

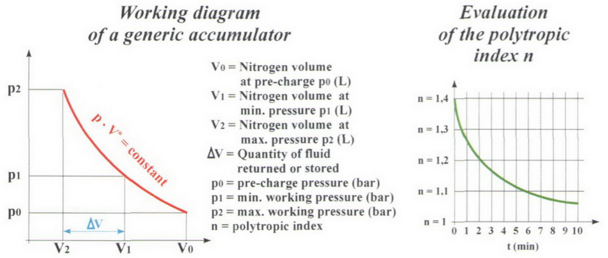


Figure 14.30

The polytropic index n (transformations according to the specific application) is strictly linked to the change of state (isothermal or adiabatic type). With a rapid and approximate calculation, its value is:

n = 1 (isothermal transformation)
n = 1.4 (adiabatic transformation)

If a precise calculation is needed, the polytropic index n can be identified in Figure 14.30 (on the right) given the time t. For instance, if the transformation time is 2 minutes, n equals 1.2.

Isothermal transformation

Since nitrogen temperature does not change, the polytropic index is 1. Boyle and Mariotte's equation is:

$$p_0 \cdot V_0^n = p_1 \cdot V_1^n = p_2 \cdot V_2^n \qquad \text{therefore} \qquad V_1 = V_0 \cdot \frac{p_0}{p_1} \quad \text{and} \quad V_2 = V_0 \cdot \frac{p_0}{p_2}$$

The maximum amount of fluid that can be stored ΔV is the difference between V_1 and V_2:

$$\Delta V = V_1 - V_2 = V_0 \cdot \frac{p_0}{p_1} - V_0 \cdot \frac{p_0}{p_2} \quad \text{so,} \quad \Delta V = V_0 \cdot \left(\frac{p_0}{p_1} - \frac{p_0}{p_2} \right)$$

The volume of the accumulator is:

$$V_0 = \frac{\Delta V}{\frac{p_0}{p_1} - \frac{p_0}{p_2}}$$

As we have already said, isothermal calculations can be used when storage and release take some time and heat exchange occurs.

Adiabatic transformation

A polytropic coefficient other than 1 is needed:

$$p_0 \cdot V_0^n = p_1 \cdot V_1^n = p_2 \cdot V_2^n \qquad \text{so} \quad V_1^n = V_0^n \cdot \frac{p_0}{p_1} \quad \text{e} \quad V_2^n = V_0^n \cdot \frac{p_0}{p_2}$$

If n = 1.4, the maximum amount of fluid that can be stored ΔV is the difference between V_1 and V_2:

$$\Delta V = V_0 \cdot \left[\left(\frac{p_0}{p_1} \right)^{\frac{1}{1.4}} - \left(\frac{p_0}{p_2} \right)^{\frac{1}{1.4}} \right]$$

As 1/1.4 = 0. 7143, the volume of the accumulator is:

$$V_0 = \frac{\Delta V}{\left(\frac{p_0}{p_1}\right)^{0.7143} - \left(\frac{p_0}{p_2}\right)^{0.7143}}$$

Mixed transformation

Polytropic or mixed transformation is not rare. It consists in a slow storage (isothermal type) and a fast release (adiabatic type). Under these circumstances, if the polytropic index equals 1 for isothermal transformation and 1.4 for adiabatic transformation, the maximum volume ΔV of fluid that can be stores and the capacity V_0 of the accumulator are:

$$V_0 = \frac{\Delta V \frac{p_2}{p_0}}{\left(\frac{p_2}{p_1}\right)^{0.7143} - 1} \qquad \Delta V = V_0 \bullet p_0 \bullet \frac{\left(\frac{p_2}{p_1}\right)^{0.7143} - 1}{p_2}$$

Temperature ranges

As temperature changes dramatically during operations, it is important to remember that according to Gay-Lussac's law volume and temperature are directly proportional if the pressure is constant (Chapter 1).

As a result, if we consider the maximum working temperature T_2 and the minimum temperature T_1 in Kelvin degrees (respectively, °C_{max} + 273 and °C_{min} + 273) and the accumulator capacity formerly calculated, an increase in the working volume of the accumulator V_{tot} is needed:

$$V_{tot} = V_0 \bullet \frac{T_2}{T_1} \text{ (litres)}$$

Correction coefficient for high pressures

Nitrogen changes in respect to pressure rises are different from the proportional changes of the ideal gas: therefore, with a minimum working pressures p_2 exceeding 200 bar, a correction coefficient is needed (not only in isothermal transformations but also in adiabatic transformations): volumes V_0 or ΔV, divided by the coefficient, determine the actual volumes V_{0r} or ΔV_r. Figure 14.31 shows different coefficients; what follows are simple calculation methods:

Isothermal transformation: $V_{0r} = V_0/C_i \qquad \Delta V_r = \Delta V \cdot C_i$

Adiabatic transformation: $V_{0r} = V_0/C_a \qquad \Delta V_r = \Delta V \cdot C_a$

Correction coefficients

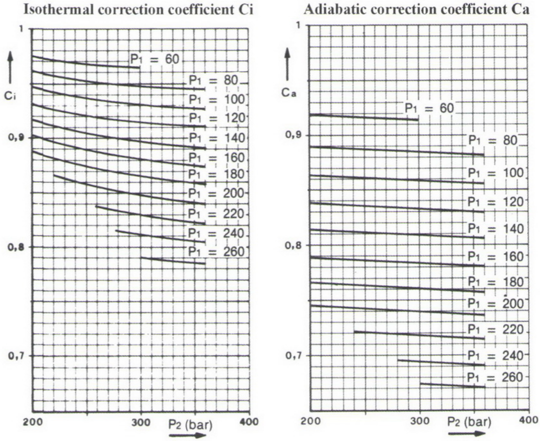
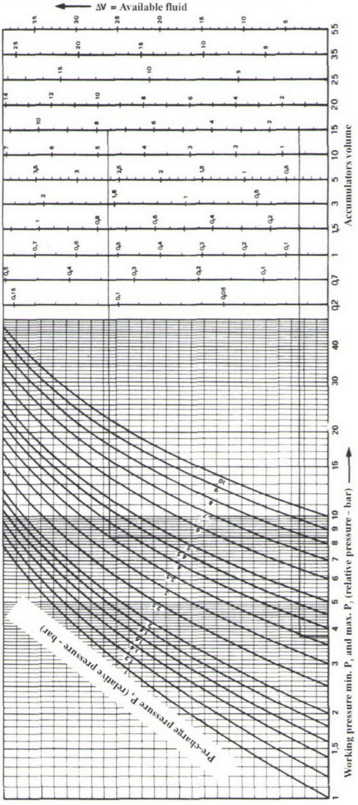


Figure 14.31

Quick selection tables

Isothermal transformations at low pressures



Example 1: Determination of the accumulator volume
DATA:
p2 = 8.5 bar
p1 = 3.8 bar
p0 = 3.5 bar
ΔV (fluid needed) = 1.3 L

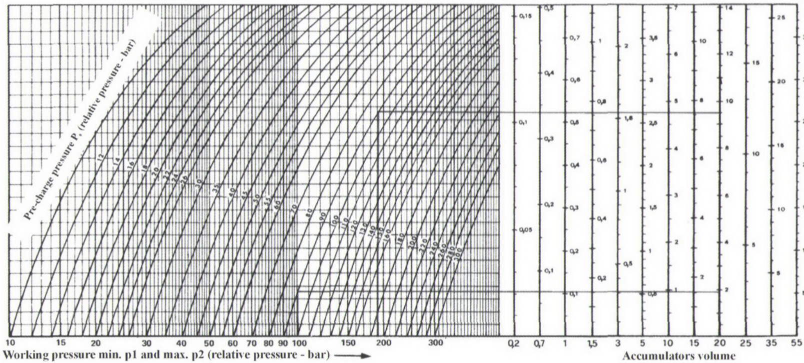
After identifyng the two points of intersection of the p0 curve with p1 (=3.8) and p2 (=8.5) ordinates, two lines parallel to the abscissa axe must be traced in order to intersect "delta" V. For each size of accumulator, the volume stored results from the distance between the two lines. In our example, the accumulator that best satisfies the needs (1.3 L) has capacity of 3 L.

Example 2: Determination of the available fluid ΔV
DATA:
p2 = 8.5 bar
p1 = 3.8 bar
p0 = 3.5 bar
V = 15 L

After identifyng the two points of the intersection of the p0 curve with p1 and p2, two lines parallel to the abscissa axe must be traced in order to intersect the ΔV corresponding to 15 L. The volume is equal to 6.7 L.

Figure 14.32

Isothermal transformation at high pressures



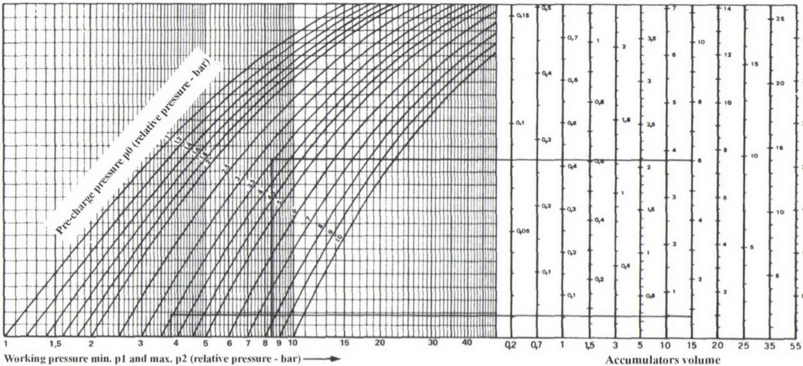
Example 1: Determination of the accumulator volume
DATA:
p2 = 190 bar
p1 = 100 bar
p0 = 90 bar
ΔV (fluid needed) = 7 L
After identifyng the two points of intersection of the p0 curve with p1 (100) and p2 (190) ordinates, two lines parallel to the abscissa axe must be traced in order to intersect ΔV. The volume results from the distance between the two lines. In our example, the accumulator that best satisfies the needs (≥ 7 L) has a capacity of 20 L.

Example 2: Determination of the available fluid ΔV
DATA:
p2 = 190 bar
p1 = 100 bar
p0 = 90 bar
V = 1.5 L

After identifyng the two points of the intersection of the p0 curve with p1 and p2, two lines parallel to the abscissa axe must be traced in order to intersect the ΔV corresponding to 1.5 L. The volume is ≅ 0.615 L.

Figure 14.33

Adiabatic transformation at low pressures



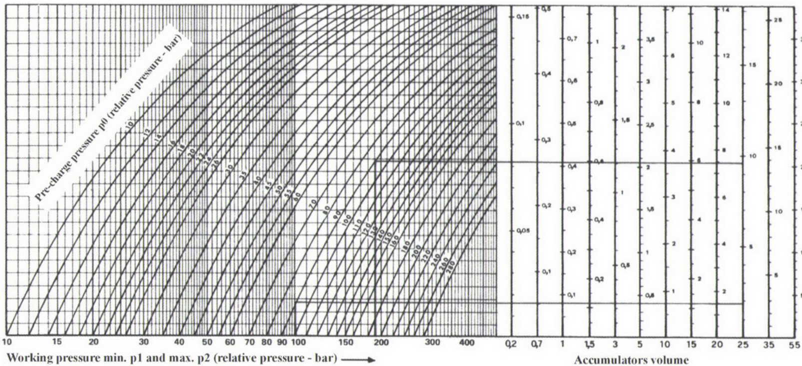
Example 1: Determination of the accumulator volume
DATA:
p2 = 8.5 bar
p1 = 3.8 bar
p0 = 3.5 bar
ΔV (fluid needed) = 1.3 L
After identifyng the two points of intersection of the p0 curve with p1 (3.8) and p2 (8.5) ordinates, two lines parallel to the abscissa axe must be traced in order to intersect ΔV. The volume results from the distance between the two lines. In our example, the accumulator that best satisfies the needs (= 1.3 L) has a capacity of 5 L.

Example 2: Determination of the available fluid ΔV
DATA:
p2 = 8.5 bar
p1 = 3.8 bar
p0 = 3.5 bar
V = 15 L

After identifyng the two points of the intersection of the p0 curve with p1 and p2, two lines parallel to the abscissa axe must be traced in order to intersect the ΔV corresponding to 15 L. The volume equals ≅ 5.3 L.

Figure 14.34

Adiabatic transformation at high pressures



Example 1: Determination of the accumulator volume
DATA:
p2 = 190 bar
p1 = 100 bar
p0 = 90 bar
ΔV (fluid needed) = 7 L
After identifyng the two points of intersection of the p0 curve with p1 (100) and p2 (190) ordinates, two lines parallel to the abscissa axe must be traced in order to intersect ΔV. The volume results from the distance between the two lines. In our example, the accumulator that best satisfies the needs (= 7 L) has a capacity of 25 L.

Example 2: Determination of the available fluid ΔV
DATA:
p2 = 190 bar
p1 = 100 bar
p0 = 90 bar
V = 1.5 L
After identifyng the two points of the intersection of the p0 curve with p1 and p2, two lines parallel to the abscissa axe must be traced in order to intersect the ΔV corresponding to 1.5 L. The volume is ≅ 0.49 L.

Figure 14.35

Most manufacturers' catalogues include detailed explanations of calculation methods concerning isothermal, adiabatic and polytropic transformation for each application; excellent software is available for high precision calculations. In case of applications that do not require precise calculations, quick selection tables enable one to make sure of the fluid quantity ΔV that can be stored or the volume V_0 of the accumulator (Figures 14.32, 14.33, 14.34, 14.35).

ACCESSORIES, INSTALLATION, MAINTENANCE

Companies are forced to equip accumulators with specific accessories not only because of safety standards but also because of the complexity of some systems. Therefore, the pre-charge operation (which is essential after a certain working period) adds to the ordinary practices of oil hydraulic maintenance.

Anti-pulsation baffle

When the accumulator is used as pulsation dampener, it is useful to introduce a conical baffle provided with a series of holes in the T fitting that matches the liquid connection (Figure 14.36).

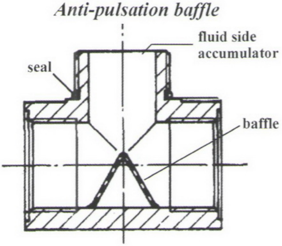


Figure 14.36

Gas pressure relief valve

Pressures that are higher than the maximum working pressure p_2 can damage the accumulator and what is more pose serious threats. The safety valve or pressure relief valve set to the pressure p_2 releases over-pressurised nitrogen, especially in case of excessive temperatures.

The simple operating principle of the safety valve is based on the force of the spring that acts on the conical poppet (Figure 14.37); when a higher pressure than p_2 develops, the gas is released through the air bleed. In this valve, the port of the gas 'connection' must be in contact with the nitrogen held in the accumulator. Accumulators provided with a spring demand a connection device in order to connect this valve with the inflating valve.

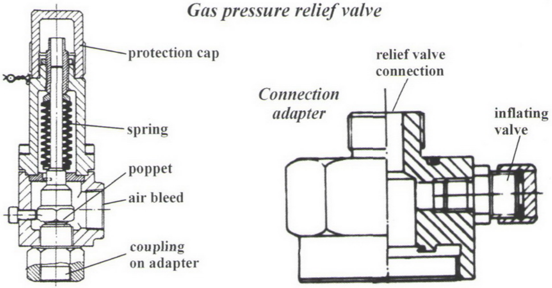


Figure 14.37

Safety manifold on the hydraulic fluid side

Theoretically, the accumulator needs a simple two-way valve in order to be connected to the hydraulic circuit: when this valve is closed, the circuit works without the accumulator, while it stores or releases the pressurised fluid when it is open; when the pump is not working and the valve is open, the fluid flows to the tank.

Actually, in order to respect safety standards, the accumulator must be equipped with a shut off valve, a tank valve and a pressure relief valve set to the maximum pressure p_2. Furthermore, the accumulator must be equipped with a wire-locked and lead seal protection cap if standardisation bodies (like TÜV) establish it. The relief valve must be used exclusively for the accumulator safety and it cannot absolutely be employed for the control of the whole system.

The other directional and flow control Manifold components range from simple 2- or 3-way ball valves to different types of valve (mainly with a poppet). Figure 14.38 shows standard operating diagrams. Manifold (a) is the simplest one: the movement on the lever of the 2/2 operates or by-passes the accumulator; the manual butterfly valve (ball valve) connects the accumulator to the tank and allows disassembly or maintenance operations. The block (b) is made up of the relief valve and a 3-way ball by-pass valve: the accumulator is connected to the delivery; the movement of the lever connects it to the tank (the restrictor controls its speed). Manifold (c) allows remote control; the accumulator is operated when the solenoid valve is no longer energised. System (d) is also equipped with a throttle check valve that allows flow adjustment during fluid release only.

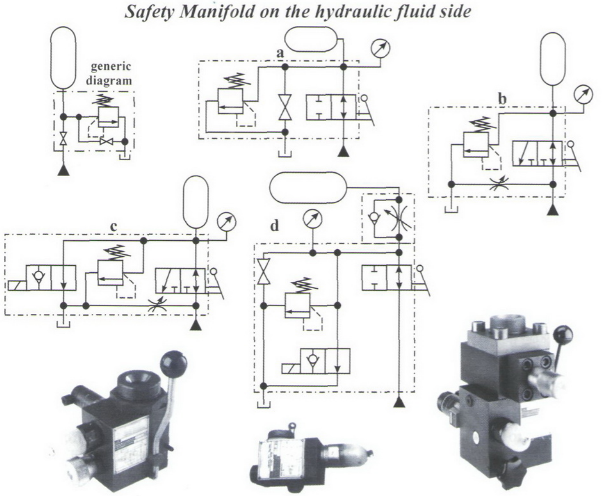


Figure 14.38

Rings and shelves

The external design of bladder and diaphragm accumulators needs mounting by means of rings fixed to the wall and tightened to the cylindrical part of the accumulator; a rubber dampening ring is placed between the shelf and the fluid side cap (Figure 14.39).

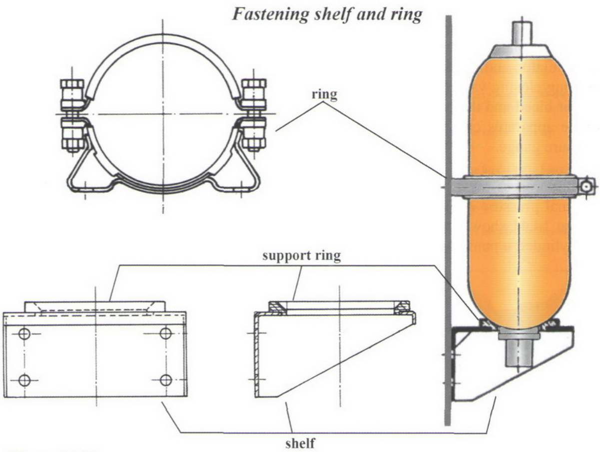


Figure 14.39

Pre-charge and control apparatus

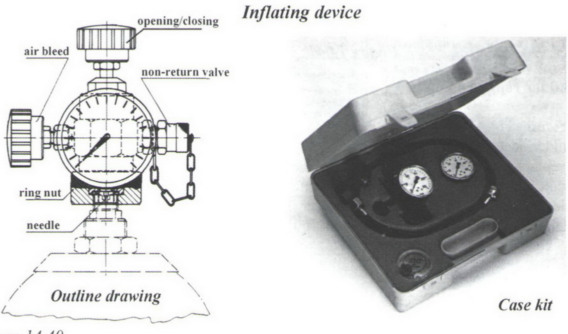


Figure 14.40

Nitrogen pre-charge, examinations (they have to be periodically carried out as recommended in the instruction manual) and the inflating to replenish leakages demand a special Manifold tightened through a ring nut to the one-way gas valve of the accumulator and holding a fastening needle; on the sides of the block there are the opening/closing valve, the non-return valve for the connection to the nitrogen cylinder, the air bleed and the pressure gauge (Figure 14.40). Since it does not need tightening, a single apparatus can be used in any high/low-pressure gas accumulator along with a pressure gauge.

This process must be carried out when the machine is not operating; otherwise the nominal pressure of the system would be recorded instead of the pre-charge pressure. Figure 14.41 shows the inflating process (if pressure p0 is higher than the pressure of the cylinder, a pumping unit is needed).

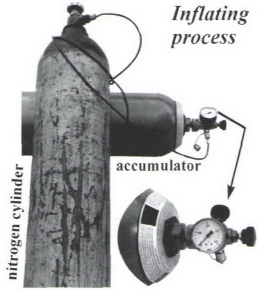


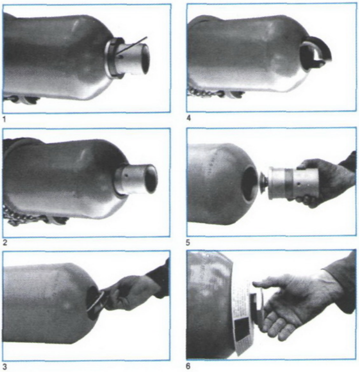
Figure 14.41

Bladder replacement

Figures 14.42 and 14.43 show the correct disassembly/reassembly process of a bladder accumulator. When this process is operated some components needs examining or replacing. Fist of all, the accumulator has to be isolated from the rest of the hydraulic circuit: the pump must thus be disconnected and the tank valve has to be opened in order to release nitrogen.

Diaphragm accumulators are disassembled and reassembled as Figure 14.44 shows.

Bladder accumulator disassembly



1. Unscrew the air bleed screw.
2. Unscrew and remove the ring nut and the retaining ring.
3. Push the valve body inside the accumulator and remove seals.
4. Remove the rubber ring by bending it.
5. Remove the liquid valve body.
6. Remove the nut that fastens the gas valve and the plate.
7. Remove the bladder the liquid side by rolling it gently.

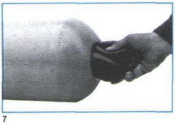
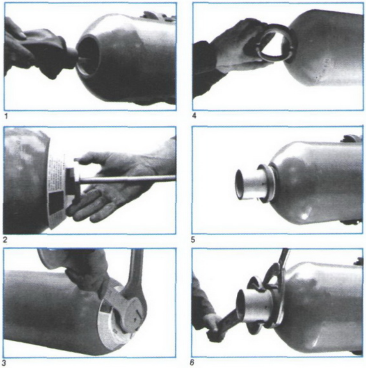


Figure 14.42

Bladder accumulator assembly



1. Insert the bladder (use a threaded hose M 12 x 1.5 for larger sizes).
2. Assemble the plate and the gas valve fastening nut.
3. Tighten the nut and the gas valve with a spanner.
4. Insert the liquid valve and then the rubber ring.
5. Adjust the valve position after arranging it in the ring and add seals and retaining ring.
6. Tighten the metal ring firmly (make sure the shoulder ring adhere to the surface perfectly).
7. Assemble the air bleed screw and its seal. Insert some fluid into the accumulator in order to lubricate its internal part.

Assemble the inflating valve; pre-charge the accumulator and tighten the gas valve nut firmly.

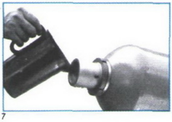
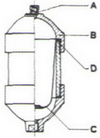


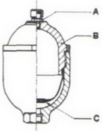
Figure 14.43

Disassembly / Reassembly of a diaphragm accumulator



DISASSEMBLY:

1. Block the lower part with a vice.
2. Remove the inflating valve A (in case of accumulators with M 28 x 1.5 connection unscrew the Allen screw.
3. Unscrew the upper part B with a spanner (AM or AMM type). In case of AML type it is enough to unscrew the metal ring E that fastens the diaphragm disc F.
4. Remove diaphragm C and seals D.



REASSEMBLY:

After cleaning, replace damaged components.
The internal side of the diaphragm and seals must be humidified with the operating fluid.
Reassembly the metallic ring by tightening it firmly and the inflating valve (35 Nm).

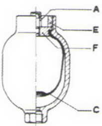


Figure 14.44

Chapter 15

MEASUREMENT INSTRUMENTS, TRANSDUCERS AND PRESSURE SWITCHES

The precise measurement of parameters is fundamental for the adjustment, maintenance and repairing of any operating machine. Parameters in oil hydraulics are measured with pressure gauges, flow meters, thermometers (for fluid temperature) and level gauges (for the fluid in the tank). Measuring instruments for mechanical parameters, such as limit switches, sensors and transducers, are explored in other parts of this text. Force and torque measuring instruments instead are not covered because these parameters can easily be determined from pressure in oil hydraulics.

Pressure measurement considers the delivery pressure of the pump or the pressure of the inlet/outlet port of a specific component, the pressure of tank pipes and the major suction vacuum. In many relatively simple systems delivery pressure measurement with a pressure gauge fixed next to the relief valve is sufficient in order to verify whether the whole systems is working properly, whereas complex systems need more devices arranged in different points. If anomalies are detected and there are not enough measuring instruments according to the staff, an additional temporary pressure gauge will be connected to other specific parts of the delivery or tank pipe; a vacuum gauge mounted on the pump suction port measures the absolute suction pressure in case of vibrations, overheating, poor performances and other factors that can be caused by cavitation.

Flow meters allow verifying whether flow is constant or variable and therefore they are very useful for actuator speed adjustment.

Pressure switches that use electric signals to signal the minimum and maximum tolerable pressure ensures safety and protects the components of the system; they are suitable for simple and inexpensive automatisms.

The continuous measurement of temperatures and pressures by means of transducers that send signals to a control unit (often combined with a whole electrohydraulic proportional system) ensures a high-level automation.

All measuring instruments are affected by the following factors:

- ✓ *Repeatability* – It is the variation that can occur when measuring the same item, even under critical conditions such as vibrations, temperature changes, etc.
- ✓ *Response time* – It is the time the instrument takes to provide the exact measurement; response time depends on the mechanism of the device. For example, if the temperature of a fluid subjected to heating is measured with a mercury-in-glass thermometer at an environmental temperature of 20°C, mercury takes some time to reach the temperature level of the fluid. The response time of traditional pressure gauges depends on the inertia of the Bourdon spring.
- ✓ *Sensitivity* – It refers to minimum measurement change that occurs as physical size increases/decreases slightly. Some consider sensitivity as the minimum effective size needed to trigger the movement only at the beginning of the scale of the instrument, while throughout the measurement spectrum the minimal size used to obtain a change in the index is referred to as '*resolution*'.
- ✓ *Full scale or range* – It is the maximum measurement value the device can detect.
- ✓ *Precision or full scale error* – It is the maximum error compared to a sample instrument. It consists in a percentage of the full scale and divided into classes that are equivalent to the percentage (for instance, Class 1= error ± 1%, Class 3 = error ± 3%, etc.). It is important to stress that the precision error is strictly related to the instrument it refers to: for example, the measurement of two different pressures (10 bar and 100 bar) need two pressure gauges with these two different full scales. If devices belonging to Class 1 (mistake ± 1%) are employed, the full scale error of the lower pressure measurement ranges from 9 to 11 bar, which means it is not reliable, whereas that of the higher pressure ranges between 99 and 101 bar, which is almost irrelevant.

The quality of the device depends on many other features, like its cost, its size and its weight. A qualitative improvement in terms of precision is not directly linked to high manufacturing cost needed to obtain such a result. Pressure gauges placed on test benches are expected to perform high-precision measurement, while other pressure gauges on the machine can be less precise as errors of few bars due to the instrument or the process are absolutely tolerable. For instance, a change from 243 to 247 bar can be due to leakages, vibrations, temperature and viscosity changes, or any other unexpected phenomenon that is tolerable during full speed operations.

In general terms, measuring instruments can be divided into two groups: **analogue** devices (the temperature is displayed by an indicator, like a pointer or a segment, that moves on a linear or semicircle scale) and **digital** devices, which displays numbers.

PRESSURE GAUGES

These devices, which are connected to a pipe or any other apparatus, record the pressure (mechanically or electronically) and show it on a display. Sometimes pressure gauges are referred to as 'manometers' (from the French word *manomètre,* which is derived from the Greek *metron* 'measure' and *manos* 'not very dense', hence 'measuring device for fluid substances').

Liquid column gauges are not employed as they can be used only for pressures that are slightly higher that atmospheric pressure and that do not approach 2 bar (1 bar of relative pressure demands a hose that can be as high as 10 metres depending on the liquid density).

There are two types of pressure gauges used in oil hydraulics and in pneumatic transmissions: mechanical pressure gauges and electronic pressure gauges. The latter are divided into 3 groups: piston pressure gauges, Bourdon spring pressure gauges and diaphragm pressure gauges. Digital pressure gauges receive the signal from a transducer.

As the worker in charge of a machine is likely to know little or nothing about oil hydraulics, he needs no pressure gauges; actually, operations based on pressure gauge monitoring are counterproductive because they can lead to serious setting or manoeuvre mistakes. Nonetheless, nowadays many (especially mobile) applications are equipped with large and bulky pressure gauges that are exposed to the risk of being hit by other objects; what is more, as far as parameter measurement is concerned, these gauges are often inefficient in the event of a technical problem because under these circumstances it is often essential to use a portable device that can be placed in specific points other than those of fixed pressure gauges so as to detect the problem.

Furthermore, workers are told to use a specific minimum and maximum pressure and, if these parameters vary, they tend to adjust them via a knob on the control panel, perhaps even the relief valve knob that should instead be blocked and placed out of reach, as if present machines could not be equipped with self-control systems. Pressure gauges are instead a key device for maintenance workers since they enable them to detect damage and to perform adjustments.

Piston pressure gauges

Piston pressure gauges are the simplest pressure measuring instrument in oil hydraulics but they are rarely used.

Unlike Bourdon spring pressure gauges, piston pressure gauges can easily sustain peak pressures exceeding the full scale; they are not sensitive to pulsations and can be used permanently. On the other hand, they are not very precise or sensitive.

In their simplest version (Figure 15.1 -a-), the pressurised fluid that acts on the piston solidly connected to the rod (2) pushes the mobile element (4) countered by the spring (1) upward. The pointer (5) indicates the pressure acting on the connection point of the device on the scale (3).

Figure 15.1 b shows another version: the mobile element ends with some tie rods (instead of the pointer) that act on the pointer moving over a semicircle scale. When the pointer reaches the full scale end, the mobile element (4) must be in the end-of-stroke position in order to avoid damage to the tie rods and the pointer.

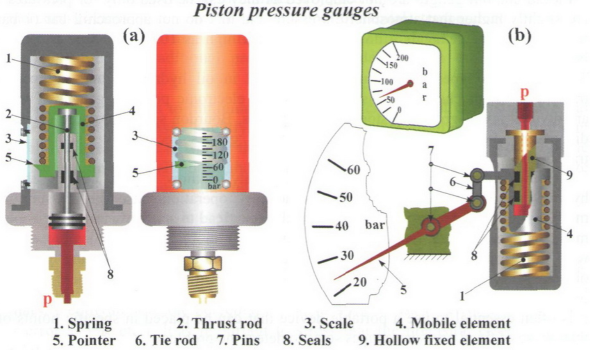


Figure 15.1

Bourdon spring pressure gauges

Most pressure gauges used in oil hydraulics are based on the Bourdon spring principle. This spring is made up of a very sensitive bended elastic metal hose with an elliptical cross-section. This hose is closed at the end next to the mechanism of movement amplification (rod, toothed sector and gear) while the other end receives the hydraulic fluid. When some pressure acts on the point where the pressure gauge is placed, the fluid that enters the spring deforms it according to the pressure.

This triggers a movement of the tie rod, of the toothed sector and the wheel; as the pointer hinges on the gear, it revolves thus pointing at the pressure on the scale (Figure 15.3).

Bourdon spring pressure gauges are particularly sensitive to pressure changes and they break down easily if system pressure exceeds their full scale. In addition, continuous operation reduces their working life and increases the full scale error dramatically.

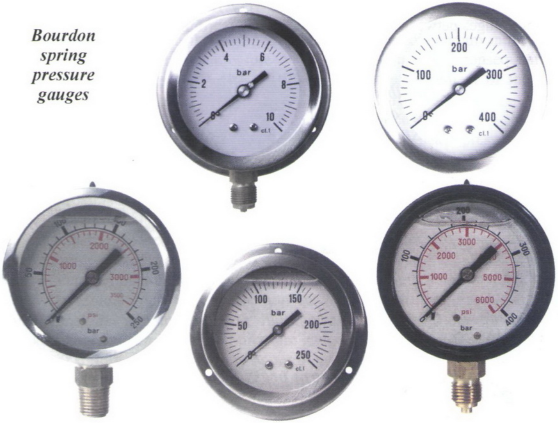


Figure 15.2

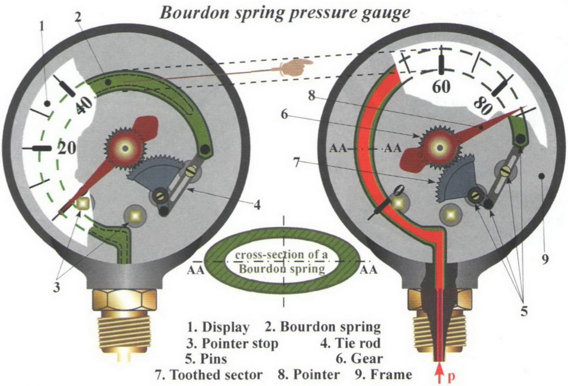


Figure 15.3

Except for sample tools, which must be very reliable, the full scale used in oil hydraulics ranges between Class 1 and Class 2.5 according to the precision needed.

Calibration of a standard pressure gauge with a sample pattern tool

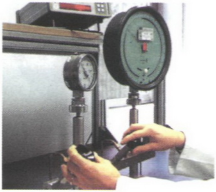
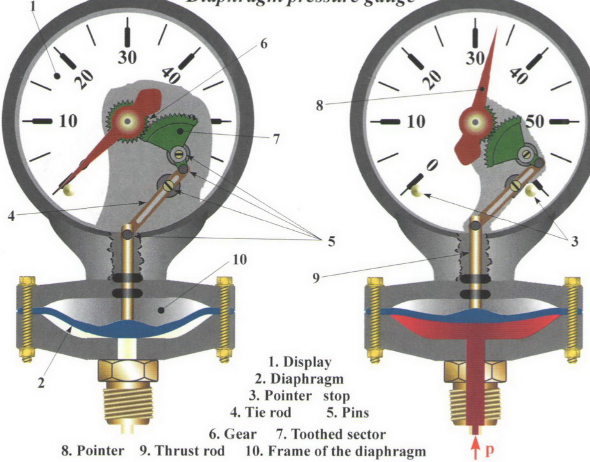


Figure 15.4

Diaphragm pressure gauges

Diaphragm pressure gauge



1. Display
2. Diaphragm
3. Pointer stop
4. Tie rod 5. Pins
6. Gear 7. Toothed sector
8. Pointer 9. Thrust rod 10. Frame of the diaphragm

Figure 15.5

There are two main types of diaphragm pressure gauges: single diaphragm pressure gauges and double diaphragm pressure gauges.

In the former, the fluid that flows on the lower side of the diaphragm moves it; this movement is proportional to the pressure of the connection point; consequently, the thrust rod solidly connected to the diaphragm triggers the movement of the mobile elements (rod, toothed sector and gear) and the pointer (Figure 15.5).

Unlike Bourdon spring pressure gauges, these devices does not experience overpressure problems since the diaphragm itself absorbs peak pressures. Single diaphragm pressure gauges are used at pressures lower than 60-70 bar.

The measurement of absolute suction pressures with **vacuum gauges** guarantees an excellent approximation through double diaphragm devices. In oil hydraulics, the vast majority of double diaphragm pressure gauges can be defined as real positive pressure gauges: as a matter of fact, the measurement range varies from -0.5 bar for absolute pressures to some relative bars.

The two diaphragms are connected over their maximum circumferences; a fluid or another deformable component fills the gap between the two diaphragms so that the pressure signal is transformed into mechanical energy and overpressures are dampened. Like in single diaphragm pressure gauges, the signal is then transmitted to the thrust rod solidly connected to the upper diaphragm, the mobile elements and the pointer.

Digital pressure gauges

Figure 15.6

The pressure displayed (Figure 15.6) is recorded by a built-in transducer that transforms the hydraulic signal into an electronic signal. These devices are widely used since they are very versatile and portable (they can be held in multifunction cases that measure not only pressure but also fluid temperature, flow and speed) and they can record pressures ranging from atmospheric pressure to 1000 bar; furthermore, they do not require connections to a power supply when they are equipped with batteries.

Pressure gauges featuring electrical contacts

Apart from traditional pressure measuring instruments equipped with a pointer and a scale, some devices also act as one or two-threshold pressure switches (see related paragraph). The single or double electrical contact is placed on the display: as the pointer moves over the point where the contact is placed, its electric state changes; as a result, the component connected to that specific contact is activated/deactivated (Figure 15.7).

For example, upon reaching the maximum pressure set, the one-threshold pressure gauge opens, stops the movement of the pump or controls a specific directional valve. Two-threshold pressure gauges instead are equipped with two contacts that generally correspond to the maximum and minimum tolerable pressure. For example, they can open a stop valve when the system reaches a specific pressure and start the unloading of the relief valve (venting) as the system reaches the maximum pressure.

In standard versions when the frame is dry or filled with antivibration fluid, electrical contacts consist of traditional electromechanical contacts, but manufacturers can provide specific contacts on demand.

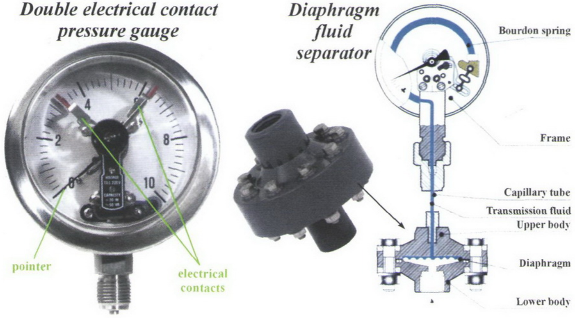


Figure 15.7

Accessories and recommendations

Some synthetic fluids are not compatible with the Bourdon spring and other components of a pressure gauge. That is the reason why versions with flexible diaphragm need the inclusion of a **fluid separator** upstream of the pressure gauge (Figure 15.7). Manufacturer usually supply a separator already connected to the pressure gauge and provided with an appropriate transmission fluid. It is recommended not to disassemble the two components since it is difficult to replenish the fluid.

It is advisable at high working temperature not only to check the temperature range the pressure gauge can sustain but also to add a tubular siphon or curl pipe **coil** that can both reduce the possible pulsating pressure (Figure 15.8) and ensure heat dissipation.

It is advisable to include a pulsation dampening cartridge between the pressure gauge and the connection pipe in systems experiencing dramatic temperature changes; this cartridge is made up of a cap containing a spiral capillary tube or a bearing made of a sintered porous material (Figure 15.8).

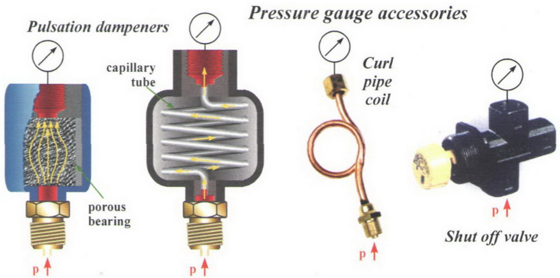


Figure 15.8

As we have already explained, Bourdon spring pressure gauges precision decreases considerably under continuous operation. Since stop valves are not very practical, they are replaced by monostable **shut off valves** 2/2 or 2/3 with a button (Figure 15.8); the pressure gauge is not working when the valve is in the rest position, but by pressing the button the clearance opens and the pressurised flow can reach the device.

A **rotary distributor** allows pressure measurement in many areas of the circuit. Pipes converge at the shut off valve equipped with a little panel with reference notches; the rotation of the knob connects that area, but in order to avoid continuous connections, the inclusion of the gauge depends on the monostable feature of the knob: the pressure gauge is by passed when workers stop acting on the knob placed on the pressure gauge.

A capillary hose serves as the **flying connection** of the pressure gauge (Figure 15.9); its ends are equipped with quick connect couplings fitting the threaded connections of the machine.

Coupling and connection hose

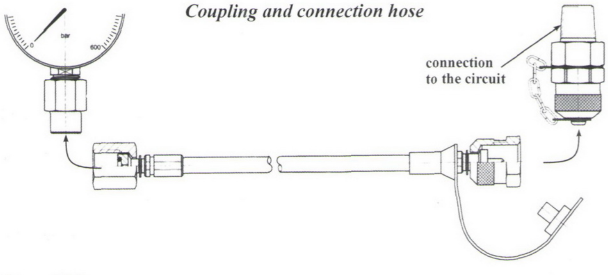


Figure 15.9

If there are vibrations, pressure gauges should be provided with an **anti-vibration fluid** (Figure 15.10). This fluid (usually transparent glycerine) occupies almost the whole frame and cushions the mechanism that amplifies the signal and the pointer itself.

Furthermore, it reduces the effects of the pulsating pressure even though it is advisable to add the dedicated devices formerly described in order to solve this problem.

Pressure gauges with anti-vibrations fluid

Figure 15.10

Pressure gauges with dampening fluid can be easily recognised by the air bubble that develops on the upper part of the display; the bubble results from the partial filling of the fluid, which is needed in order to allow the expansion of the spring and the free movement of gauge devices and glycerine expansion due to temperature.

It is important to remember that pressure gauges, above all Bourdon springs, do not support full scale measurements. As a matter of fact, manufacturers recommend that the full scale of devices be higher than the nominal pressure of the system by about ¼, while overpressures equalling the full scale can be sustained only for a few minutes.

A signal of pressure that is higher than this can damage the device, even if it lasts for a few seconds.

In the vast majority of standard versions and except for high-precision devices, damage is irreparable.

Pneumatic and oil hydraulic pressure gauges are not compatible with very deflagrating gases such as oxygen and methane; in any case, as copper and copper alloys are found in most systems, it is vital to make sure there are no fluids or corrosive gases in the system.

Pressure gauges must **never** be tightened/loosened with one's hands or different adjustable tools but by acting on the nut below with a spanner with fixed jaws. Even though pressure gauges can work in any position, the vertical or almost vertical position guarantees the best results, especially in low-pressure gauges.

It is also important to consider *parallax errors* carefully because a wrong sight trajectory (for instance, an angular position) can lead observers to see misleading pressure values, especially in small devices.

Figure 15.11 shows the right position of pressure gauges and different fastening methods.

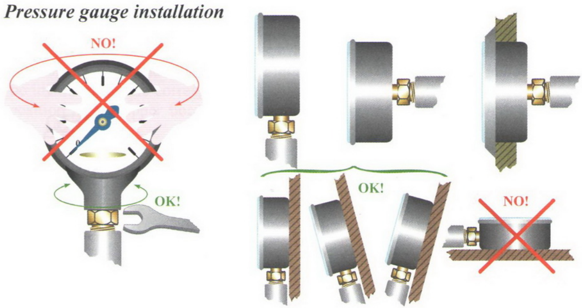


Figure 15.11

The design, installation and examination standards of pressure gauges are set by EN 837; in Italy these devices must comply with the safety standards established by Decree-Law 626/94.

FLOW METERS

Like pressure gauges, **flow meters** too have to be connected to the measurement point; however, unlike pressure gauges, which need only a T-shaped joint, they require a removable pipe having the same length as the pipe of the flow meter. For this reason, if a flow meter is really essential for machine control, it is advisable to install it permanently in systems with pipe whereas there are no problems for temporary connections in circuits with hoses.

Electronic devices with a digital display provide precise measurement, are easy to read and occupy little space; however, mechanical hydraulic devices are still available and popular because they are inexpensive, albeit rather imprecise.

Flow meters are rarely used for the speed control of actuators, but they are widely employed for the control of the ratio of the inlet flow to the outlet flow of valves, pump volumetric efficiency and overall leakages.

Flow gauges

Flow gauges are made of a sleeve inside which there is a helical component; flow sets the helix into motion and the movement can be observed through the transparent display of the sleeve (Figure 15.12).

Flow meters are not widely used in fluid power applications; as a matter of fact, they are not suitable for relative pressures (even equalling few bars) and hydraulic flows start an actuator thus already providing visual evidence of the motion.

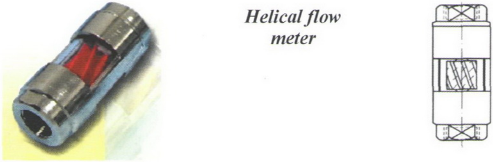


Figure 15.12

Flow meters with float

Flow meters with float (also known as **hydrodynamic** flow meters) are the most common and cheapest flow meters. They are insensitive to high contamination and quite precise, especially with low/medium flow rates. However, this kind of flow meter cannot detect reverse flows and their measurement is not reliable if there are dramatic changes in viscosity.

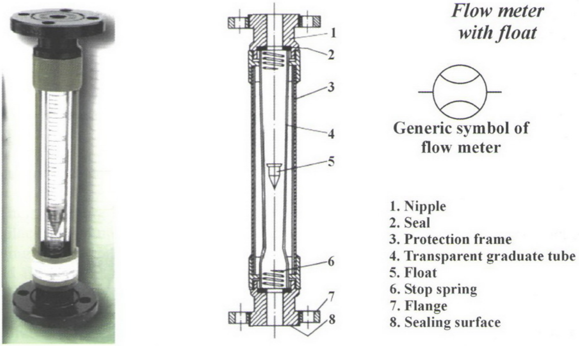


Figure 15.13

These flow meters consists of a conical glass tube ending with flanges and having a graduated scale (l/min); it contains a metal float with a conical or round section whose stroke ends are dampened by springs (Figure 15.13). The flow level inside the tube can be identified by the correspondence between the notch of the graduated scale and the position of the upper border (conical section) or the horizontal diameter (round section).

These flow meters must strictly be placed in a vertical position with the inlet port facing downward. Both ports must be connected to a straight pipe whose internal diameter equals the diameter of the flanges because bends or restrictions undermine measurement.

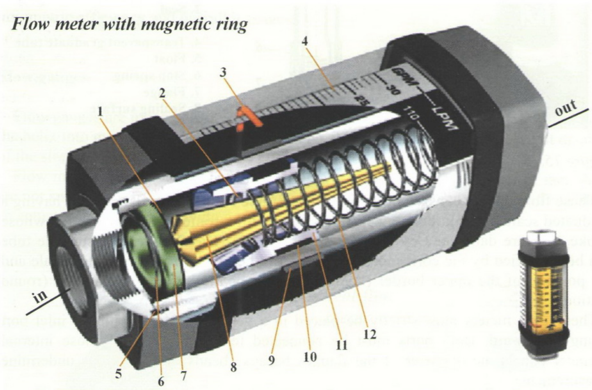
Its operating principle, partially based on Archimedes' principle, is due to the vertical action of the fluid on the float that changes its position according to the thrust it is subjected to. In other words, the float is an obstacle to the fluid and causes a pressure drop; the contrast between the pressure of the fluid and the weight of the mobile element determines the height change according to the internal bore of the glass tube.

Despite its advantages, these flow meters need some important precautions. First of all, it is important to be aware of the maximum tolerable pressure since the part of the flow meter made of glass could break or explode; however, the main problems arise at the nominal pressures of the system: notches are generally referred to a pressure up to 10-15 bar and the simple measurement at oil hydraulic nominal pressures can entail errors.

As a result, the installation of these devices in an area subjected to delivery pressure can hardly provide acceptable measurement: apart from the inclusion of a by-pass valve, an handbook about measurement interpretation laid out during the system fine-tuning is needed too (for example, the 75 l/min notch is equivalent to 50 l/min at the pressure X and 37 l/min at the pressure Y etc…). Its connection to the outlet instead does not cause any particular problems.

The external wall of the transparent piping of pressure gauges with float can be equipped with magnetic sensors: electrical signals that provide information on flow levels can be used for specific automation of the operating machine.

Meters with magnetic ring



1. Seeger ring 2. Calibrated hole 3. Pointer
4. Graduated scale 5. Seal 6. Stop spring 7. Disc 8. Measurement cone
9. Ring solidly connected to the pointer 10. Internal magnetic ring 11. Piston 12. Spring

Figure 15.14

Meters with magnetic ring share the same operating principle as traditional flow meters, although they withstand shocks better and can be used at pressures higher than 400 bar in an horizontal or inclined position. They sustain high temperatures (up to 110 °C or, in some particular versions, even higher than 200 °C); they are stable even if viscosity changes and they cause no considerable differential pressure (for instance, with a maximum flow of 500 l/min they develop a Δp of 2 bar); their best versions have a good repeatability with a 2[nd] Class of precision. Furthermore, some devices can measure the flow in both directions; the main features in the main direction are those described so far while they are slightly less brilliant in the opposite direction.

The cone (8), which plays the same role as the float in the flow meter, is pushed by the inlet fluid that flows through the calibrated hole (2). The cone triggers the movement of the piston (11) equipped with a magnetic ring (10); the ring (9), solidly connected to the pointer (3) makes this point at the flow level on the graduated scale (4) according to the movement of the magnet (Figure 15.14).

Volumetric meters with oval wheels

Their structure is similar to that of the lobe pumps described in Chapter 4 (Fixed displacement pumps). Their wheels are attached to their gears and unlike the pump having the same name they are simply oval with the axe positioned at 90°. The fluid flowing through the inlet and outlet ports sets the wheels into motion; gears are essential in order to ensure a synchronous and opposite motion. The flow can be calculated by considering the volume of the fluid flowing throughout a wheel revolution and the number of rotations performed over a specific time. For example, if the displacement (c) is equal to 20 cm^3 and wheel speed is 300 rpm, the flow (Q) is:

$$Q = \frac{c \cdot rpm \cdot \eta_v}{1000} = \frac{20 \cdot 300 \cdot 0.9}{1000} = 5.4 \text{ l/min}$$

Measurement is performed through the revolution counter connected to spindles rigidly connected to their gears.

Anyway, the system can record data concerning the average flow only, that is the whole volume of fluid that flows though the device over a specific time. The measurement of an instantaneous flow is possible thanks to the connection of the spindles of a tachometric dynamo or a transducer (connected to another electronic device with digital display).

Meters with oval wheels are used in medium/low pressure systems. Because of their volumetric mechanism they are very precise and they are insensitive to viscosities ranging from 30 to 100 cSt. As shown in Figure 15.15, they can measure even the reverse flow.

Meter with oval wheels

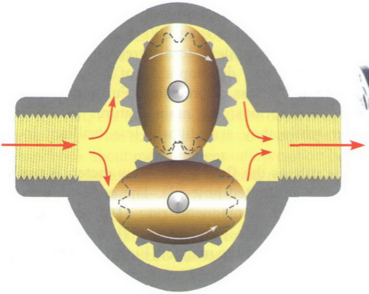


Figure 15.15

Turbine meters

They have the same volumetric characteristics as meters with oval wheels. Their rotating group made up of many vanes on the rotor is supported by a spindle with bearings; a series of tie rods attached to the bearings on the one side and to a dedicated ring on the other keep the turbine stable.
Fluid flow triggers the revolution of the turbine: the number of rotations is proportional to the flow. A sensor emits an electrical signal at the passage of each vane. Signals are sent and processed by the electronic unit that counts the number of vanes that passes over a specific time. Afterwards, it calculates the real instant flow according to the initial setting; the processing is then transformed into inputs and the display shows the instant flow in GPM or l/min (Figure 15.16).

In order to manage the operating system appropriately, apart from the digital display, the electronic processing can be interfaced with appropriate devices of conversion such as square wave frequency amplifiers, PCs, PLC and so on.

Turbine flow meters ensure precise results and a considerable measurement range: a small turbine flow meter can measure flows ranging from 1 to 25 l/min; a medium one is suitable for flows from 15 to 350 l/min, while large flow meters can be used with flows from 35 to 1300 l/min. Some special versions can sustain pressures up to 420 bar and pressure drops are less than 2 bar; manufacturers ensures precision class 1 and a repeatability of ± 0.2%. These data refer to optimum working conditions, with fluid viscosity lower than 35 cSt; as a matter of fact, turbine meters are not recommended for contaminated fluid and viscosity level exceeding 40 cSt.

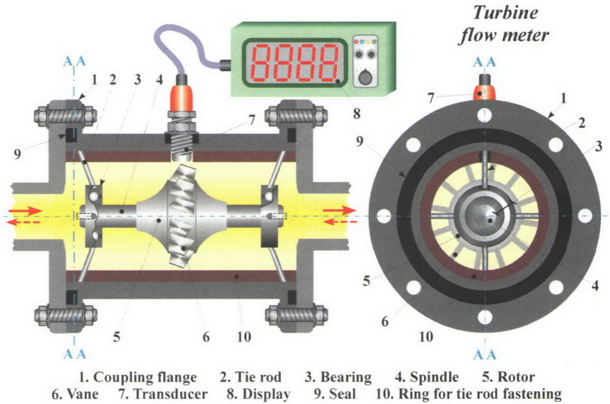


Figure 15.16

Flow switches

Flow switches signal the passage of the fluid in a tube. The most popular and cheapest versions are based on the transformation of a mechanical signal into an electrical signal: a foil in a T joint in series with the tube involves switching an electrical contact (placed over the fitting and held in a container) when there is flow (Figure 15.17).

Flow switches are widely used in chemical, pharmaceutical and food industries as well as in lubrication systems and many other processes while in oil hydraulics they are not common because of high pressures.

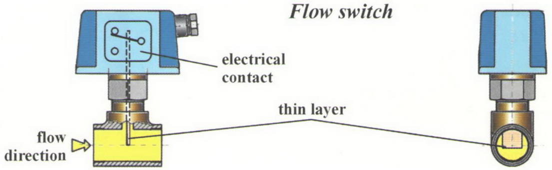


Figure 15.17

FLUID LEVEL

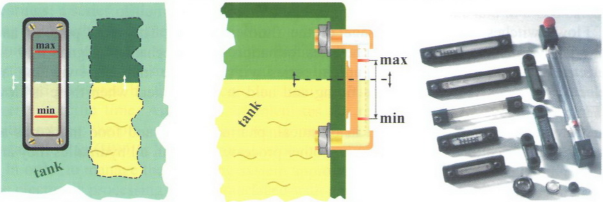
In oil hydraulics the control of the fluid level involves the control of the minimum and maximum level of fluid in the tank. This control is performed through direct reading pointers or electric devices of automatic control. In electric devices of automatic control, the part subjected to electricity must be placed outside the tank and isolated from the feeler pin mechanical element immersed in or placed above the fluid since mineral oil is flammable. If there are semi-immersed electrical devices, they must be isolated with seals.

The isolation of mechanical parts and the mechanical feeler pin is strongly recommended with non-flammable fluids (water, mixtures, synthetics..) since their contact can cause a change in their electrical state (for example, given that water is a good conductor, the wetting of a NO contact turns it into NC); furthermore, fluids rich in oxygen and the air on the free surface of the tank cause the contact oxidation.

Optical minimum and maximum level gauges

The cheapest method of optical reading consists in the creation of a transparent display on one vertical wall of the tank where there are the minimum and maximum levels required. Two coloured notches indicate the fluid level (Figure 15.18). A simpler method consists in the creation of two holes that correspond to the supposed levels with the application of two transparent indicators. Nevertheless, in the event of modification of the maximum or minimum level, the display must be enlarged and holes modified.

Optical minimum and maximum level gauges



Transparent display ***Transparent tube***

Figure 15.18

Conditions improve considerably with the application of a transparent graduated tube placed in a small parallelepiped box; this tube must be placed on the vertical wall where it can be read more easily. According to the principle of communicating vessels, the fluid (that must be compatible with indicator materials) occupies the same level as the tank in the measuring tube (Figure 15.18).

Optical level gauges

These devices measure the quantity of the volume, from 0 litres to the maximum volume that can be contained in the tank. The simplest way to know the exact level is to observe the maximum wetting point of the fluid on a graduated bar arranged in the tank through a hole in the tank cap: by knowing the flat surface of the tank (dm^3) and by multiplying it by the height (notches on the bar must clearly refer to dm), it is possible to know how many litres of fluid there are in the tank.

This awkward and empirical method can be replaced by the inclusion of a tube having the same features as the previous one (maximum and minimum level) but whose height is equal to the height of the tank. Therefore, in most versions, the tube contains a float with two functions: it is equipped with a magnetic ring in order to attract the indicator metal slider that can be seen more easily than the previous one where the fluid indicates the notch; otherwise, it can activate a series of electrical sensors placed along the external wall of the reading tube (Figure 15.19)

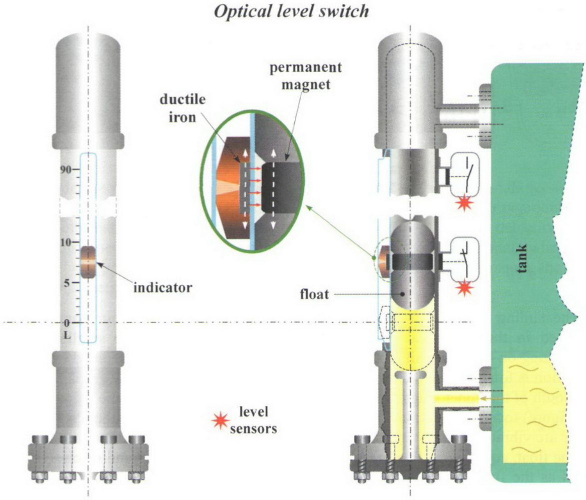


Figure 15.19

Figure 15.20 shows an interesting version of this device.

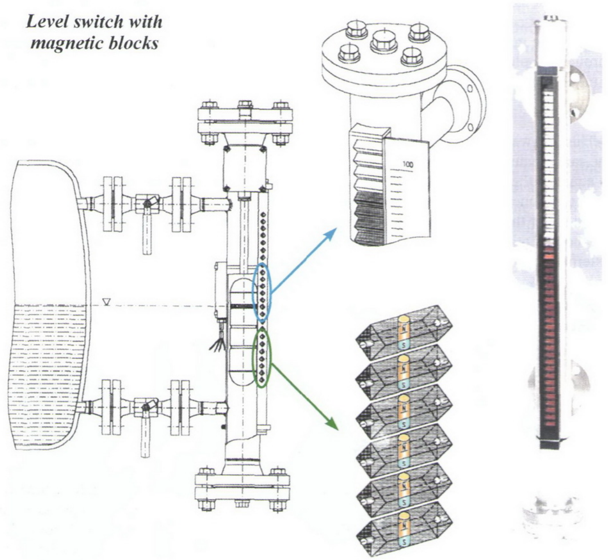


Figure 15.20

The sliding indicator is replaced by a series of small two-colour parallelepipeds retained in the horizontal position by pivots coming out of the smaller surfaces, fluctuating on the side wall of the graduated scale. A little magnet oriented in a specific direction is found inside the parallelepipeds; since the north of the lower magnet attracts the south of the upper magnet, each element turns the angle of the same colour (white in the figure) toward the display; furthermore, the magnetization keeps them stable even if there are vibrations.

The float, equipped with a magnetic ring, is pushed by the fluid and reaches the same level as the fluid in the tank; during this process, it attracts the little magnets of the parallelepipeds and overturns them by 180°: in this manner, they show their other colour on the display (red in the figure). When the level decreases, the opposite process occurs.

Level switches with side float

They are made up of a mechanically-operated mobile element that acts on an electrical contact (Figure 15.21). Devices must be installed at the level detection height with the electric device case out of the tank while the float lies on the fluid. When the level decreases, the float drops and switches the electrical contact.

It is also possible to install two level switches with float (one for the maximum level and the other for the minimum level) or even just one element equipped with a contact switch that measures both levels. In this specific case, the connection bar between the float and the contacts requires an appropriate height in order to balance the difference of levels; it must also be rigid since the thrust of the fluid could damage it undermining precision.

The use of two level switches does not cause any particular problems in most mobile and stationary applications, while the system with one device for the measurement of two levels is rather unreliable if there is instability: the float can fluctuate because of vibrations and recoils.

Level switch with side float

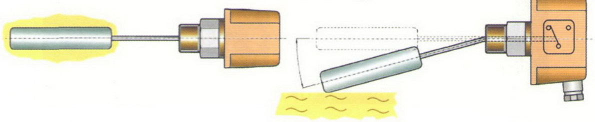


Figure 15.21

Another device is the **micro level switch** with side float; this is the small version of level switches with side float (Figure 15.22). In this case, a Reed bulb is positioned on the fixed bulb that is placed outside the tank (see Chapter 4 – Position detection); the float contains a permanent magnet which keeps closed the Reed bulb contact when it is in the horizontal position (Figure 15.22 on the right). When the level decreases, the float bends: the magnetic field is reduced and the contact opens.

Micro level switch with side float

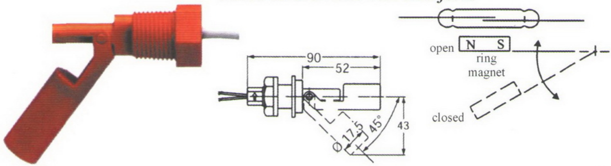


Figure 15.22

Given their small size, level switches with side float are particularly suitable for small tanks and the measurement of the minimum level only. Under normal conditions, the float is immersed in a horizontal position (Reed closed) without any damage since it can withstand pressures up to 4 bar, that is to say pressures higher than the thrust of the fluid in the tank. The float bends opening the contact only when the minimum level is reached.

Level switches with vertical float

Level switches with vertical float

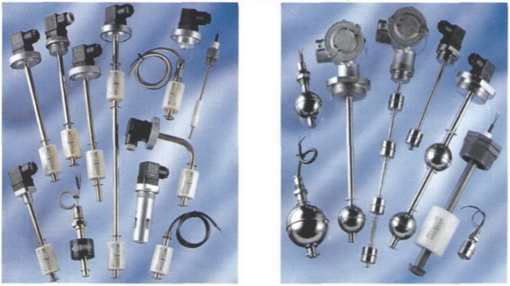


Figure 15.23

These devices are equipped with a vertical bar whose upper part consists of a bulb supported by a strong flange. This bulb is placed on the upper external wall of the tank (an L-shaped element on the side wall can be fixed in some versions); one or more floats slide along the bar for level measurement (Figure 15.23).

Like micro level switches, level switches with vertical float are usually equipped with a Reed bulb hermetically enveloped inside the bar. The magnetic ring for Reed opening/closing is placed inside the float and it is attached to it (Figure 15.24).

Sensor in level switches with vertical float

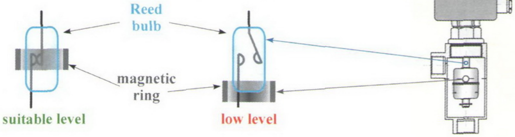


Figure 15.24

The correct installation of vertical floats needs the adoption of a special measure. The floating line of the mobile element is exactly at the level of the liquids whose density is equal to 1000 Kg/m^3 (water); depending on density, the floating line is under the level of the fluid (if there is mineral oil the gap is about 15 mm) if it does not exceed 1000 Kg/m^3, whereas if there are heavier liquids than water (such as most synthetic fluids), the lower cap slightly touches the free surface. In other versions, level switches consist of a magnetostrictive transducer (see Chapter 19 - Feedback transducer): the 'hoop' that generates the magnetic field slides on the floating line.

Level sensors

Figure 15.25 shows two types of capacitive level sensor. Level sensors, tightened to the internal side wall at the height of the level that must be measured, require a connection to an electronic device that processes signals.

Figure 15.25

TEMPERATURE MEASUREMENT AND CONTROL

As we have already said, temperature control is crucial in any oil hydraulic circuit. This parameter is visually measured through a common thermometer; automatic control is performed by thermostats. There are many versions of these two elements and their costs range from a few Euro to thousands of Euro. We are going to consider only the thermometers employed in oil hydraulics.

Thermometers

Bulb and glass column thermometers are cheap and easy to use: for this reason, they are still widely employed despite their drawbacks. Thermometers are essentially made of three parts: the transparent box consisting of a bulb that ends with a capillary tube, mercury (replaced by alcohol in some versions) and the body, usually made of glass (Figure 15.26).

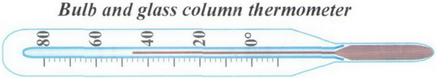


Figure 15.26

Mercury occupies the whole bulb at the minimum measurable temperature. An increase in the external temperature causes the heating of the bulb and the ensuing dilatation of mercury, which begins to flow through the tube: the temperature is indicated by notches on the graduated scale printed on the tube.

These devices are not suitable for fluid power because vibrations and shocks can break the glass. Furthermore, their measurement field is limited and not very precise.

On the other hand, bimetallic and inert gas mechanical thermometers are very reliable; they are both equipped with a display. In **bimetallic** mechanical thermometers, the steel pipe contains a bimetal helical spiral whose ends are welded to the lower part of the pipe on the one side and to a transmission spindle on the other; the spindle ends inside the frame where it is connected to the pointer. The deformation temperature changes cause on the bimetal entails the rotation of the spindle and consequently the movement of the pointer (Figure 15.27).

Inert gas thermometers are made of a thermometric bulb, a capillary transmission pipe and a helical Bourdon spring held in the frame of the device; these components are pressurised with inert gas. Pressure changes caused by temperature variations activate the Bourdon spring, which transmits the movement to the pointer (Figure 15.27).

Both versions need a thermometric pocket for the protection of the bulb in the event of medium/high pressures.

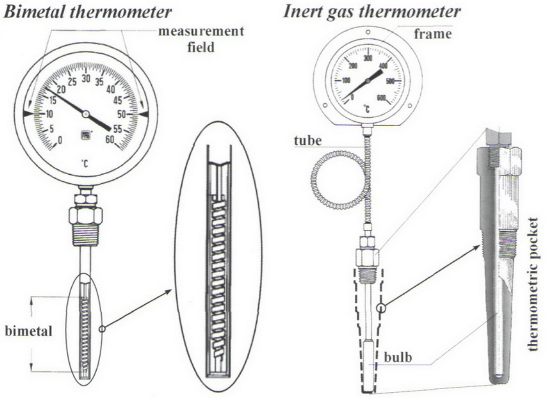


Figure 15.27

There are many versions of **digital** thermometers (Figure 15.28). They are essentially based on the transposition of an electric signal on a display through sensors like those used in thermostats. These devices are very often used as thermostats and thermometers.

Digital thermometers

Figure 15.28

Thermostats

Thermostats transform a thermal signal into an electrical signal and they send it to the control unit: they monitor the temperature of a component within certain limits. There are many versions of thermostats with different costs and precision levels. In general, thermostats are made of a bimetallic layer, a thermocouple, an electric resistance and other modern thermo-electronic components.

In the **bimetallic** technique, two layers with a different dilatation coefficient (example steel and aluminium) are held inside the bulb tightened to the component to be controlled; these two layers overlap and one of their ends is fixed to the bulb while the other end is free; the NO, NC electrical contacts or the switch are at these ends. When temperature increases, the more sensitive metal dilates but this is hindered by the other metal, which is stronger: the first metal bulges and switches the electrical contact (Figure 15.29). In **thermocouple** thermostats, two metal layers or threads made of different metals are welded together at their ends. When one end is heated, a current proportional to the difference of temperature of the two elements develops within the circuit and the signal is transmitted to the control unit.

Bimetal thermostats

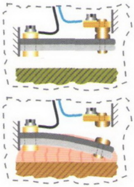


Figure 15.29

An **electric resistance** system is based on the fact that the ohmic resistance of a coil with a platinum thread changes according to temperature.

Electromechanical and digital thermostats

Figure 15.30

PRESSURE SWITCHES AND PRESSURE TRANSDUCERS

Pressure switches are the devices that transform a (pneumatic or hydraulic) pressure signal into an electrical signal. They ensure the proper operation of a system as well as its safety.

Pressure switch
Operating principle

1. Operation piston
2. Mobile electrical contact
3. Fixed electrical contact
4. Connection clamps
5. Electrical conductors
6. Fluid inlet

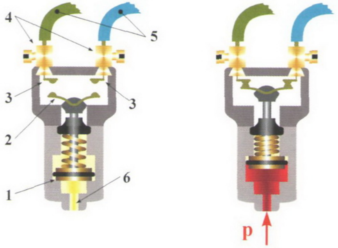
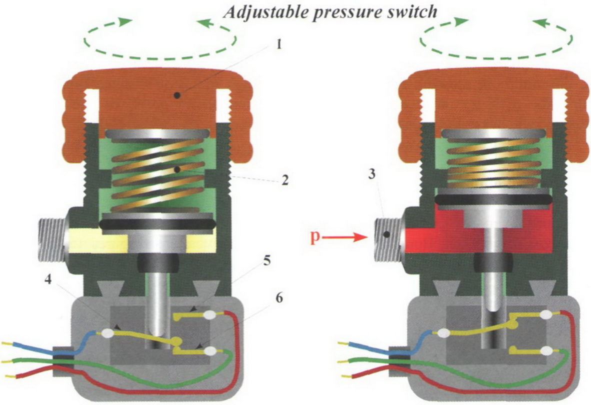


Figure 15.31

Apart from some versions whose calibration is fixed by manufacturers, most pressure switches on the market can be calibrated according to the minimum and maximum pressure; in other words, the switch commutates signals only upon reaching the minimum or the maximum pressure formerly set via the adjustment screw or turning knob.

Single threshold pressure switches

The adjustment screw or knob determines the tension of the opposing spring. As the pressurised fluid overcomes the force of the spring, the contact can switch (Figures 15.31 and 15.32).



1. Adjustment knob **2. Opposing spring** **3. Pressurised fluid inlet**

4. Common electrical contact **5. NC electrical contact** **6. NO electrical contact**

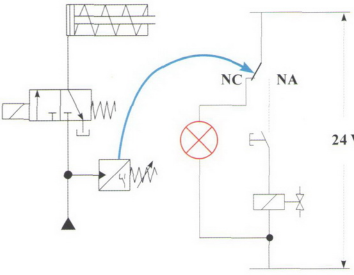


Figure 15.32

If the control electric circuit has to be started when the pressure reaches the maximum calibration requested, the NO contact signal is obtained; if pressure drops considerably, the pointer in the centre moves on the NC contact, which can be connected to a sound or visual signal.

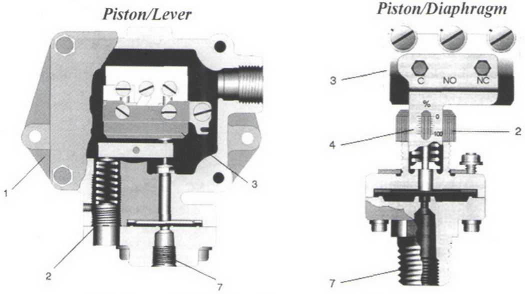
Pressure switches with two or more thresholds

These complex devices have an adjustable dead band: once the maximum pressure is set, the minimum pressure can be defined with high precision and the system works within the pressure range of the dead band. Intermediate pressures can be set on pressure switches with two or more thresholds.

Construction options

Versions available on the market offer many options ranging from piston type, diaphragm with piston, Bourdon spring and electronic versions (Figures 15.33, 15.34, 15.35, 15.36). Costs depend on their protection degree IP and whether they are held in a flameproof box.

Pressure switch - Version types



1. Frame 2. Adjustment screw 3. Micro switch
4. Intervention point signalling 7. Pressure connection

Figure 15.33

Electrical micro switches deserve much attention: the tension of contacts must be chosen according to the working tension and excessive inductive, resistive and capacitive loads that can dramatically reduce the average working life of components.

Transducers and electronic systems integrated in pressure switches ensure a good precision and they are very reliable; the digital display on the components shows the pressure in the circuit; adjustment buttons allow the modification of the dead band and quick adjustments.

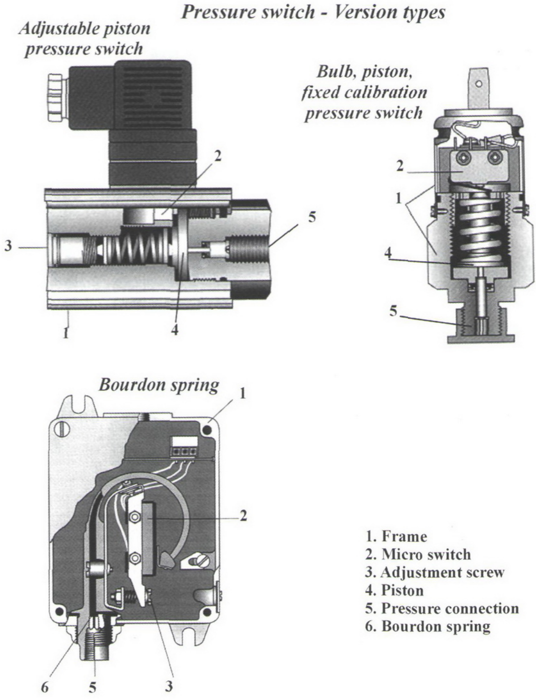


Figure 15.34

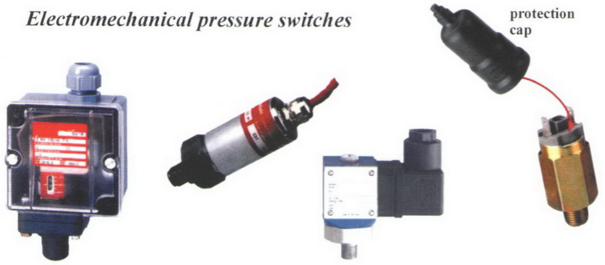


Figure 15.35

Figure 15.36

Pressure transducers

Pressure transducers commutate an electric signal into a pressure signal. The difference between pressure transducers and pressure switches is clear: pressure switches send a signal when a certain pressure is reached but the signal is not proportional; transducers instead constantly send data concerning the pressure of the point where they are placed. It is evident that transducers cannot be used in pure electromechanical circuits but only in systems equipped with electronic controls.

Most catalogues list pressure transducers that are suitable for many applications. Transducers must be compatible with both the fluid and the system. There are very expensive transducers designed for pressures other than oil hydraulic pressures: they are equipped with a cap and their linings are compatible with corrosive fluids and gases. These kinds of transducers have nothing to do with fluid power.

What follows is a brief description of the three most popular types of the detection component of transducers.

In **capacitive** transducers, the sensitive element, which is contained in a cap, is an electric condenser that changes its capacity (μF) according to the force exerted on its structure. This change is proportional to the force. This force is hydraulically expressed by the pressure of the point where the transducer is placed; the measurement is defined by the capacity of the condenser. The final signal is obtained with the application of a capacitive Wheatstone bridge supplied with a specific input tension; the output tension is sent to the control unit.

Piezoelectric transducers exploit the principle of some materials, which emit electrical charges when subjected to mechanical deformations. The mechanical action (pressure on the element) is proportional to the electric phenomenon also in these transducers: this allows constant pressure measurement. The most suitable substance for piezoelectric devices is quartz, which is shaped as a small disc protected by a diaphragm: pressure modifies its shape and triggers signal emission.

Silicon is the best detection element for **strain gauge** transducers or extensometer because of its low coefficient of thermal dilatation, its resistance and its mechanical hysteresis, which approaches zero. Silicon too exploits the deformation of the element held in a ceramic cell; the electric signal results from the resistive modification.

Pressure transducers

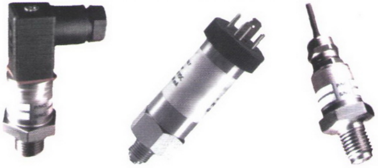


Figure 15.37