Response time of an ER-fluid under shear and flow modes

B Abu-Jdayil
Chemical & Petroleum Eng. Dept., UAE University, Al-Ain, UAE
E-mail: babujdayil@uaeu.ac.ae

Abstract. The response times of an ER-fluid in shear and flow modes under the effect of AC- and DC-fields were investigated experimentally. In shear mode, the response time was obtained under the effect of different shear rates and electrical field strengths by comparing the shear stress measured statically with that measured dynamically. The response times in shear mode decreased with increasing the field strength and decreasing the shear rate. In flow mode, the response times of the ER-fluid under various electric field strengths and flow rates were determined from the pressure measurements in channel flow. The response times in flow modewere exponentially decreased with the increase of the volumetric flow rate and the electric field strength. In both modes, increasing the frequency of the AC-field led to increase of the response time of the ER-fluid.

1. Introduction
The electro–rheological (ER) phenomenon is related to changes in rheological behavior of certain suspensions or solutions upon the application of an electric field [1]. The possibilities for employing the ER-effect in practical applications have long been recognized, e.g. in clutches [2], shock absorbers, hydraulic valves [3], vibration dampers, motor bearings [4], etc. The principle attraction of using ER-fluids in these devices is their fast response time. This feature makes possible feedback control systems for robotics and automotive applications, which are greatly improved over existing models. Therefore, an important parameter to characterize an ER-fluid is the response time, which has different definitions in the literature [5]. Most of the researchers have used the total time needed by the fluid to reach the saturated structure after the application of the electric field. The response time of structure formation in ER-fluids is thought to be controlled by a competition between the field-induced particle interactions and the viscous drag forces.

Wen et al. [6] have studied the response time of microspheres suspended in electrorheological fluids. They found that both the initial response time depends on the conductivity of the microspheres. Lee and Choi [7] identified that the response time of the ER-fluid to the step electric field is almost the same between the shear and flow modes. But a lot of parameters that can affect the response time of ER-fluids have not studied. In shear mode, the response time was found to relate to shear rate and the applied electric field strength [8]. It was found that the rising time decreased with the increase of the shear rate. On the other hand, for constant shear rate, the applied field strength only slightly affected the time constant. The constant increased a little when the applied field strength was very strong [8]. Rejon et al. [5] found that the response time of different ER-fluids in DC field was proportional to $1/E^a$, where $E$ is the applied field and $a$ is an adjustable parameter. In flow mode, Nam et al. [9] found that the response times are exponentially decreased with the increase of the flow velocity and the decrease of the electric field strength. Ulrich et al. [10] approximated the effect of the
electric field on the response time in a valve arrangement by a mathematical model. Recently, the study of Perera et al. [11] revealed that the response time of an ER-fluid developed for a medical device and measured by the dielectric analyser was temperature dependent. However, most of the studies on the response time of ER-fluids did not consider the effects of electric field type and the frequency of the AC-field.

In this study, the response times of an ER-fluid under the effect of AC and DC electric fields in shear and flow modes were investigated. The effects of different operating parameters such as the volumetric flow rate, shear rate, electric field strength, and field frequency on the time response were examined.

2. Experimental

2.1. ER-fluid

The ER-fluid used in this study was supplied by Bayer Company (Leverkusen, Germany). It is an ER-fluid based on soft, crosslinked polyurethane particles in silicone oil (BAYSILONE OIL M – Polydimethylsiloxan). The ER-fluid is water-free and contains additional additives and emulsifier. The polyurethane particles contain dissolved metal ions which are necessary for fast polarization and for the ER effect.

2.2. Rotational viscometer

The rheological data of the ER-fluid were measured with a Haake M5/SV1 conventional rotational viscometer (Searle type) with a fixed outer cylinder and a rotating measuring bob. The radius of the rotating cylinder is 10.5 mm, length of the cylinder 60 mm, and the gap width 1 mm. The software SROT of Haake Co. was used to record the rheological data.

2.3. Channel flow

A PVC rectangular channel (flat channel) was used to investigate the time response of the ER-fluid under the flow mode. To prevent sedimentation of the particles in the ER-fluid the channel is mounted vertically. The rectangular channel had a length of 280 mm with cross-sectional dimensions of 2 mm height and 20 mm in width. In this study, two stainless-steel smooth plates with 40 mm long were used as electrodes. These electrodes are flush with the channel walls and extending over the entire width. The volumetric flow rate of the ER-fluid was adjusted by a gear pump and bypass valve. With this arrangement it was possible to vary the volumetric flow rate (Q) from 0.316 up to 5.50 cm³/s. In addition, the volumetric flow rate was measured with a mass flow meter (Type Mass 2100, Dan Foss, Denmark) at the outlet of the channel. The pressure drop (Δp) was determined in the midplane of one of the 74 mm long inlets over a length of 60 mm, using two pressure transducers (Rosemount, type G1151) with Δp ranges from 0 to 50 mbar and from 0 to 1000 mbar. The temperature of the ER-fluid was measured at the inlet of the channel and controlled by a heat exchanger at 25 °C. Further details on the channel flow set up can be found in ref. 12.

2.4. High voltage devices

The high voltage power supply of alternating current (AC) used in this work was a device developed according to the standards of the Society of German Electrician (VDE). Its working range is: Voltage, U: 0–6 kV (effective); Current, I: 0–10 mA (effective); Frequency, f: 50–500 Hz.

For direct current (DC) measurements a high voltage power supply unit from the company HEIZINGER (type HNC 10000-1) was used. Its working range is: Voltage, U: 0–10 kV; Current, I: 0–1 mA.
3. Results and discussion

3.1. Rotational viscometer results
To investigate the response time of the ER-fluid under the shear mode, the shear stress of the ER-fluid was measured in the rotational viscometer at constant shear rate using the static and dynamic methods. In static measurements, the electric field was applied on the system before starting the shearing process, while in dynamic measurements the electric field applied after starting the shearing process. The response time was determined as the total time needed by the fluid to reach the saturated structure (i.e. the static shear stress) after the application of the electric field. Figure 1 shows the typical effect of the strength of DC-field at high shear rate. By considering the steady-state conditions, it is clear that the response time of the ER-fluid decreased with the field strength.

![Figure 1. Rising response of the ER fluid in shear mode (DC-field).](image)

On the other hand, it was observed that the response time of the ER-fluid increased by increasing the shear rate, see figure 2. This behavior can be explained by recalling the determination method of the response time. In static measurements the electric field is induced before shearing, which means that the cluster formation process is already completed prior to the cluster deformation due to the hydrodynamic force [13]. While in the dynamic measurements, where the electric field is induced after shearing, the cluster begins to form the quasi-stable structure as the electric field is induced on the ER fluid already subjected to the hydrodynamic force. In other words, the cluster formation and deformation are occurred in the dynamic measurements simultaneously. Therefore, the calculated response time here, which is the difference between the rising time of static stress and the rising time of the dynamic stress, can be considered as the cluster formation time [13]. The obtained relationship between the response time (cluster formation time) and the shear rate is in consistence with the results obtained by Choi et al. [13]. The increases of the cluster formation time is increased with the increase of shear rate because the collision chance among the aggregated ER particles and the deformation rate of the cluster structure are increased with the increase of hydrodynamic force.

As can been seen in figure 2, the response time of the ER-fluid used varied between 2.94 s at 1.5 kV/mm and shear rate of 10.19 s⁻¹ and 34.9 s at 0.5 kV/mm and shear rate of 321 s⁻¹. The results are in accordance with those obtained by Rejon et al. [5] for different ER-fluids. The dependence of the response time (\(t\)) of the field strength (\(E\)) was modeled by the following equation:
where $\alpha$ is an adjustable parameter. This behavior was found by Klingenberg et al. [14] where $\alpha$ was approximated to 2. Rejon et al. [5] found an $\alpha$ parameter varying between 0.41 and 1.05. In this study, the parameter $\alpha$ in DC field varied with the shear rate between 0.85 and 1.40, see Table 1.

Table 1. Parameter $\alpha$ of the relationship between response time and electric field (Eq 1) for DC- and AC-fields.

| Shear rate (s$^{-1}$) | DC-field | AC-field |
|-----------------------|----------|----------|
|                       | $f = 50$ Hz | $f = 100$ Hz | $f = 200$ Hz | $f = 300$ Hz |
| 10.19                 | 0.56      | 0.31      | 0.31      | 0.33      |
| 30.19                 | 0.37      | 0.26      | 0.28      | 0.31      |
| 140.50                | 0.38      | 0.28      | -         | -         |
| 321.00                | 0.40      | 0.27      | 0.30      | 0.26      |

The same dependence of the response time on field strength and shear rate has been also observed in the AC-field. On the other hand, a dependence of the response time on the field frequency has been detected. The effect of AC-field frequency $f$ on the response time of the ER-fluid is illustrated in Figure 3. With increasing frequency (at constant field strength and shear rate) the response time of the ER-fluid increased. The response time increased with increasing field frequency because the time available for charge transport during polarization (in one direction per half cycle) decreases with increasing frequency, which has delayed the structure formation [15].

Figure 4 shows the effects of the field strength and on the response time fitted to equation 1. The regressed values of $\alpha$ parameter are reported in Table 1. It is clear that none of the values is close to 2.0, where they varied between 0.26 at high shear rate and field frequency and 0.56 at low shear rate and field frequency. On the other hand, it is noticeable in Table 1, that the $\alpha$ values of DC-field are greater than that of AC-field at the same shear rate. In other words, the response time of ER-fluids in DC-field is shorter than that in the AC-field for the same field strength and shear rate.
3.2. Channel flow results

Most of the previous studies have adopted the shear mode experiments and the DC field in simulation to investigate the response time of ER-fluids. But the flow mode is no less important than the shear mode due to its applicability in different engineering devices such as valves, clamps and dampers. The study on the pressure response with time for ER-fluids is important for the effective design and control of such devices [9].

For flow mode measurements, the pressure drop $\Delta p = f(Q)$ was measured under steady-state conditions; firstly, a constant volumetric flow rate of the ER-fluid was fixed. Then after 60 s an electric field was applied and the pressure drop as a function of time was measured. The time response of the ER-fluid was determined as the time needed to reach a steady state value of $\Delta p$.

As can be seen in figure 5, the response time of the ER-fluid decreased slightly with the strength of the DC-field. This behaviour was also function of the volumetric flow rate, where the dependence of the response time on the field strength was very clear at low volumetric flow rate, see figure 6. The volumetric flow rate and the electric field strength were changed in the ranges of 0.316-5.50 mL/s and 0.25-1.75 kV/mm.
0.5 – 2.0 kV/mm, respectively. Figure 6 shows also that the response times and their decreasing rates were decreased with the increase in the volumetric flow rate. At high field strength, and volumetric flow rate more than about 2.0 mL/s, the rise response time tends to be nearly constant. Compared with the previous studies on the dynamic response of the ER-fluid in flow mode [9], the similar inverse relationship between the pressure response time and volumetric flow rate was obtained. In addition, Nam et al. [9] have also observed the decrease of the pressure rising time with the field strength. The pressure rising times in DC-field were proportional to the volumetric flow rate \( (t \propto Q^{-n}) \) with the exponent of about -0.256 and -0.593 at low and high electrical field strength, respectively. An exponent of -0.412 has been found by Nam et al. [9] for pressure response time of an ER-fluid. This behaviour was explained by Nam et al. [9], that when the flow volumetric flow rate is increased at the same electric field, the densification process is promoted and the average size of the clusters in steady state is decreased. Therefore, the dynamic response time of the ER fluid in the pressure flow is exponentially decreased due to the densification period shortened with the increase of the volumetric flow rate.

![Figure 5](image1.png)

**Figure 5.** Rising response in flow mode for different field strengths (DC-field).

![Figure 6](image2.png)

**Figure 6.** Rising response time for ER-fluid in channel flow as a function of volumetric flow rate and field strength (DC-field).
Figure 7 shows the typical pressure response of the ER-fluid under the effect of the AC-field. Similar trends have also been observed here as in the case of DC-field, with some dependence of the response time on the field frequency. In addition to its effect on the response time, the volumetric flow rate has affected the range of the pressure values at steady state conditions. As can be seen in figure 7, increasing of the volumetric flow rate has increased the fluctuations in the measured pressure drop. The degree of fluctuations also increased with increasing the field frequency at constant volumetric flow rate and constant field strength. When the volumetric flow rate is increased at constant field strength, the hydrodynamic force will increase in competition with the field-induced particle interaction forces, which leads to this fluctuated behavior.

![Figure 7](image.png)

**Figure 7.** Rising response in flow mode for different volumetric flow rates (AC-field).

The effects of volumetric flow rate and field strength on the pressure response time at f = 50 Hz are illustrated in figure 8. For all field strengths, and volumetric flow rate more than about 2.0 mL/s, the rise response time tends to be nearly constant. The pressure rising times in AC-field were proportional to the volumetric flow rate \( t \propto Q^{-n} \) with the exponents of about -0.469 and -0.410 at low and high electrical field strength, respectively, which are in accordance with the previous findings of Nam et al. [9]. It was also observed that the response times under DC-field conditions were shorter than that under AC-conditions with 50 Hz for the same volumetric flow rate and field strength. An exception was the field strength of 0.5 kV/mm.

The main important difference between the shear and flow mode is that the response time has an inverse relationship with the volumetric flow rate in flow mode, while in the shear mode the response time is proportional to the shear rate. It was indicated in previous studies that there is a difference in the mechanism of the structure formation in both modes [9]. It is expected that the pressure response of the ER-fluid in channel flow is mainly determined by the densification process in the competition of the field-induced particle interaction forces and the hydrodynamic forces, unlike those in steady shear dominated by aggregation process.
Figure 8. Rising response time for ER-fluid in channel flow as a function of volumetric flow rate and field strength (AC-field).

4. Conclusions
Response times of an ER-fluid in shear and flow modes were investigated experimentally. The effects of electrical field strength, field type, shear rate and volumetric flow rate on the response time of ER-fluid were determined. In shear mode, where the measurements were carried out in a rotational viscometer, high field strength and low shear rate correspond to quicker response. While in flow mode, where the measurements were carried out in a channel flow, high field strength and high volumetric flow rate correspond to quicker response. In both modes, it was observed that at the same field strength and flow conditions, the response times under DC-field are shorter than those under AC-field (50 Hz). In addition, increasing the field frequency of AC-field results in longer response time in shear and flow modes. For practical applications, where short response time is required in different ER devices, using of DC field or AC field with low frequency is recommended.

References
[1] Brunner P O, Abu-Jdayil B 2004 *Rheologica Acta* 43 62
[2] Hartsock D L, Novak R F and Chaundy G J 1991 *J. Rheol.* 35 1305.
[3] Strandrud H T 1966 *Hydraulic Pneum* Sept 139
[4] Duclos T G 1988 *Automotive Eng.* 96, 45
[5] Rejon L, Ramirez A, Paz F, Goycoolea F M and Valdez M A 2002 *Carbohydrate Polymers* 48 413
[6] Wen W, Zheng D W and Tu K N 1998 *Physical Review E* 57 4516
[7] Lee H G and Choi S B 2002 *Materials and Design* 23 69
[8] Tian Y, Zhang, Meng Y and Wen S 2005 *J. Colloid Inter. Sci.* 290 289
[9] Nam Y J, Park M K and Yamane R 2008 *Experiments in Fluids* 44 1196
[10] Ulrich S, Böhme G, Bruns R 2009 *J. of Physics: Conference Series* 149 012031
[11] Perera N I, Maheswaram M P, Mantheni D, Perera H D, Matthews M E, Sam-Yellowe T and Riga A 2011 *American Journal of Analytical Chemistry* 2 85
[12] Abu-Jdayil B, Asouid H and Brun P O 2007 *Materials and Design* 28 928
[13] Choi B H, Nam Y J, Yamane R and Park M K 2009 *J. of Physics: Conference Series* 149 012004
[14] Klingeberg D J, Zukoski C F and Hill J C 1993 *J. of Applied Physics* 73 4644
[15] Abu-Jdayil B and Brun P O 1997 *Chemical Engineering and Processing: Process Intensification* 36 281