MECHANICAL CHARACTERISTICS OF STARCH BASED ELECTRORHEOLOGICAL FLUIDS

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ABSTRACT

Electrorheological fluid's (ERF) are formed by suspension of dielectric particles with base non-conducting fluid. If an external electric field applied, the polarised particles of the ER fluids are charged and arranged like chains between electrodes. In this way, flow resistance and applied stress on electrodes can be increased. This effect is proportional with electric field, reversible and fast acting which can be used in hydraulic valves. This study presents experimental result of ERF which was prepared by transformer oil contaminated in 40% mass ratio of corn starch particles. Its flow curves under the application of different electric fields were obtained by rotational viscometer. Then, a rectangular multi-plate hydraulic valve was designed on the basis of these results and its pressure drop characteristics were given.

1. INTRODUCTION

An ER fluid is a mixture of finely divided particles suspended in a non-conducting base. The application of the sufficient electric field causes polarisation of the particles which forming chains between the electrodes. In this way, the mechanical properties of the ER fluids in shear, tension, and compression are subject to dramatic variations with applied electric field, [1].

This special characteristic of the ER fluids allow some potential applications. Squeeze-flow, shear and flow modes are three major application methods of the ER effect in practical devices, [2]. In squeeze-flow mode, the ER fluid is sandwiched between two electrodes, one fixed and one moving in a direction normal to its own plate. In this mode, the variation of the transmitted pressure with the applied electric field on the upper plate are investigated. In shear mode, the electrodes of the ER fluid devices are free to rotate or translate in relation to each other. Control of the shear properties of the fluids lead to application torque transmissions such as clutch, brakes, shock absorbers, vibration dampers etc. In flow mode, the electrodes of the ER devices are assumed fixed. The ER devices can be constructed in which the flow rate-pressure characteristic is controlled by varying the applied electric field. This leads to the concept of ER actuators in which ER valves to control the fluid flow in a hydraulic circuit. Electrohydraulic servovalves have been used conventionally in hydraulic control systems. However, this type valves are complex and expensive. ER valves are designed to control the hydraulic system by using the ER effect. They are desirable to introduce an alternative means of reversible and fast control since they have no moving parts.

The aim of this work is to find out the rheological characteristics of the ER fluids and to manufacture a valve by using this phenomenon. Shear mode and flow mode operation of transformer oil based ER fluid which was produced by mixing with corn starch was investigated. Rotational viscometer was designed and constructed to get the Bingham property of the ER fluid as a function of electric field. The relationship between shear stress, shear rate and electric-field magnitude on such a devices was obtained in order to determine geometrical dimensions of an ER valve. After setting the dimensions, it was manufactured. Single ER valve was connected directly to a pump to evaluate the pressure drop against flow characteristics of it under the application of electric field.

2. IDEALISED BEHAVIOUR OF ER FLUIDS

Understanding of the ER fluid's behaviour is the key to design ER devices. The relationship between shear stress and shear rate is the most important parameter in understanding this behaviour and it depends on some criteria. Increasing weight ratio of the polarised particles, field strength and temperature increase ER effect, but increasing shear rate decrease this effect, [4].

ER fluids have been modelled as Bingham plastics which means that flow is observed only after exceeding a minimum yield stress. Idealised behaviour of the ER fluid is shown in Figure 1.

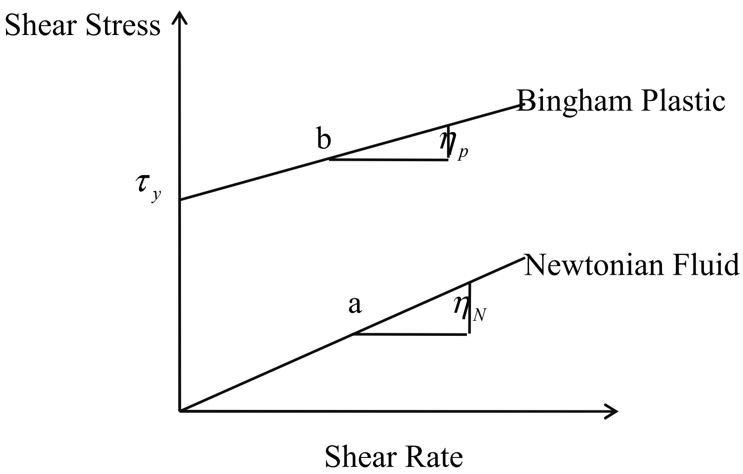

Figure 1. Ideal Behaviour of ER Fluid.

Slopes of these lines are the dynamic viscosities of fluids. With no electric field applied an ER fluid behaves like a Newtonian fluid and the applied stress will cause the liquid to flow. Eq.1 is a first order model approximating the behaviour of a Newtonian fluid.

$$\tau = \mu_N \partial u / \partial y \tag{1}$$

Where μ_N is the Newtonian viscosity, in Pa.s,
$\partial u / \partial y$ is the shear rate, in s^{-1},
τ is the shear stress in Pa.

Flow only occurs for a stress greater than the yield stress in Bingham plastics. Below the yield stress, applied stress will strain the plastic but not cause it to flow. The equation for a Bingham body is:

$$\tau = \tau_y + \mu_p \partial u / \partial y \tag{2}$$

Where τ is the shear stress, in Pa,
τ_y is the yield stress, in Pa,
μ_p is the plastic viscosity, in Pa.s.

The yield stress increases proportional to the applied electric field while the plastic viscosity unchanged, [4].

3. EXPERIMENTAL SET-UP

Viscous behaviour of the ER fluids can clearly be seen by plotting the change in shear stress with respect to shear rate. And this curve are clearly describe the rheological behaviour of the ER fluids in detail. Flow curves are obtained by using rotational viscometer which comprises of two concentric cylinders with 0.8 mm radial separation of two faces as shown in Figure 2. ER fluid is filled between these cylinders.

With no electric field present, rotating the inner cylinder creates the shear stress but littler or no motion and torque on the outer cylinder. When the electric field is applied, the ER fluid stiffen with field strength and stress is transferred to the outer cylinder as a torque. When the electric field great enough, the ER fluid turns out to be like a solid and the cylinders behave as tough, they were pressed together with no fluid between them.

The electric field between two concentric cylinders is obtained from a high voltage power supply capable of providing voltages from 0-1000 Volts. Outer cylinder of the viscometer is connected to a cantilever beam on which two strain gauge were stuck. Transmitted stress is determined by using a strain indicator. The flow curves of the ER fluid were drawn by using a plotter. X direction on the plotter corresponds to the DC motor speed which is proportional to the shear rate and Y direction corresponds to the voltage of the strain indicator which is proportional to the transmitted stress. The speed of the inner cylinder is transformed to the shear rate and the voltage of the strain indicator is transformed to the shear stress. Thus, the output graph of the plotter is arranged with these new values

1) 0-12 Volt DC Motor.
2) Rotating Inner Cylinder.
3) Outer Cylinder.
4) Strain Gauge.
5) ER Fluid.
6) 0-30 Volt Power Supply.
7) Plotter.
8) Strain Indicator.
9) 0-1000 Volt High Voltage Power Supply.

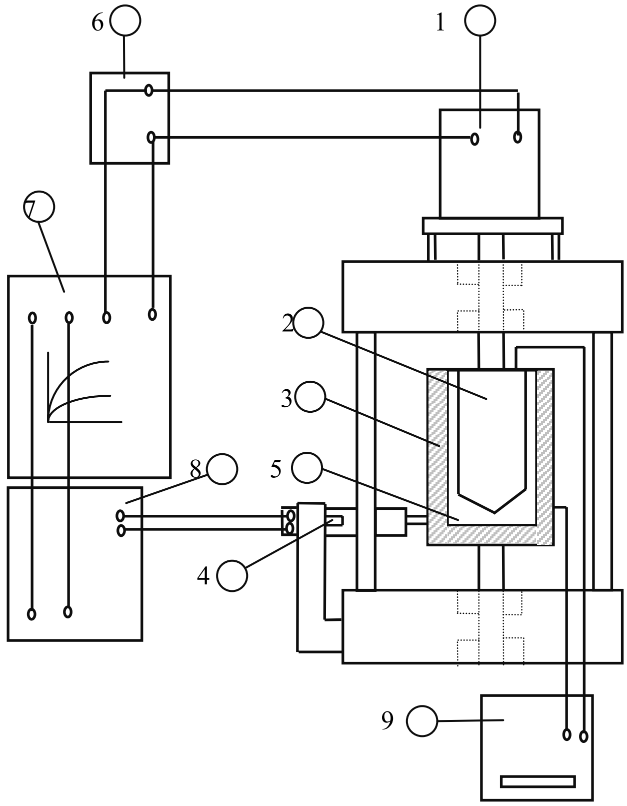

Figure 2. Rotational Viscometer.

Rotational viscometer result of the transformer-oil based ERF are given in Figure 3. This graph presents both Newtonian and Bingham property of the ERF and the effect of the intensity of applied electric field on ER behaviour.

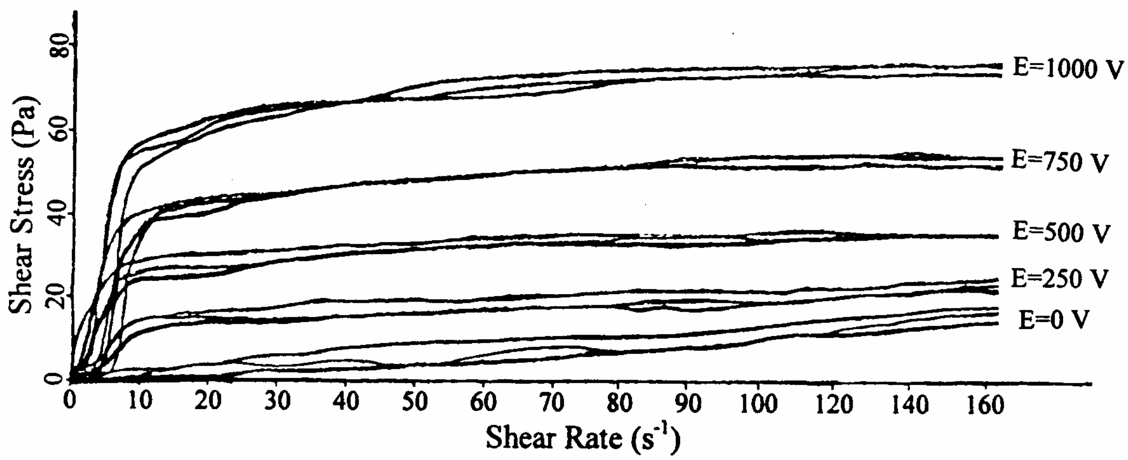

Figure 3. Viscous Behaviour of Transformer Oil-Based ERF Containing 40% Corn Starch by Weight.

The curve which is obtained under 0 V/mm electric field have Newtonian fluid characteristics. Under the application of high voltage, this fluid behaves like Bingham body. When the viscous behaviour of transformer oil-corn starch ER fluid is examined, it is seen that the slopes of the curves under electric field are not parallel to the slope of the curve without electrical field. It can be stated that shear stress difference between with and without electric field is reduced by increasing the shear rate and yield stress is linearly proportional to the applied electric field, [5].

4. DESIGN OF AN ER VALVE

When we consider an ER valve which has a single flow path, in the absence of the electric field the pressure drop produced only by the Newtonian viscosity of the ER fluid and it is proportional to the flow rate of the ER fluid pumped through the gap. Assuming that the flow between two plates is laminar, then the pressure drop becomes, [3,6];

$$P_N = 12\mu_N l Q_G / (wh^3) \tag{3}$$

where Q_G is the flow passing through a single gap valve without electric field, in m^3/s,
μ_N is the Newtonian viscosity, in Pa.s,
l is the length of valve electrode, in m,
w is width of the valve electrode, in m,
h is the gap between two plates, in m.

Upon applying electric field, a pressure drop due to the yield stress of the ER fluid is additionally generated. Resistance force on a single plate caused by yield stress can be written as;

$$F_y = 2\tau_Y lw \tag{4}$$

Where τ_y is the yield stress, in Pa.s.

This resistance yields a pressure drop across the gap then, force on the fluid body contained between the plates becomes;

$$F_f = \Delta P_{ER} hw \tag{5}$$

Equating these forces each other; the pressure drop due to the yield stress becomes;

$$\Delta P_{ER} = 2\tau_y l / h \tag{6}$$

Total pressure drop of the ER valve with single path in the presence of the electric field is obtained by adding the pressure drop due to the Plastic viscosity to the pressure drop due to the yield stress. This is given by,

$$\Delta P = 12\mu_P lQ/(wh^3) + 2\tau_y l/h \tag{7}$$

When we consider the ER valve which has a multi-flow path, the contribution of shear resistance and the pressure drop due to the yield stress increase with number of flow path. The total pressure drop of the ER valve with multi-channels under the application of applied electric field can be obtained as:

$$\Delta P = 2m\tau_y l/h + 12m\mu_P Q_G l/(wh^3) \tag{8}$$

Eq. 8 reveals that the total pressure drop over an ER valve increases directly as the number of the energised paths increases. In the absence of electric field, number of energised paths are zero so that the total pressure drop of the ER valve is produced by only the Newtonian viscosity of the ER fluid. Eq. 8 also implies that the performance of the ER valve is dependent on the number of energised paths, rheological behaviour of the ER fluid and design parameters such as the electrode width, w, length, l , and height, h. Rheological behaviour of ER fluids are controlled with the electric field intensity applied and the concentration of polarised particles. Consequently, they directly affect the ER valve performance.

Figure 4 shows a rectangular multi-plate ER valve, which was designed on the basis of desired pressure drop analysis. The material of the electrode is carbon steel and is isolated from each other by rubber plates. The fluid gasket is applied between the valve and rubber plates to prevent the leakage of the ER fluid. The number of electrodes is 6 and they form five flow paths. The gap spacing is 0.7 mm. The length and width of each electrode is 100 and 25 mm, respectively.

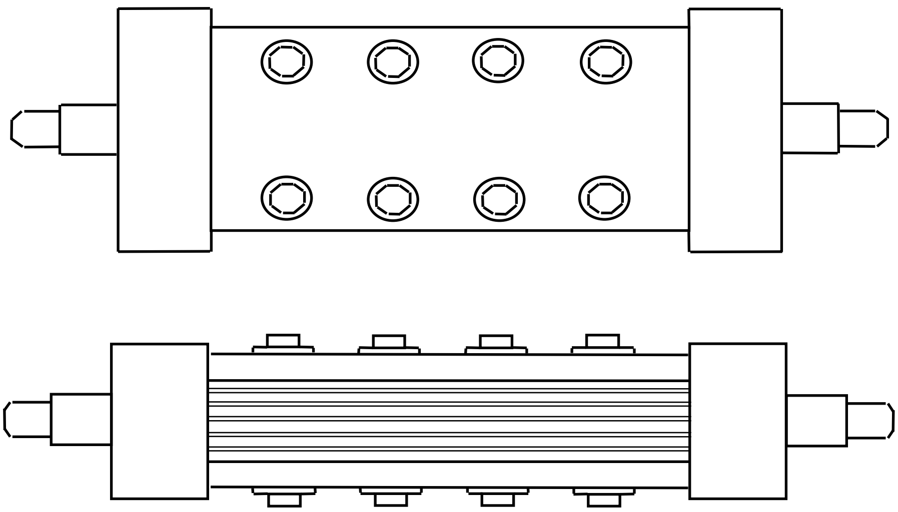

Figure 4. Multi-Plate ER valve.

5. PRESSURE ANALYSIS OF ER VALVE

While designing an ER valve-actuating system, it is necessary to known the pressure drop characteristics of an ER valve. Multi-plate ER valve is connected directly to a pump which has the proportional flow rate with pump speed. The nominal displacement of the pump is $50\times10^{-6} m^3 / rev$ and it is driven between 0-100 rpm. Pressure transducers which have the range of 0-1000 Psi were calibrated by using Dead Weight Tester and mounted at the inlet and outlet of the ER valve. Transducer signals are conditioned by a 5 kHz frequency amplifier. 0-1000 Volt high power voltage supply was used to create electric field between valve plates. The ER fluid used in single valve circuit comprised of Transformer oil containing 40% corn starch.

Experimental results are given in Figure 5 which present the field-dependent pressure drop with respect to the pump flow rate. The agreement between measured and theoretical values is important for valve design, thus the validation of the proposed pressure analysis is proved.

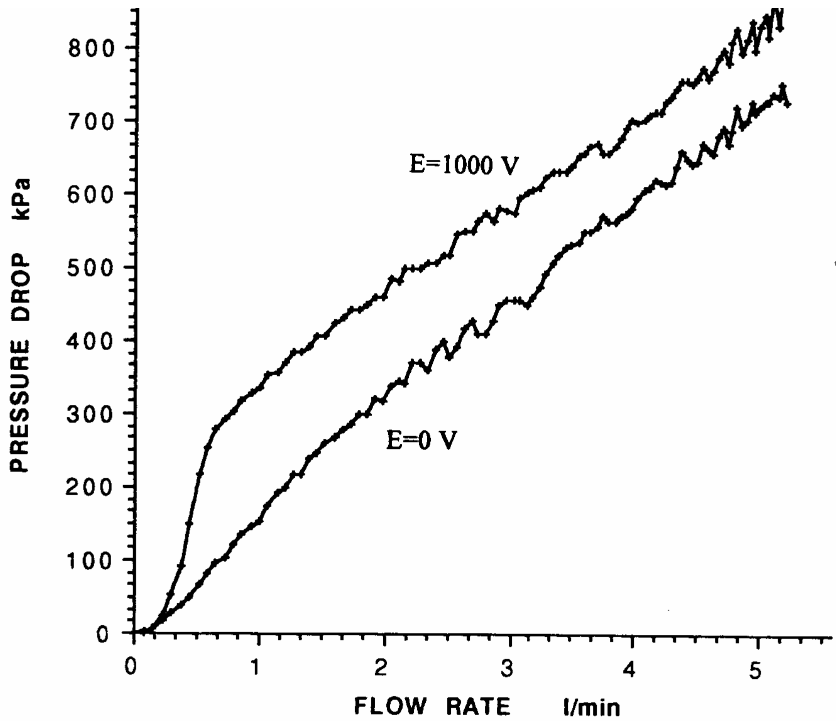

Figure 5. Valve Pressure Drop Against Pump Flow Rate.

As it can be seen from this figure, pressure drop due to yield stress shows similar trend as the shear stress curve obtained from the rotational viscometer. The electro-rheological pressure drop decreases with the pump flow rate. The pressure drop due to yield stress is approximately 85 kPa at a flow of 5 l/min under the application of the 1 kV high voltage and the total pressure drop is approximately 850 kPa, shown in Figure 5 and the theoretical pressure drop due to yield stress is 75 kPa at the same conditions.

6. CONCLUSION

This study presents the shear and flow mode operations of the ER fluid. Design parameters of the ER valve was determined. A multi-channel plate for the ER valve was designed and manufactured on the basis of the field depended Bingham model. The pressure drop of the ER valve was evaluated experimentally and theoretically with respect to the intensity of the electric field.

The performance of the ER valve dependent on the number of energised paths, rheological behaviour of the ER fluid and design parameters such as the electrode width, w, length, l , and gap height, h. No-field viscosity effects can be reduced by increasing the gap between the electrodes, but on the other hand to increase voltage must be very high. Experimental results show that the pressure drop due to yield stress decreases with the increase of the pump flow rate which is directly affected by the shear rate in the ER valve. The reason for this behaviour is the yield stress decrease by increasing of the shear rate.

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