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Towards a Valveless Electro-Rheological Valve

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Abstract

Electro-Rheological (ER) fluids can change phase from liquid to a solid-like gel in response to being exposed to electric field. This property makes ER fluids useful in motion control applications. The motivation of this paper is to present a technique such that ER fluids may be used in designs of valves where "valving" can be achieved without any moving mechanical components. Such designs should be attractive as control agents.

Introduction

Electro-Rheological (ER) fluids have the desirable feature of being able to change phase between a liquid and a solid-like gel. These are normally suspension fluids, mostly made up of some variety of semi-conducting particles and a suspending oil. There are literally hundreds of different recipes to make ER fluids [3], and the one used in this work is a corn starch – mineral oil suspension.

Normally, an ER fluid has its particles suspended in quite random fashion as shown in Figure 1(a). When an electric field is applied across the fluid, however, the semi-conducting particles are polarised electrically, and form chains. These chains are shown in Figure 1(b). The flat regions shown at the top and the bottom in Figure 1, are the conductor plates though which the electric potential is applied. The required electric field strength is in the order of kilo Volts per mm. The phase change takes place in milliseconds. More importantly, the liquid phase is recovered upon removal of the electric field.

When the conductors required to apply the electric field, are kept at a fixed distance from each other, there are two different modes of operation, namely the shear mode and the flow mode. In the shear mode, the two electrodes are given a relative motion to cause shearing of the fluid placed between them. In the flow mode, the electrodes are kept stationary to form a channel, and the fluid is pushed through them. In the shear mode, the application of electric field increases the shear resistance, or shear strength, of the fluid. In the valve mode, the application of electric field increases the pressure drop along the length of the conductors.

A typical set of results are shown in Figure 2, where the shear resistance of a corn starch-mineral oil ER fluid is given for different strain rates [5]. The solid to liquid weight ratio of the ER fluid suspension is 0.70 for this case. Details of the shear stress measurements are given in Reference 5.

Five sets of shear stresses are plotted in Figure 2 corresponding to five different electric fields, including zero. For zero electric field, the behaviour may be represented with that of an ideal Newtonian fluid where the shear stress, τ, is linearly proportional to the rate of strain, γ, and the proportionality constant represents the dynamic viscosity, μ:

$$\tau = \mu \dot{\gamma} \tag{1}$$

Note that the curve fit for the linear behaviour is also given next to the trend line. The value of R^2 indicates the reliability of the linear trend, in mean square sense, to the experimental points where an R^2 of unity would correspond to a perfect fit.

When an electric field is applied, the shear stress variation seems to shift up, approximately parallel to the zero-field trend. What is of significance here is the presence of an intercept on the vertical axis, representing shear resistance for a zero rate of strain. This intercept may be interpreted as an "equivalent stiffness" as a result of the level of solidification. Stiffness, or resistance to deformation, is, of course, the property of a solid.

Although the R^2 reliability of the existence of the linear trend of the new cases, is somewhat lower than that of the zero-field case, the shear stress may still be expressed as

$$\tau \approx \tau_b + \mu \dot{\gamma} \tag{2}$$

Here, τ_b represents the intercept to indicate the effect of applied electric field [2, 4-6]. τ_b may be expressed as

$$\tau_b = \alpha E^{\beta} \tag{3}$$

where α and β are the material properties of the fluid, and E is the electric field strength [2, 4-6]. Equation 2 also represents the condition for Bingham Plastic Flow [2, 4-7]. It should be mentioned here that there is also a class of ER fluids (such as those of liquid crystal type) which behave quite differently than what is suggested in Equation 2. These fluids do not acquire an intercept in response to an electric field. They maintain a shear stress variation similar to that of a Newtonian fluid, but they experience an increase in their viscosity.

In the next section, the treatment of the Bingham model is extended into the valve mode of operation. The objective of this extension is to demonstrate the possibility of controlling the pressure loss, with the electric field as the control parameter. The further objective is to compare this control process against the performance of a generic pump.

Behaviour In Valve Mode

In Figure 3, the thick lines at the top and bottom indicate the conductors which form the channel in which the ER fluid flows from left to right. The length of the channel is L. ΔP is the pressure drop along the length L. The width and the depth of the channel are h and b, respectively, where b is in the direction normal to the view given in Figure 3. The profile of the velocity u(y) is also indicated in the flow direction. The middle section of the channel acquires a plug, of total thickness, δ, in response to the gradual solidification of the fluid. The plug thickness grows as the electric field strength increases [2, 4-7].

Establishing the force balance between the shear force and the force due to pressure drop, once at the wall and once at the interface of the plug, leads to the following expression:

$$\frac{\tau_b}{\tau_w} = \frac{\delta}{h} \tag{4}$$

indicating that the ratio of the plug thickness, δ, to the width of the channel, h, is the same as the ratio of the static shear strength, τ_b, to the shear stress at the wall of the channel, τ_w. Further rather lengthy manipulations lead to [4,5,7]

$$4\left(\frac{L}{h\Delta P}\right)^3 \tau_b^3 - 3\left(\frac{L}{h\Delta P}\right)\tau_b + \left(1 - \frac{12\mu LQ}{bh^3\Delta P}\right) = 0 \tag{5}$$

In this expression, the parameters L, b and h are the dimensions of the channel; μ is the Newtonian viscosity of the fluid; Q is the amount of flow through the channel; and ΔP is the resulting loss of pressure. The ER effect is represented only through τ_b whose value may be determined as a function of the applied electric field as suggested in Equation 3.

The relationship between ΔP and Q for zero electric field may be obtained by setting the τ_b term to zero in Equation 5. The resulting equation is analogous to Equation 1:

$$\Delta P = 12\frac{\mu L}{bh^3}Q \tag{6}$$

For increasing values of the electric field strength E, or equivalently, for increasing values of τ_b , the variation of ΔP with Q is similar to the variation of the shear stress, τ, with the strain rate. As illustrated in Figure 4, increasing E shifts up the linear relationship of the zero-field case. The intercept with the ΔP axis may be obtained to be

$$\frac{L}{h\sqrt{3/4}}\tau_b \tag{7}$$

from Equation 5, by setting Q to zero.

In Figure 5, the variation of ΔP with Q from Figure 4, is repeated along with a generic performance curve of a pump to provide the flow in the channel. This pump curve indicates the amount of possible Q as a function of the amount of pressure loss ΔP which the pump has to overcome. Amongst all possible pairs of $(\Delta P_i, Q_i)$ which the pump can provide, the point of operation is obtained by the simultaneous solution of the pump (supply) and system (demand) characteristics. This simultaneous solution is represented graphically by the intersection of the two such characteristic curves.

For a zero electric field, the intersection with the pump curve indicates Q_o as the volume flow rate at the operating point. When an electric field is applied, however, the point of intersection moves towards left, effectively increasing the amount of pressure loss to be overcome by the pump. This decrease in Q continues monotonically with increasing E, until such a point that the pressure demand of the "ER valve" is so large as to stall the pump and to completely shut off the flow.

Conclusions

A brief summary is presented in this paper of an extensive study to model the shear and flow modes of a particular ER fluid. The suggested procedure indicates that the amount of flow through a channel may be valved by varying only the applied electric field, and with no moving mechanical components.

Acknowledgement

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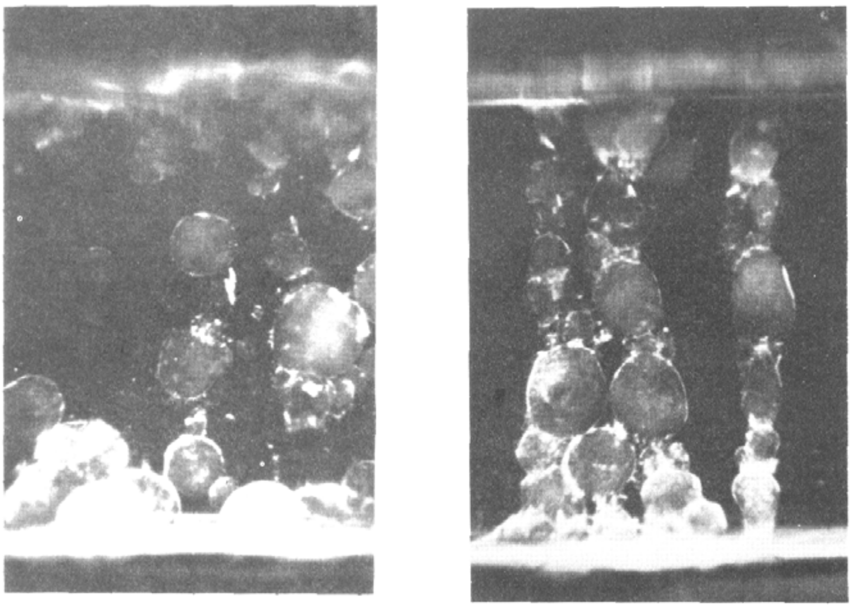

(a) (b)

Figure 1. Electron-microscope photograph of an ER fluid (a) without, (b) with an electric field from Reference 2.

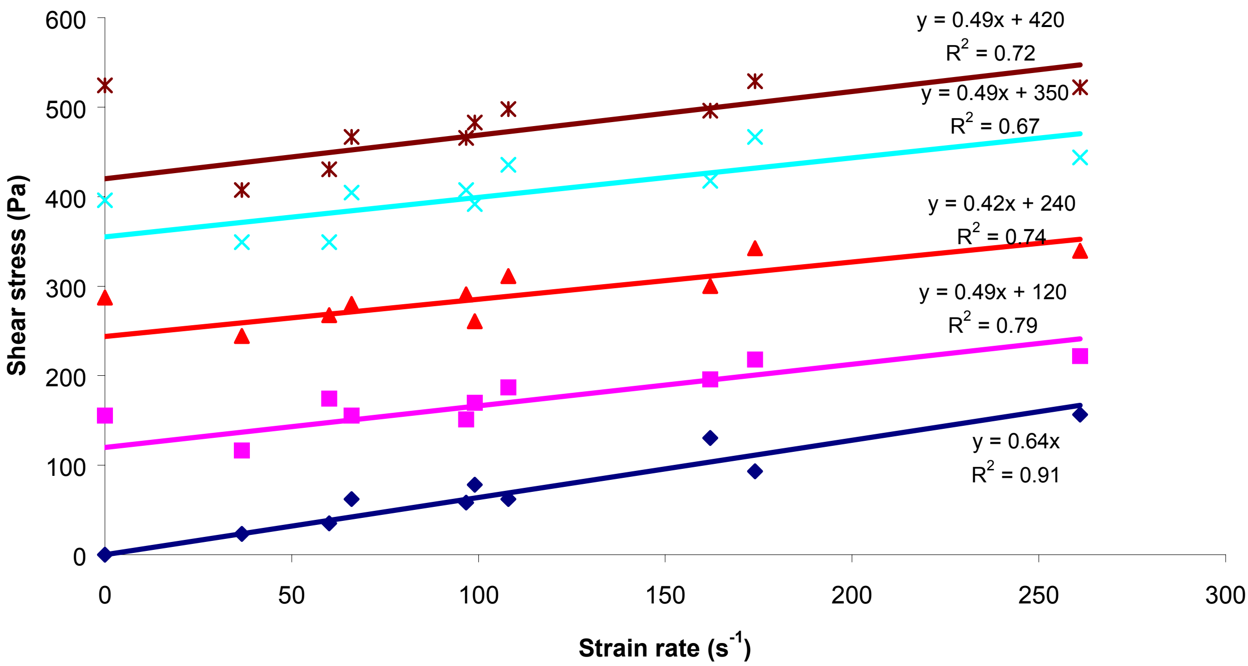

Figure 2. Variation of shear stress with strain rate for 70% weight fraction [3].
(♦) 0 V/mm, (■) 333 V/mm, (▲) 667 V/mm, (x) 1000 V/mm and (*) 1333 V/mm

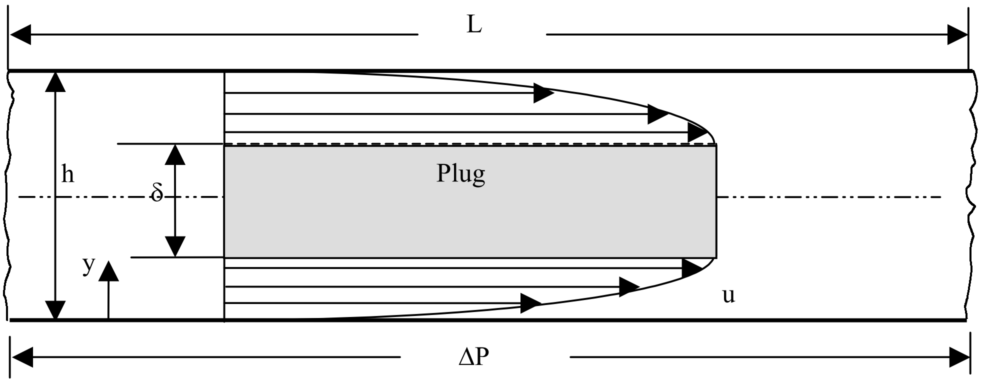

Figure 3. Showing the Bingham plastic valve flow and relevant parameters

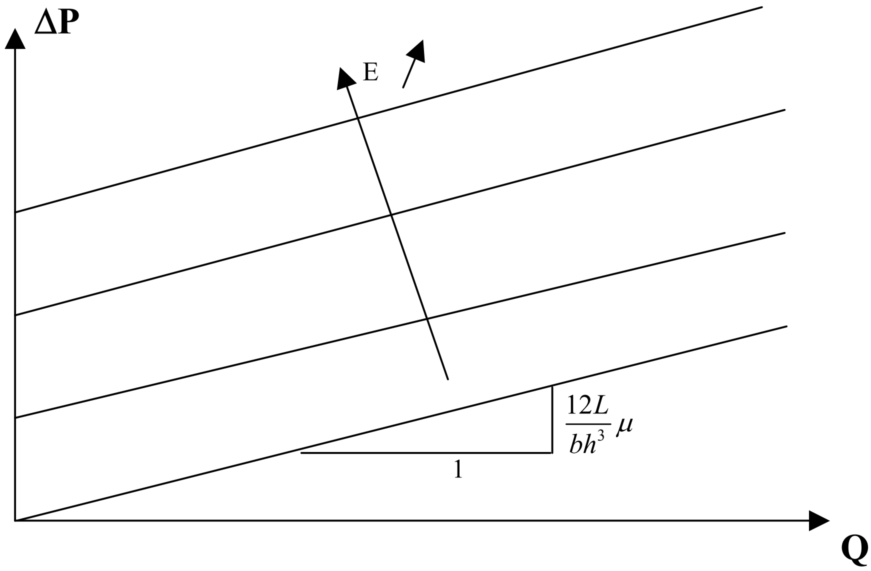

Figure 4. Variation of pressure drop with volumertic flow rate for a Bingham fluid in valve mode.

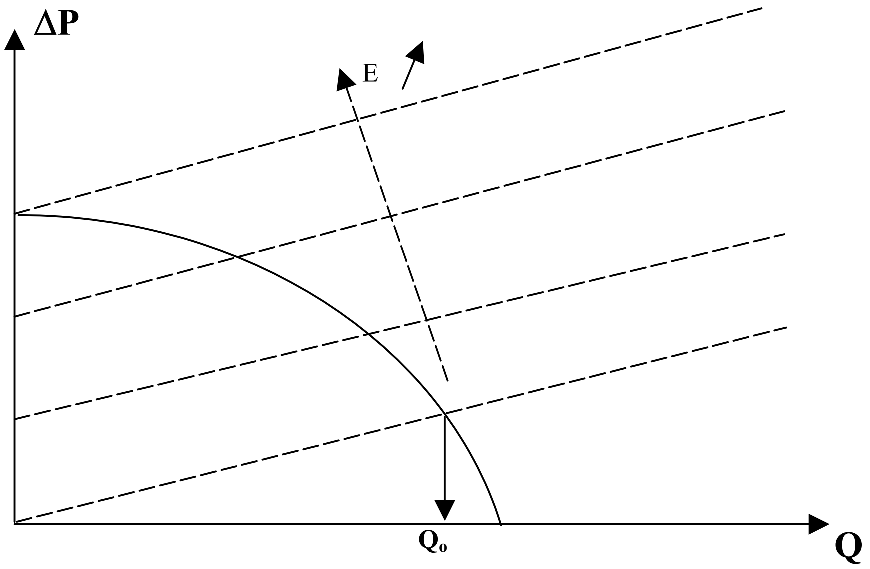

Figure 5. Same as in Figure 4, but with a generic pump charcteristic curve.