PLUNGER HYDRAULIC MACHINES. TYPOLOGY, CALCULATION PRINCIPLES AND APPLICATIONS IN MINING

SORIN VĂTAVU[1]

Abstract: Hydraulic systems are either self-sustaining structures or structures incorporated into different machines, equipment or installations which have different uses, such as: the hydro-mechanical equipment of hydro-electric plants, mining machines and equipment, various machines and tools, construction machines, etc. These systems carry out the transport of the fluid, cool down equipment and, using a pressurised fluid, ensure the lubrication or the transfer of mechanical energy from one conducting element to another. The role of hydraulic energy generators, called pumps, is to supply the systems with the required flow and pressure depending on the destination. As far as the actuating / hydraulic transmission systems are concerned, the pump supplies the operation systems (hydraulic motor and operating device) with the necessary energy for the device to carry out an operation. Mining uses a large variety of operational and constructive types of pumps, piston / pistons machines being integrated in a large and diversified range, determined by the end use of the system, by the domains of the flow, pressure and the operating liquid. The paper deals with the generalities regarding constructive, operational and determination particularities of this type of hydraulic machines largely used in mining.

Key words: Hydraulic System, Hhydraulic Machines, Reciprocating Pumps.

1. INTRODUCTION

Hydraulic systems may be used for various purposes and situations, the most important and widely met are:

- Actuation operating machineries;
- Elastic connection for the shafts;
- Lubrication;
- Fluid transportation.

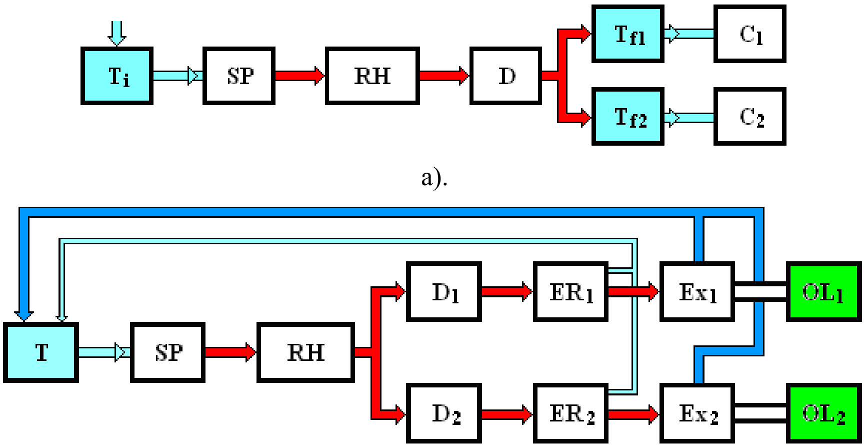
[1]*Assoc. prof., Ph D. student, University of Petrosani*

The general progress reached in different fields of technics have highlighted the remarkable qualities of the hydraulic systems which may be found in wide range of applications, i.e. from agriculture and the low pressure domain to the technical domain with high pressures required to obtain artificial diamonds, over-conductive materials, respectively hydraulic jet stream cutting.

Independent on their destination, the structure of the hydraulic systems comprise sources which generate hydraulic energy, also called pumping assemblies: they are composed of pumps, motors to drive them and eventually monitoring and regulation systems for the hydraulic energy parameters, namely pressure and flow. Moreover, they comprise a hydraulic network composed of a wide range of devices (safety and regulatory elements for pressure and flow, distribution elements, etc.), pipes, tanks and conditioning elements.

Actuation systems comprise execution elements (hydraulic motors) which controllably move the working parts, while the consumers are connected at the end of the transport systems.

Figure 1 brings forward the block diagram of a fluid transport system while Figure 1,b deals with the structure of a hydraulic driving system.



b).

Fig. 1. Block diagram:
(a) hydraulic system used for transport; **(b)** actuating hydraulic system

2. BASIC INDICATORS FOR HYDRAULIC ACTUATION SYSTEMS

The use of hydraulic actuation systems is explained by their flexibility which allows the construction of any machine or installation as well as the change and shift from a structure to another according to the changes which might appear.

The experience in the field concerning the use of hydraulic actuation systems to carry out the rotation movement in different domains, proves the necessity to continuously improve the volumetric systems in order to extend the usage range. These systems ensure the possibility to create a series of transmission reports which lead to the creation of momenta or increased speeds at the outlet shaft. In what the rotary hydraulic motors are concerned here are preferences for the ones with axial pistons (70%) and then for those with radial pistons (15%), the rest representing other types of units. The rapid extension of the servo-dynamic electro-hydraulic automatic regulation systems of the cinematic and dynamic parameters of the installations which are not fitted with a mechanic reducer must therefore be mentioned.

Taking into consideration a rectilinear movement it must e mentioned that linear hydraulic motors have been reconsidered, building therefore systems comprised by a single compact pumping assembly also called an electric-hydraulic linear amplifier. Some of the qualities of this equipment are: increased static rigidity in relation to the load, independent on the length of the track; increased response speed; superior reliability; constructive simplicity; lack of mechanic transformer; continuous speed regulation; the easy connection of the measurement and command electronic devices. The improvement of the dynamic qualities of such systems is carried out with the use of command equipment as well as through the improvement of the actuation system.

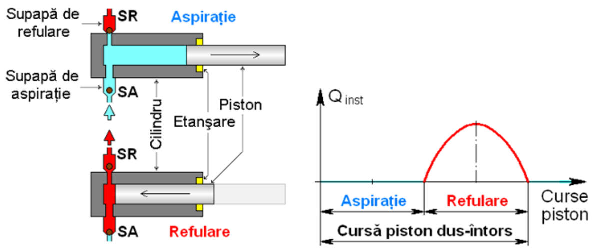
The development of the technique and the automation systems lead to the extension of the use of pressurised liquid for the operation, command and regulation of the movement of a series of mechanisms which are used for the construction of aircrafts, ships, machineries, agricultural machineries, etc.: namely from the most commonly used hydraulic crank to the huge hydraulic ship lifting installations; from the minuscule servo-valve used in spacecraft technics to the artificial intelligence robot; from the servo-commands of an automobile to those of a tip lorry or giant bucket wheel excavators; from small pressing installations to huge presses used for the synthesis of rough materials and last but not least from simple hydraulic props used to support mine works to complex installations for the actuation of modern mining machines; these are only some of the many applications offered by this large field of hydraulic automated actuations.

3. FUNDAMENTS FOR PISTON HYDRAULIC MACHINES

As it has been previously mentioned, hydraulic machines are used in almost all human activity domains.

Pumps are generator type machines which turn mechanical energy into hydraulic energy, a characteristic specific to all hydraulic systems. Hydraulic motors are a characteristic component of driving hydraulic systems where they move the operating parts of the machines; the turbines of comprise by the hydro-energetic settings are also a part of this category and they drive the electricity generators.

Generally speaking, hydraulic pumps and motors may be found in categories which are established on different criteria. Any classification of hydraulic machineries being either relative or incomplete, the main classification criteria being thus the following: the operating principle, the geometry of its operating parts, its destination, the operating liquid, the actuating mechanism, the operating pressure, etc.



$$Q_{inst} = A \cdot v = A \cdot \omega \cdot r \cdot \sin\alpha$$
$$Q_{min} = A \cdot \omega \cdot r \cdot \sin 0 = A \cdot \omega \cdot r \cdot \sin\pi = 0$$
$$Q_{max} = A \cdot \omega \cdot r \cdot \sin\frac{\pi}{2} = A \cdot \omega \cdot r$$

a. b.

Fig. 2. Simple effect piston pump (plunger):
a. operating principle; **b.** the variation of instant flow

Taking into consideration the operating principle, the hydraulic machineries may be classified in:

• Kinetic machineries (centrifuge), also called turbo-machines which, for the conversion of mechanical and hydraulic energies, partially use the pressure energy resulted from the centrifugal forces and the kinetic energy;

• Volumetric machines, for which the energy conversion is generated by the periodic change of the liquid volume which fills in the variable space created by the moving operating parts (pistons, membranes, paddles, cogs, etc.).

The main classification criterion for volumetric machines takes into consideration the shape and the direction of movement of the machine has. According to the direction of movement determined by the closing parts, volumetric machines may be classified as follows: alternative, rotational, rotational-alternative and oscillating.

Piston hydraulic machines have a wide range of usage due to their distinct mechanical and hydraulic performances: from agricultural and building machines to mining machines and hydraulic jets, this type of machines may be encountered as pumps or motors. Nevertheless, the range of piston pumps is much more diverse and ample than the one of hydraulic motors which belong to the same family.

The liquid of the piston pump is pumped through a linear movement into the cylinder of the pump, while, successively and practically in sync, the suction and discharge valves open and close allowing therefore the access of the liquid into the immobilised cylinder of the pump respective the discharge of the liquid from the cylinder.

Piston pumps are classified according to different criteria: depending on the number of active sides of the piston (simple effect, double effect, differential); depending on the build of the piston (disk or plunger); depending on theplace of the cylinder and the number of longitudinal axes (simplex, duplex, triplex, multiplex); depending on the pressure during the discharge (low, medium and respectively high pressure); depending on the actuation device (steam, internal combustion, electricity, etc.).

The pumping action of the simple effect pumps only occurs in one direction in which the piston moves (Also called a plunger), only its large surface being active as it is presented in Figure 2.a. When the plunger moves to the right the chamber of the cylinder expands creating thus in the increasing cavity a gap leading to the suction valve SV to be opened and the discharge one DV to be closed: liquid from the suction pipe will replace the free volume created by the movement of the plunger. When the plunger moves to the left it acts upon the liquid increasing its pressure and under the increased pressure the SV closes and the DV opens allowing the liquid to pass through the discharge valve respectively to the consumer. When the operation is repeated the pumping effect is thus obtained.

The pumped flow has an accentuated sinusoidal and pulsatory characteristic related to the active movement (dis-charge) of the piston: the shape of the instant flow characteristic depending on the movement is presented in Figure 2.b.

In line simple effect piston pumps are largely used, the triplex and pentaplex configuration being the most frequent one, i.e. pumps with 3 and respectively 5 cylinders with plungers placed in line, with lagged operation by 120o for triplex pumps and respectively 72o for five cylinder ones. This is then the result for having compacted in one casing three or five units as it is presented in figure 2, driven by a shaft which has a corresponding number of crankpins.

In line plunger pumps are frequently met while operating with increased pressures but also for the hydraulic supply of actuation hydraulic systems found in coal longwall installations. There are also special constructions which contain more units with plungers driven according to a certain logic: for instance, the lubrication systems which are used for the general lubrication of the swivelling mechanisms of bucket wheel excavators.

Piston and block pumps of the swivelling cylinder represents a pumping assembly the operation of which is similar to the operation of plunger pumps. These pumps however lack the suction and discharge valves, and the closing of the operational volumes is carried out through the successive passing of the cylinders into the suction area respectively the discharge area: the pistons have therefore an alternative and rotational movement. These pumps are generally classified as follows:

• Considering the orientation of the plungers compared to the axis of the rotor they may be axial – Figures 3.a and b and radial – Figure 3.c;

• Considering the actuation organ which drives the plungers (cylinder casing – Figures 3.a and c, respectively the driving disk – Figure 3.b).

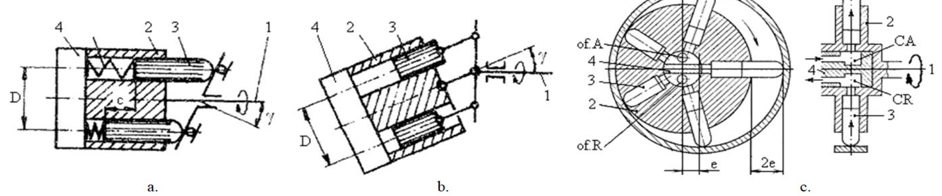


Figure 3. Plunger pumps: a, b. axial; c. radial.

The significance of the indicators presented in Figure 3 is the following: 1 – actuating shaft, 2 –cylinder block, 3 – plunger, 4 –distribution element, SI / DO - suction inlet, discharge outlet, SC / DC –suction / discharge chamber.

Axial and radial piston units are widely used in underground mining as well as surface mining as pumps and hydro-engines comprised by actuation systems for different machines and mining machineries: longwall advance feed cutter and loader units, loading machines, drills, excavators, etc. It must be also mentioned that pumps and hydro-engines are similarly built the difference being the distribution element.

4. PARAMETERS AND DETERMINATION PRINCIPLES FOR SIMPLE ACTION PISTON (PLUNGER) HYDRAULIC MACHINES

Units having one or more plungers are volumetric machines the parameters of which have a geometric nature (geometric volume / cylinder capacity - V_g), hydraulic (effective power of the pump - P_{hP} , respectively that for driving the motor P_{hM} , with the flow parameters - Q and pressure - p) and mechanical (pump's driving power - P_{aP}, effective power of the motor P_{mM} with revolution parameters - n and torque - M).

Each movement of the plunger shall develop in the cylinder an active volume which has the following value:

$$V = A \cdot c = A \cdot 2r \tag{1}$$

with one of the measurement units: [cm3/rev], [dm3/rev] or [L/rev], respectively [m3/rev], the measurement unit being adequate to the geometric dimensions of the pump. This volume defines the geometric cylinder capacity, the main parameter of this volumetric machine being:

$$V_{gPP} = A \cdot c = \frac{\pi}{4} d^2 \cdot c \cdot z, \quad \text{[volume/rot]} \tag{2}$$

where d is the diameter; A- area, c- the sliding of the plunger and z is the number of plungers, r- the length of the crank.

The paper will next bring forward only plunger pumps which are used as components by the actuating hydraulic systems. As it has been previously mentioned, their hydraulic parameters are pressure and discharged flow.

The theoretical value of the discharged pressure p_{TP} is determined by the load S_{rezM} on the operating organ driven by the motor supplied by the geodesic height for the discharge network $H_{gP\text{-}M}$ (the level difference between the discharge valve of the pump and the supply one of the motor) and the density of the operating liquid ρ:

$$p_{TP} = p\left(S_{rezM}\right) + \rho \cdot g \cdot H_{gP-M} \tag{3}$$

expressed by one of the measurement units: MPa, bar or daN/cm^2, respectively at or kgf/cm^2.

The real value of the pressure is increased by the load losses $\Sigma h_{rP\text{-}M}$ on the connection network between the pump and the motor:

$$p_P = p\left(S_{rezM}\right) + \rho \cdot g\left(H_{gP-M} + \Sigma h_{rP-M}\right) = \\ = p\left(S_{rezM}\right) + \rho \cdot g \cdot H_{gP-M} + \Delta p_{P-M} = p_{TP} + \Delta p_{P-M} \quad (4)$$

where $\Delta p_{P\text{-}M}$ is the pressure loss on this route; for short or quasi-horizontal routes, $H_{gP\text{-}M} = 0$.

It is thus observed that the discharge pressure of the pump is determined by the load and the hydraulic resistance of the network.

The flow of the pump is in fact the quantity of liquid expressed in volume units or mass units in relation to time units, quantity which the pump takes over from the supply source and transports it towards the consumer. Usually, the volumetric flow is expressed in m^3/s, m^3/h or L/min.

If the reciprocating pump operates with speed n_a, then the plunger carries out n complete slides/time unit and shall discharge an average flow

$$Q_{TPP} = V_{gPP} \cdot n_a = \frac{\pi}{4} d^2 \cdot s \cdot z \cdot n_a, \quad \text{[volume/time]} \quad (5)$$

which evidently emphasises a theoretical flow as it does not take into account the pump's losses considering the measure unit of the capacity and the revolution count, which is expressed in m^3/min or m^3/h, respectively L/min; most often n is expressed in rev/min.

In order to have a real pumped flow then the relation takes into account the volumetric efficiency η_{vP}:

$$Q_{PP} = \eta_{vP} \cdot Q_{TPP} = Q_{TPP} - k_{vP} \cdot p_P \quad (6)$$

where k_{vP} is the coefficient of volumetric losses at the pump; the volumetric efficiency depends on the value of the leaks interstices of the pump as well as on the nature of the transported liquid: thus, throughout the same interstice the losses are larger for liquids which have more reduced viscosities. The usual values of η_v which are taken into consideration for the determination of the real flow of a reciprocating pump are comprised between 0.8 and 0.98. the volumetric efficiency does not depend only on the losses through interstices but also on the percentage of filling the free volume generated by the piston during its suction movement: therefore, while using viscous liquid, if the speed of the pump is not correlated to the viscosity, the filling of the space is incompletely carried out with blank spaces into the mass of liquid which obviously deteriorates the volumetric efficiency of the pump.

As it has been previously mentioned (Figure 2.b) the flow of the plunger pumps has a pulsatory characteristic while the characteristic of the instant flow is sinusoidal $Q_i = f(\sin\varphi_i)$, a phenomenon which represents one of the main disadvantaged of these type of pumps in comparison to the centrifugal pumps the flow of which is continuous: the coefficient of pulsation / the degree of non-uniformity of the flow of piston pumps is the parameter which characterises this pulsation and it is:

$$\delta_Q = \frac{Q_{\max} - Q_{\min}}{Q_{med}} \tag{7}$$

where Q_{max} is the instant maximum flow, Q_{min} – the instant minimum flow and Q_{avg} – is the average flow of the pump which may be determined using relation (5):

$$Q_{med} = V_{gPP} \cdot n_a = A \cdot \omega \cdot r / \pi \tag{8}$$

The pulsation coefficient of the flow depends thus on the type of reciprocating pump because even if the numerator of relation (7) would remain constant the denominator is changed through the cylinder capacity V_{gPP}.

Therefore, for the simple effect simplex pump (Figure 2.a) taking into account the diagram in Figure 2.b the following may be observed:

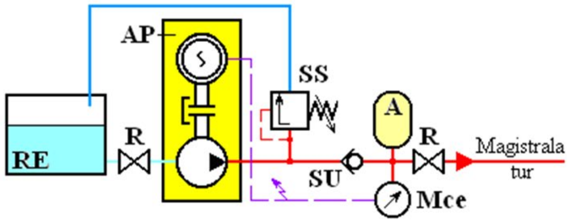
$$Q_{\max} = A \cdot \omega \cdot r \cdot \sin \pi / 2 = A \cdot \omega \cdot r$$

while $V_{gPP} = A \cdot c$ and it results the coefficient of pulsation $\delta_Q = \pi$. There is, though, an analogic procedure for the simple effect duplex pump, the only difference being that for such a type the flow is delivered by two plungers with a delayed operation *of* 180°: the flows Q_{max} and Q_{min} have the same values, but $V_{gPP} = 2A \cdot c$ resulting in the following value $\delta_Q = \pi / 2$

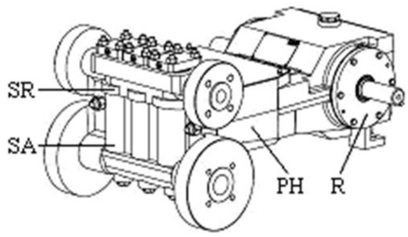
Considering all what has been mentioned before it results that the non-uniformity degree decreases as the number of cylinder increases: pumps with more plungers with delayed operational phases and equal angles carry out a rather good uniformity of the flow. The pulsation of the flow leads to a pulsation of pressure as well producing a phenomenon of fatigue of the pipes and the sealing elements and deteriorates the dynamic operation mode of the hydraulic motors, reducing their lifespan.

Such a pump is used to supply the hydraulic supports used in coal mines. In Jiu Valley in order to supply the open circuit individual hydraulic roof supports, the main hydraulic pumping assembly ACH 40/200 manufactured by S.C. UPSRUEEM S.A. of Petroşani is used: this have a three cylinder horizontal plunger pump which is able to produce a 40 L/min flow at a maximum pressure of 20 MPa, the pressure regulation domain being between 5 and 16 MPa.

The pumping installation is simple, being foreseen with only one safety valve SV and an accumulator A, without any possibility to regulate the flow, it is installed on the storage tank ST which contains an already prepared oil in water solution. It must be mentioned that the pneumatic-hydraulic accumulator A ensures the attenuation of the pulsations of the flow of the pump as well as the hydraulic shocks in the installation.



a.



b.

Fig. 4. ACH 40/200 pumping assembly: **a.** hydraulic diagram; **b.** basic structure of the three plunger pump: PH - pump, R - reducer, SV – suction valves, DV – discharge valves.

The main technical characteristics of the simple action triplex pump are: the cylinder capacity 103 cm3/rev; the diameter / the sliding of the plunger 25 mm / 70 mm; the revolution speed which drives the shaft 415 rev/min; the nominal power of the electric motor 30(22) kW.

Based on the calculation principles of the plunger pumps and the nominal characteristics mentioned before the geometrical cylinder capacity of the pump used by the ACH 40/200 pumping system, the theoretical discharge flow and the actuating power may be determined:

• The cylinder capacity is determined with the help of relation (2):

$$V_{g3P} = \frac{\pi}{4} d^2 \cdot c \cdot z \cong 2,355 d^2 \cdot c = 2,355\left(2,5cm\right)^2\left(7cm\right) = 103,03 cm^3 / rot$$

• The theoretical flow (i.e. the flow for a null load) is determined using relation (5)

$$Q_{T3P} = V_{g3P} \cdot n_a = 103,03 \frac{cm^3}{rot} 415 \frac{rot}{\min} = 42757,45 \frac{cm^3}{\min} \cong 42,76 L/\min = 0,71 \cdot 10^{-3} m^3/s$$

• Usually, the flow comprised by the characteristics corresponds to the nominal pressure: it allows thus for the determination of the *coefficient of volumetric losses* using relation (6):

$$k_{vP} = \frac{Q_{T3P} - Q_{nP}}{p_{nP}} = \frac{\left(42,76 - 40\right) L/\min}{200 bar} = 13,8 \cdot 10^{-3} \frac{\mathrm{L/min}}{\mathrm{bar}} = 0,28 \cdot 10^{-11} \frac{\mathrm{m}^3}{\mathrm{Pa \cdot s}}$$

• The volumetric efficiency for a nominal pressure is given by relation (6):

$$\eta_{vP} = 1 - \frac{k_{vP} \cdot p_P}{Q_{TP}} = 1 - 13,8 \cdot 10^{-3} \frac{L/\min}{bar} 200 bar / 42,76 L/\min = 0,935$$

• The power necessary to drive the pump is determined using the following relation:

$$P_{aP} = \frac{P_{hP}}{\eta_{vp}} = \frac{p_{nP} \cdot Q_{nP}}{600\eta_{vP}} = \frac{200bar \cdot 40L / \min}{600 \cdot 0,935} = 14,26kW$$

As it may be observed, the values determined confirm the parameters specified by the manufacturer: the power of the actuating electromotor may seem too high, but there is the need to have a backup due to the mechanical-hydraulic efficiency of the pump and the efficiency of the connecting transmission.

5. CONCLUSIONS

Hydraulic plunger machines are widely used in various fields of activity. Due to their qualities and performances they are also recommended to be used in mining both in liquid transport systems as well as in systems which actuate the operating parts of specific machines and equipment.