Density and Viscosity Effects of Hydraulic System Working Fluid

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Abstract: *Fluid actuation systems have proven their efficiency over time to ensure the solution of the most difficult tasks in most industries. Today we are witnessing the implementation of these systems on most of the machines and equipment that make up the stationary and mobile industry. This development is highlighted by the well-designed construction of the components, which have been modernized over time, thus enabling actuation solutions for the most divers working bodies. The working principles of fluidic drives are presented, which are based on the circulation of the working fluid that constitutes the support of this drive, the types of fluids as well as the effects related to the density and viscosity of these fluids for the operation of the hydraulic system.*

Keywords: *Hydraulic actuation, fluid density, viscosity, bulk modulus*

1. Introduction

Fluidic systems (figure 1) have been used by human communities since the beginning of their existence by using the force of water flow, or the movement of atmospheric masses represented by winds to solve certain domestic tasks related to water supply, irrigating land surfaces that they were used for growing plants, or grinding grains. Such evidence is present everywhere in the world where there have been important civilizations of mankind.
Actuations began to be used to solve other tasks with reference to various actions after the theoretical bases related to Blaise Pascal's principle were established in the 17th and 18th centuries according to which pressure is transmitted identically in all fluid directions, and later in the 18th century when Daniel Bernoulli established the energy conservation law, the kinetic-molecular theory of gases, as well as the law of fluids displacement in a fluid current tube in his published work entitled HYDRODYNAMICA (1738).
The century of sustained development of hydraulic systems was the 20th century in which water distribution systems in large cities were designed with forced actuation based on the force of steam, and later also actuation systems with high pressure values were implemented.
Regarding the fluids used to achieve the actuation, water was used in the force actions, being a liquid that has abundance and a low cost price, but it came with disadvantages related to reduced lubrication and the accentuated tendency of corrosion on the component elements of the systems with which it came in contact.

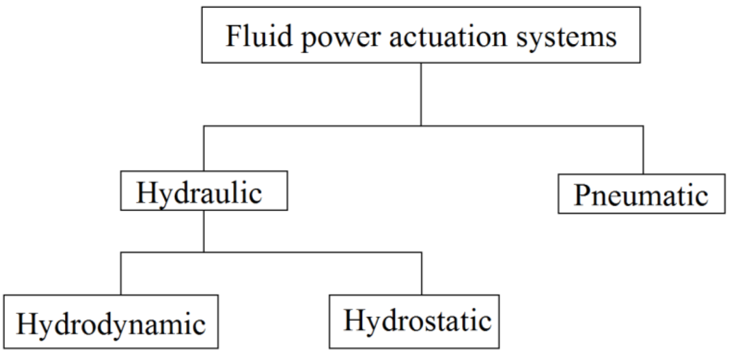
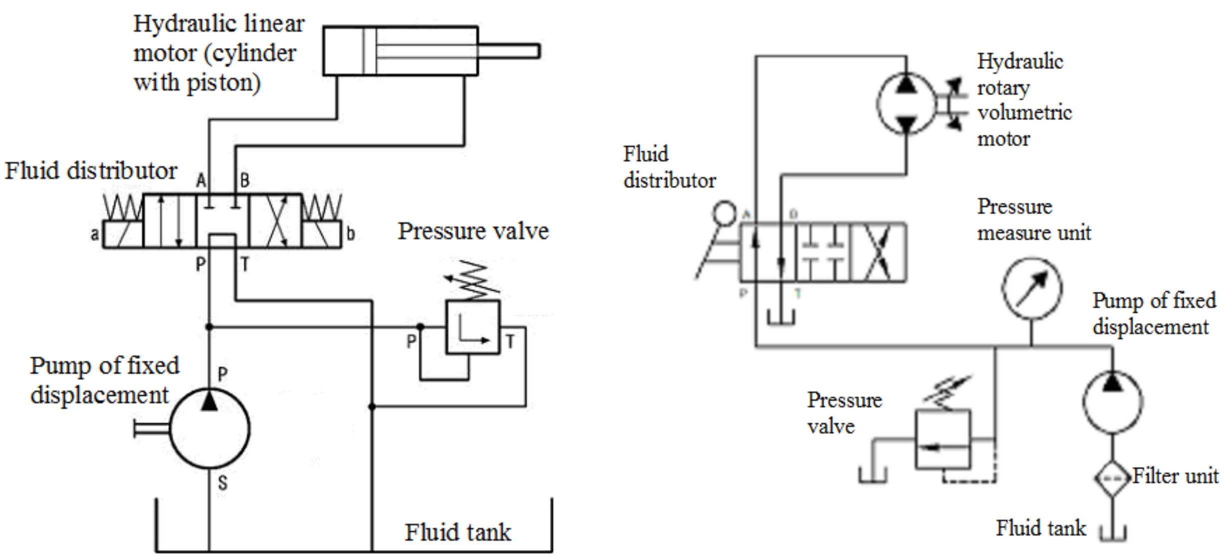


Fig. 1. Fluidic actuation classification

2. Main principles of fluidic systems

The possibility of energy transmission and conversion between different sources and receivers is highlighted, which can be achieved through the fluidic link that highlights the working fluid within a type of system. The energy source that can provide mechanical energy to a fluidic system can be of the electrical or thermal type, the energy is impregnated into the working fluid to then be used to drive a motor that can be rotary or linear.
The hydraulic system (figure 2) presupposes the existence of a hydraulic generator represented by a pump-type volume unit that has the ability to take a fluid on the suction area and send it to the network through the discharge connection. The hydraulic energy thus obtained from the continuous operation of the pump is in the form of fluid flow and pressure capable of acting directly on the moving parts of a motor that can be rotary or linear causing its rotor to come into action. The connection between the pump and the motor is ensured by the presence of circuit pipes and connecting elements of specific construction.
The advantages of using this type of system are represented by the reduced dimensions of the components that can provide high value powers, multiple possibilities of layout and assembly of the constituent elements of the circuit, as well as high efficiency values in operation.



a) linear motor hydraulic actuation b) rotary motor hydraulic actuation

Fig. 2. Principle of hydraulic actuation in open circuit

All power hydraulics applications are carried out by means of the working fluid which constitutes the support of energy transmission and conversion.

3. Hydraulic fluids

The working fluids used in industrial hydraulics for multiple drives are represented by mineral oils that are circulated through complex working circuits inside various components such as pumps, motors or various other devices that are intended for the distribution of the volume of circulated fluid, or the adjustments of the values of pressure or flow required during the operation of the plant to carry out various work tasks.
In particular, there are hydraulic drives for the equipment and machines used in construction, agriculture, but also for the car, shipbuilding, mining, or aviation industries, so it can be said that we have a clear coverage with drives hydraulics of industrial branches.
In order for the work process to take place in optimal conditions, the working fluid must have a good behaviour in terms of energy transfer, but at the same time have lubricating, cooling, or insulating qualities so as to avoid leakage to outside.

There is a classification of working areas for industrial hydraulics, and this can be done by classes for stationary hydraulics, mobile hydraulics and hydraulics used in the aeronautical industry.
For each individual class, a fluid class is adopted to suit the work and environmental requirements.
It must be said that a fluid used for marine applications must be designed in such a way as to have absorption properties (biodegradable) so that in case of contact with water it does not affect the marine environment.
Hydraulic fluids are mineral and synthetic. Fluids of mineral origin are obtained from petroleum, and synthetic fluids are obtained by sintering.
Mineral oils are enriched with additives aimed at obtaining certain properties for the resulting mixture, which relate to ensuring anti-wear properties, rust and oxidation inhibition properties, viscosity index improvement properties and others.
Table 1 shows the typologies of additive hydraulic fluids that are usually marked with the indicator H for hydraulic oil and A for additive, (acc. STAS 9691-94) together with their own characteristics.

Table 1: Hydraulic fluid with proper values

Characteristics	**H18A**	**H32A**	**H46A**	**H60A**
Density (at 25 ˚C) (g/cm^3)	0.900	0.900	0.905	0.905
Kinematic Viscosity (at 40 ˚C) (cSt)	21.2	33.4	49.0	63.7
Conventional Viscosity (˚E)	3.0	4.5	6.5	8.4
Flammability point (˚C)	150	175	180	190
Temperature range for use (˚C)	-30 +85	-30 +85	-25 +85	-20 +85

Depending on the stress range of working fluids in hydrostatic actuation systems, fluids intended for light stress (used in circuits with pressure up to 15 MPa) are presented, being represented by mineral oils marked with H (H32-H100), fluids used in medium pressure circuits (up to 30 MPa) being considered medium stresses applied to the working fluid where additive fluids are used, and for the higher pressure group pressure fluids (45 MPa) are used which are additive.
The density of hydraulic fluid can vary depending on temperature, pressure, and the specific composition of the fluid.
Due to operation conditions the temperature of the hydraulic fluid increases, while the density value decreases. This is because as temperature rises, the molecules within the fluid gain kinetic energy and move further apart, resulting in decreased density.
Hydraulic fluids are typically designed to operate within certain temperature ranges to maintain their desired viscosity and performance characteristics.
Changes in pressure can also affect the density of hydraulic fluid.
Contaminants such as air bubbles, water, or foreign particles can affect the density of hydraulic fluid. If air is present in the fluid, it can decrease the overall density. Similarly, water contamination can alter the density and also affect the fluid's performance and lubricating properties.
In industrial applications, it's crucial to monitor and control the factors that can influence hydraulic fluid density to ensure optimal performance and efficiency of hydraulic systems. This often involves maintaining proper temperature, pressure, and fluid cleanliness within specified limits.
In order to calculate the fluid density at a given pressure, the fluid compressibility is considered. The hydraulic fluids density can be affected by pressure due to compression effects.
One commonly used equation to estimate the fluid density under pressure values is the Bulk Modulus equation:

$$\frac{dV}{V} = -\frac{dp}{K} \Rightarrow K = -V\frac{dp}{dV} = \rho\frac{dp}{d\rho} \quad (1)$$

Where:

dp – pressure change;
ρ - fluid density;
K - fluid bulk modulus.

The bulk modulus (K) represents the fluid resistance to compression; it's a material experimentally determined property and can be found in material data sheets.
Given the fluid density at atmospheric pressure (ρ0) and its bulk modulus (K), we can estimate the density (ρ) at a different pressure (p) using the equation:

$$\rho = \rho_0 \cdot e^{\left(\frac{p_0 - p}{K}\right)} \quad (2)$$

Three pressure ranges are considered for analysis and a common fluid density specific value for hydraulic oil, as presented in table 2.

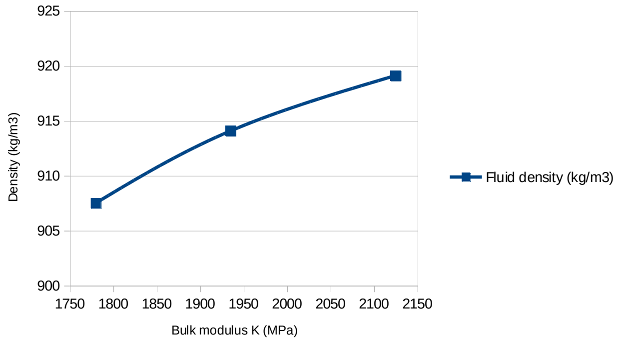
Table 2: Initial values for fluid density and pressure

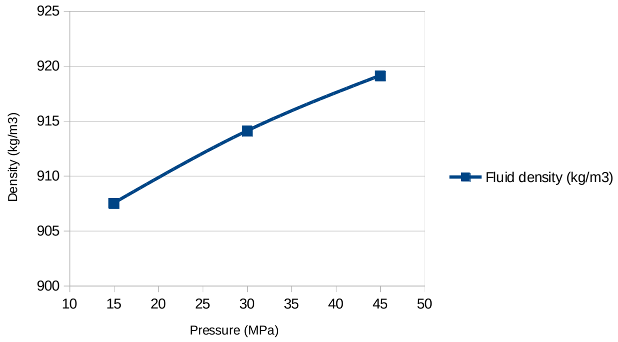
Item no.	Pressure values *(MPa)*	Initial fluid density *(kg/m3)*
1.	15	900
2.	30	
3.	45	

The calculated fluid density values applying the working pressure amounts considering the specific adiabatic bulk modulus values for hydraulic fluid at 40°C are presented in table 3.

Table 3: The calculated values for fluid density function of bulk modulus and pressure

Item no.	Pressure values *(MPa)*	Bulk modulus *(K) (MPa)*	Fluid density *(kg/m3)*
1.	15	1780	907.59
2.	30	1935	914.07
3.	45	2125	919.11





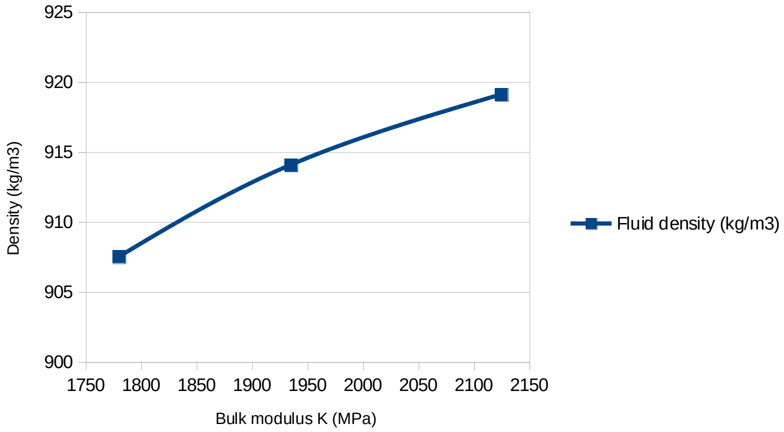


Fig. 3. The diagrams for density obtained values

The viscosity of hydraulic fluid can vary due to several factors, and understanding these variations is crucial for maintaining the efficiency and functionality of hydraulic systems.

$$\tau = \mu \frac{du}{dt} \tag{3}$$

Temperature has a significant impact on the viscosity of hydraulic fluid. As temperature increases, the viscosity typically decreases, making the fluid less resistant to flow.
As temperature decreases, viscosity tends to increase, making the fluid more resistant to flow. This viscosity-temperature relationship is essential for ensuring proper lubrication and efficient operation of hydraulic components over a range of operating temperatures.
Extreme pressure conditions, such as those encountered in high-pressure hydraulic systems or under certain operating conditions, can cause changes in viscosity due to changes in fluid density and molecular arrangement. These effects are usually accounted for in the design and selection of hydraulic fluids.
The viscosity of hydraulic fluid can also vary with shear rate, which is the rate at which adjacent fluid layers move relative to each other. Within hydraulic systems, fluid undergoes shear as it flows through narrow channels, valves, and other circuit components.
Under high shear rates, hydraulic fluids may exhibit shear thinning behavior, where viscosity decreases with increasing shear rate. This property is desirable as it helps maintain consistent fluid flow and minimizes energy losses within the system.
Different types of hydraulic fluids, such as mineral oil-based, synthetic, or water-based fluids, have distinct viscosity profiles based on the types and proportions of additives, base oils, and other components.
Manufacturers formulate hydraulic fluids to meet specific performance requirements, including viscosity at various temperatures and operating conditions.
Contaminants such as water, air, particulate matter, or degradation byproducts can affect the viscosity of hydraulic fluid. Water contamination can cause emulsification and changes in viscosity, leading to reduced lubricating properties and potential damage to system components.
Proper fluid maintenance and filtration are essential for minimizing the impact of contaminants on fluid viscosity.
When there is a need to adopt a certain hydraulic fluid for an application viscosity is an important parameter.
During operation of the hydraulic circuit higher values of viscosity ensure a reduction in operating temperatures. This is because a low viscosity hydraulic fluid will reduce the volumetric efficiency of pumps and cause fluid overheating.
Also the low viscosity hydraulic fluids lead to increased friction and circuit components wear, while some fluids with high viscosity values will cause poor mechanical efficiency, operating with a tendency to wear over time.

The best solution for hydraulic fluid adoption involves best oil viscosity in terms of volumetric and mechanical pump efficiency and in order to realize the respective project, must be considered the main requirements for the circuit main components, at specific temperature values range.

4. Conclusions

The density and viscosity of hydraulic fluid play crucial roles in the operation and efficiency of hydraulic circuits of the technological equipment.
The density of hydraulic fluid affects its ability to transmit pressure efficiently within the system.
Fluids with higher density can transmit pressure more effectively, leading to improved system response and performance.
Regarding the system dynamics a higher fluid density can result in increased inertia and damping effects within the system, affecting its dynamic response. This can impact factors such as system oscillations, response time, and stability.
Hydraulic pumps must overcome the pressure created by the fluid stream. Higher fluid density means higher pressure, which can increase the load on the pump and affect its efficiency.
The hydraulic fluid viscosity determines the resistance of the fluid to be circulated within the hydraulic circuit. Higher viscosity fluids experience greater internal friction, leading to energy losses and reduced efficiency within the system.
Viscosity influences the thickness of the lubricating film between moving parts. Optimal viscosity ensures adequate lubrication to minimize wear and prevent metal-to-metal contact.
Viscosity affects the efficiency and performance of hydraulic pumps. Higher viscosity fluids require more energy to pump, potentially reducing overall system efficiency.
Selecting hydraulic fluids with appropriate density and viscosity for the specific application is crucial. The fluid should provide adequate pressure transmission while minimizing energy losses due to viscosity.
Both density and viscosity properties of the hydraulic fluid are temperature-dependent.
Monitoring and controlling fluid temperature within recommended limits are essential to maintain optimal fluid properties and system performance.
Regular fluid analysis and maintenance practices, such as filtration and contamination control, help preserve fluid properties and ensure consistent circuit performance over time.
Hydraulic circuit design should consider the fluid properties to minimize pressure drops, optimize component sizing, and enhance overall system efficiency.
In summary, the density and viscosity of hydraulic fluid significantly impact system performance, efficiency, and component longevity.
Proper selection, maintenance, and system design considerations are essential for achieving optimum circuit operation.

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