Hydraulic Actuator Systems with Non-Newtonian Working Fluid

M. Fazil Ahamed and Sriram Chauhan

Abstract--- *The principle objective of this paper is to analyse the behaviour of hydraulic actuator systems with non-Newtonian working fluid. Non-Newtonian fluids have viscosity levels that depend upon the shear rate or shear rate history. The relation between the shear stress and the shear rate is different in the case of non-Newtonian fluid, even it is time-dependent, and where as in Newtonian fluid the relation is linear. Hydraulic actuator systems, which is used in various industrial process control and in many other applications, use hydraulic pressure to move an output member. The rate of movement of the output member can be controlled by selecting appropriate non-Newtonian working fluid with required shear rate–shear stress behaviour to improve the efficiency of system. Due to the enormous existing levels in the usage of Hydraulic actuator systems in the field of science and engineering, an improvement in the control and accuracy of these systems can have a great positive impact on the present and future applications in terms of safety and practicality, and also provides a better scope for further development.*

Keywords--- *Pascal's Law, Hydraulic Fluid, Hydraulic Actuator, Newtonian Fluid, Non-Newtonian Fluid.*

I. Introduction

EVERY machine in this world that aims at reducing manual input has a part of its process that is accomplished by actuator systems. An actuator is generally a component of machines that is responsible for converting the given energy into mechanical motion. In our case, we focus on the actuator systems that work on hydraulic fluid pressure. Hydraulic actuation systems have laid a benchmark in various engineering applications today in terms of practicality, cost, efficiency, durability and reliability. Almost every heavy engineering masterpiece today have a part of their job being accomplished by these hydraulic actuator systems. These are of mandatory use where controllable speed and large forces are required. The working fluid in hydraulic actuator system is chosen in such a way that it expresses a highly incompressible nature so that pressure applied can be transmitted almost instantaneously to the member linked to it. In case of linear actuators, which is of greater interest in this paper, the rate of movement of the output member can be controlled by selecting appropriate non-Newtonian working fluid with required shear rate –shear stress behavior to improve the efficiency of system. Numerous numbers of specialized applications are known today and that number is increasing way more than what was predicted before. An improvement in the control and accuracy of these systems can have a great positive impact on the present and future applications in terms of safety and practicality, and also provides a way for further research.

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DOI:10.9756/BIJIEMS.7575

II. Principle Used in Hydraulic Actuator System

Pascal's Law

This law states that the pressure applied to the fluid enclosed in a container is transmitted undiminished and uniformly to all the points on the inner surface of the container.

Amplification of Force

$$P = F/A$$

The given force as it is cannot be varied without any extra input, but its effect over a unit area can be. Pressure is force over a unit area. If we look at pressure just as a ratio of force and area on which it is acted upon, we can justify that however large the magnitudes of force and area on which it is acted upon be, the magnitude of pressure remains the same. This wonderful yet simple logic serves to be the key idea behind the working of heavy duty hydraulics.

Conservation of Energy

Since energy or power is always conserved, increase in force results in reduction in the velocity of fluid. In fact, if the resultant force is applied over a larger area then a unit displacement of the area would cause a larger volumetric displacement than that of a unit displacement of the small area through which the generating force is applied. Thus, what is gained in force must be lost in distance or speed and power will be conserved.

III. Components of Hydraulic Actuator System

Hydraulic Fluid

The basic requirement of a hydraulic fluid is to transmit power instantaneously from one part to another. Hence, it is required to be non-compressible. At the same time, it should also lubricate the moving parts to reduce frictional losses and cool down the components so that the system does not gets overheated. It also helps in removing the contaminants to filter. Petroleum oil due to its very slight compressibility, is the most popular choice to be used in hydraulic actuator systems. The lubricating ability of this oil is another useful property. Also, the fluid acts as a seal to prevent any leakage inside the component. The leakage rate is determined by the level of closeness of the oil's viscosity and the mechanical fit.

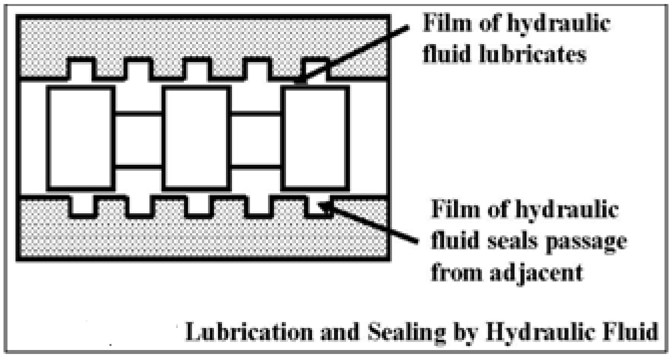

Fig. 1

Source:http://nptel.ac.in/courses/108105063/pdf/L-26(SM)%20(IA&C)%20((EE)NPTEL).pdf [15]

IV. The Fluid Delivery Subsystem

It comprises of those parts of the system that are responsible for holding and carrying of the fluid from the pump to the actuator. It is made up of the following components.

Reservoir

A part of the fluid delivery subsystem that serves as the storage for the fluid that is to be circulated and also supports the escaping of entrapped air in the fluid. The major problem with bubbles of entrapped air is that its presence considerably deteriorates the bulk modulus of the fluid, which is responsible for the determination of the stiffness of hydraulic system. It also plays a major role in heat dissipation.

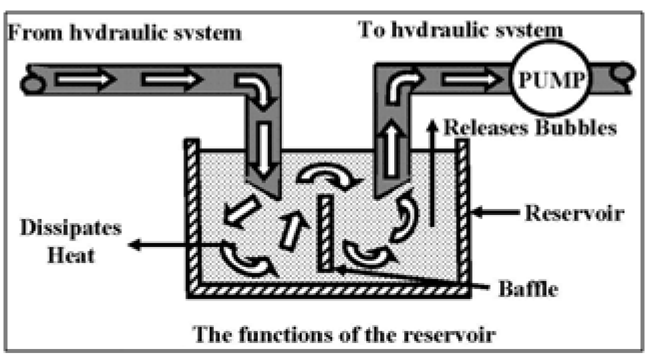

Fig. 2

Source: http://nptel.ac.in/courses/108105063/pdf/L-26(SM)%20(IA&C)%20((EE)NPTEL).pdf [15]

Filter

The hydraulic fluid is kept clean in the system with the help of filters and strainers. It plays a major role in removing minute particles from the fluid that can be responsible for the blocking of orifices of the servo-valves or even cause the spools to jam.

V. Advantages of Using Hydraulic Actuators

High Force Capabilities

The main reason for the popularity of the hydraulic actuator system is its ability to induce very high forces. Higher pressures help relatively smaller cylinders to reach very large forces. For example, a 3-inch and 5-inch bore cylinders at 2200 psi can achieve approximately 66,723 kN and 191,273 kN, respectively.

Simple Design

Simple and straight forward design of hydraulic actuator systems is one of the major reason behind its exceptional popularity among various applications.

Rugged Construction

Hydraulic actuators have a reputation for being tough enough to withstand harsh situations. When used in proper applications, they prove to be relatively more durable and also reliable. Their rugged design also helps in handling shock loads.

Affordability

The initial purchase cost of hydraulic cylinders is relatively less as compared with the electric linear actuator or a pneumatic one.

VI. Limitations of Existing Hydraulic Actuators

Hydraulic actuator systems have a good potential in producing positive results under heavy engineering applications. For example, a 3-inch and 5-inch bore cylinders when used at 2200 psi can give off approximately 66723 kN and 191273 kN, respectively. When it comes to more accurate, precise operations they just don't fit the bill. Typically, hydraulic actuator systems have an accuracy of up to one thousands of an inch. To get the kind of control that other systems are capable of, it can be very expensive. A basic hydraulic system just won't fit for the kind of precision required for many operations.

VII. Classification of Fluids

Most of the fluids that we encounter with in day to day life especially of those which are less in molecular weight exhibit Newtonian behavior or shows characteristics that resemble more of Newtonian behavior than any other. For most of the liquids, the viscosity decreases with temperature and increases with the pressure. For gases, it increases with both temperature and pressure. In general words, the resistance offered by a fluid to flow is directly proportional to its viscosity. Table 1.1 provides us with a brief information of the fluids that we see in day to day life along with their viscosity. Considering the increase in magnitudes of the viscosity levels as we go down the table, one can argue that a solid may also be treated as a fluid with its viscosity tending towards infinity, $\eta \rightarrow \infty$. Thus, the line of distinction between a solid and a fluid is not as sharp as we would imagine.

Table 1: Values of Viscosity for Common Fluids at Room Temperature

Substance	**η (Pa.s)**
Air	10^{-5}
Water	10^{-3}
Ethyl alcohol	1.2×10^{-3}
Mercury	1.5×10^{-3}
Ethylene glycol	20×10^{-3}
Olive oil	0.1
100% Glycerol	1.5
Honey	10
Corn syrup	100
Bitumen	10^{8}
Molten glass	10^{12}

Source: http://www.physics.iitm.ac.in/~compflu/Lect-notes/chhabra.pdf [14]

Substances that we encounter in our day to day life are only a part of what is actually present. Many complex substances that exhibit multi-phase nature, especially the substances of major industrial significance are found to be not conforming with the Newtonian postulate of linear relationship between (σ) and ($\dot{\gamma}$)in case of simple shear. Hence these fluids are called as non-Newtonian fluids.

VIII. Newtonian Fluid

It is sensible to begin with the definition of a Newtonian fluid. In simple shear (Fig. 3.), the behaviour of a Newtonian fluid is characterized by a linear relationship between the applied shear stress and the rate of shear,

$$\text{i.e., } \sigma yx = \frac{F}{A} = \eta\dot{\gamma} yx (1)$$

Fig. 4 shows experimental results for a corn syrup and for a cooking oil confirming their Newtonian fluid behaviour. The flow curves pass through the origin and the viscosity values are η = 11.6 Pa.s for corn syrup and η = 64 mPa.s for the cooking oil.

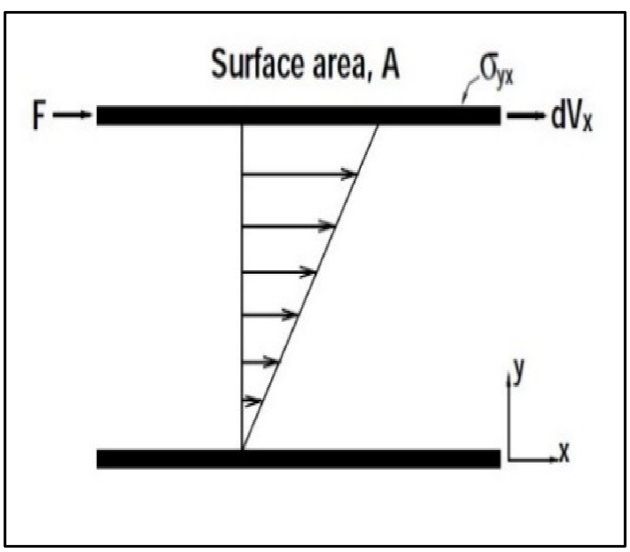

Fig. 3: Simple Shear

(Source: http://www.physics.iitm.ac.in/~compflu/Lect-notes/chhabra.pdf [14])

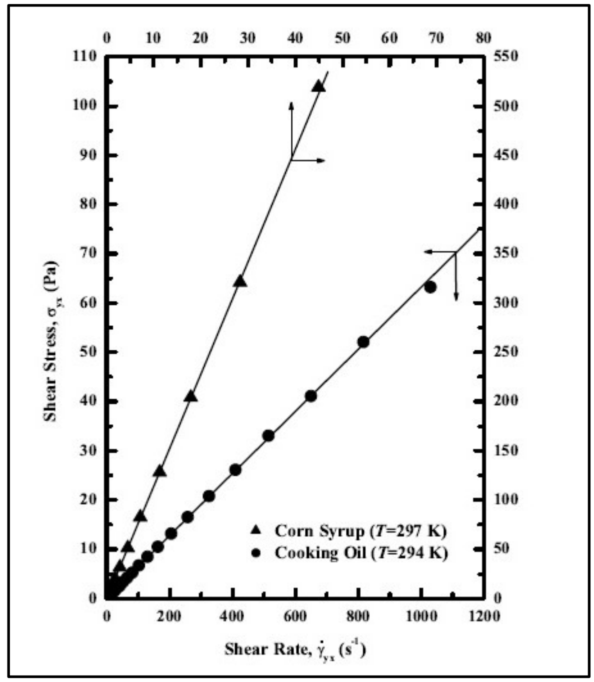

Fig. 4: Newtonian behaviour of corn syrup and cooking oil

(Source: http://www.physics.iitm.ac.in/~compflu/Lect-note s/chhabra.pdf [14])

Non-Newtonian Fluid behaviour

Any fluid whose characteristic curve of simple shear data does not pass through origin and also does not show a linear relationship between shear stress and its corresponding strain is said to have deviation from Newtonian behaviour. Conversely, it can also be said that the apparent viscosity, defined as σ /$\dot{\gamma}$, is a function of σ ορ $\dot{\gamma}$, rather than being constant. In fact, under appropriate circumstances, the apparent viscosity of certain materials is not only a function of flow conditions (geometry, rate of shear, etc.), but also depends on the kinematic history of the fluid element under consideration. It is convenient, though arbitrary, to group such materials into the following three categories:

- Time-independent fluids
- Time-dependent fluids
- Elastic-viscos or visco-elastic fluids.

Time-Independent Fluid behaviour

In this type of fluid behaviour, the magnitude of the rate of shear at any point in the fluid is dependent only upon its corresponding current value of the shear stress. In other words, their behaviour can be explained by the fact that such fluids does not have any memory of their history. Hence, from the above condition, three possibilities exist:

- Shear- thinning or pseudo plastic behaviour.
- Visco-plastic behaviour with or without shear-thinning behaviour.
- Shear- thickening or dilatant behaviour.

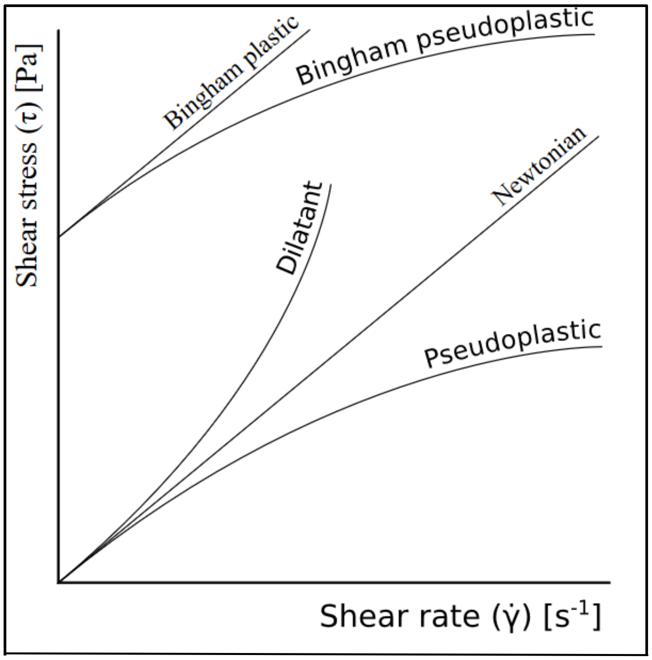

Fig. 5: Flow Curves

(Source:https://upload.wikimedia.org/wikipedia/cmmons/8/89/Rheology_of_time_independent_fluids.svg [8])

Application of Non-Newtonian Fluid in Hydraulic Actuator Systems

The behaviour of non-Newtonian fluids are relatively different as compared to the conventional fluids to which we are more used with. The difference in their behaviour can be understood from the information that Fig.5 gives. The non-linear relation of these fluids (non-Newtonian) can be used as an advantage in various engineering applications. In case of hydraulic actuator systems, non-Newtonian fluids with required capabilities and properties can be used as working fluids considering the following advantages:

Accuracy in Actuation

As mentioned earlier, the non-linearity in Shear Rate – Shear Stress relation of non-Newtonian fluids play the major role in this case also. Hydraulic actuation systems in various engineering applications that are used to support and control the movement of heavy loads and those that are at a frequent risk of losing accuracy on sudden loading and unloading can be benefitted from the nature and the behaviour of non-Newtonian fluids as seen in Fig.5. In case of sudden loading, the working fluid in the hydraulic actuator experiences sudden increase in the pressure which may cause the system to loose accuracy in actuation. Hence, usage of working fluid that has the tendency to oppose agitation can assist in holding and in slowing down the motion, ultimately increasing the accuracy of actuator. For example, usage of non-Newtonian fluid with dilatant behaviour (Fig.6) can exhibit greater levels of viscosity as the shear rate increases, i.e. it can oppose agitations and backward movement of piston under sudden loading.

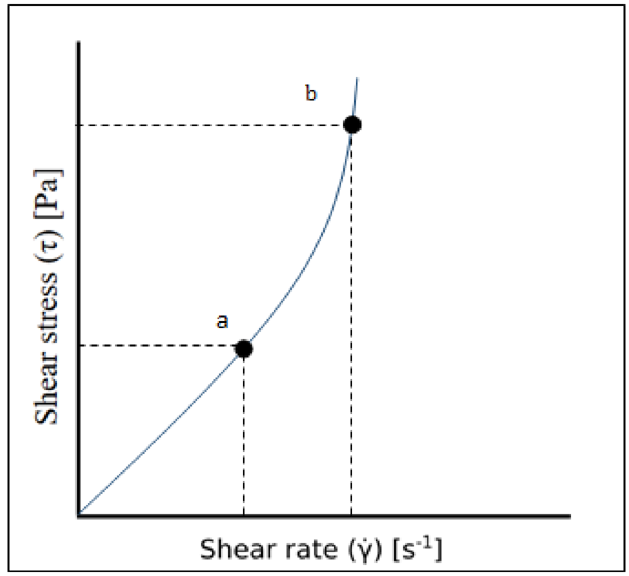

Fig. 6: Dilatant behaviour of Shear Thickening Fluids

Fig.6 shows the dilatant behaviour exhibited by shear thickening fluids. It is evident from this plot than the corresponding increase in the shear stress as we move from point ‘a’ to point ‘b’ in the curve is greater than that of the shear rate. Hence, agitation in actuation process due to sudden loading that may result in loss of accuracy can be reduced to a great extent.

Safety

As mentioned in the previous point in case of sudden loading, the working fluid in the hydraulic actuator experiences sudden increase in the pressure. This may not only cause the system to be less accurate in actuation but can even cause accidents. It is evident from Fig.5 that the viscosity of non-Newtonian fluids increase to a greater level when the shear rate increases. This behaviour can be used as an advantage in assisting the load hold check valves in many heavy engineering applications in preventing the backflow of working fluid to that of the intended flow direction.

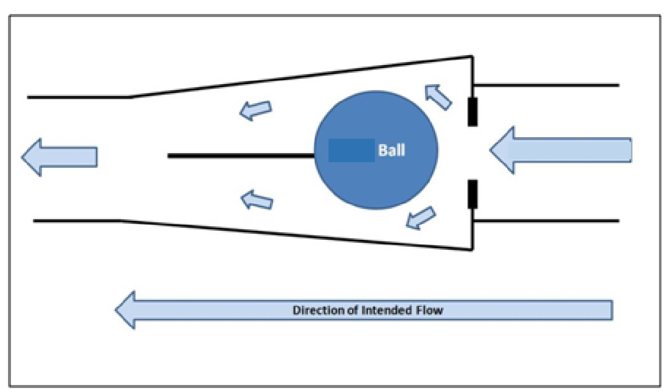

Fig. 7: Shows the Working of Ball Check Valve when the Direction of Flow is same as that of Intended Flow

(Source: http://data.reefaquarium.com/wp-content/reefer/2013/08/ballcheckvalve1.jpg [6])

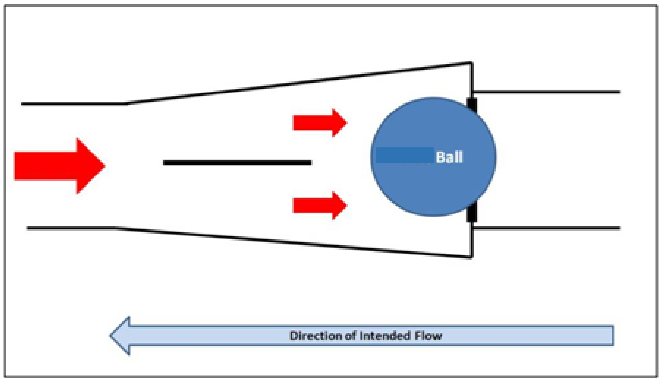

Fig. 8: shows the Working When the Direction of Flow is Opposite to that of the Intended Flow

(Source:http://data.reefaquarium.com/wp-content/reefer/ 2013/ 08/ballcheckvalve2.jpg [7])

IX. Conclusion

As a conclusion, the objective of this paper was to compare and analyse the properties of non-Newtonian fluids, especially in the field of rheology in order to bring out the advantages of using them as working fluid in hydraulic actuator systems for enhanced control, efficiency and safety. The objective was fulfilled as the comparison of the properties and behaviour of non-Newtonian fluids as working fluid in hydraulic actuator systems was successful. Further, Due to the enormous existing levels in the usage of Hydraulic actuator systems in the field of science and engineering, an improvement in the control and accuracy of these systems can have a great positive impact on the present and future applications in terms of safety and practicality, and also provides a better scope for further development.

Acknowledgment

I have to be very much thankful to the almighty who has showered me with the hope and confidence to step ahead in this part of research which has not yet been covered because of its difficulties. I am very grateful to my project guide Sriram Chauhan Sir for helping me all the way to complete my research paper. His suggestions have lightened up my way even in the tough time. With my whole heart, I will thank my parents for their unconditional support towards me in every step that I took ahead. I am very fortunate to have friends who are capable in all the various fields and cherish me with them despite of my eccentricities. It was because of these people who assisted me by their comments, remarks, compliments, and unavoidable questions to make my research paper better every time.

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