Dynamic dielectric response of electrorheological fluids in drag and pressure flow

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We have determined the response time of dilute electrorheological fluids (ER) in drag flow, in pressure-driven flow, and in the quiescent state from the dynamic dielectric response. The dependence of the response times on the electric field strength, the shear rate, and the flow velocity were investigated. In the case of ER fluids in drag flow, the response times were also determined from the stress response of the fluid measured simultaneously with the dielectric properties. Comparing the dielectric and rheological response times measured at the same conditions, a significant discrepancy was found, which was attributed to the different instrumental response times of the employed methods. The dielectric permittivity of the quiescent ER fluid was estimated on the basis of formulas derived from the Clausius-Mossotti equation. This simple theoretical model was extended and applied to ER fluids under shear to evaluate the experimental dielectric results.

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I. INTRODUCTION

One of the main advantages of a device based on electrorheological (ER) fluids (such as a clutch, actuator, brake, or damper) is the small (of the order of $10^{-3}$ s) response time compared to conventional devices. The response time of an ER device is determined by the dynamics of the external electric field induced phase transition of the ER fluid. This reversible liquid to solid-like state transition process involves the polarization of the dispersed particles and the microstructural change by the aggregation of the polarized particles into chainlike and columnar clusters. If the ER fluid is under a mechanical deformation, the phase transition is also influenced by the time-dependent flow of the ER fluid. The overall phase transition can be characterized by a response time, which is one of the most important parameters of an ER fluid. There are different definitions for the response time. For example, in some literature it is the time delay between the turn on of the external electric field and the resulting change in macroscopic properties such as the rheological behavior. It can also be regarded as the time needed to form the first electrode spanning structures. Generally, it is defined as the time required to reach a new equilibrium microstructure after the phase transition. In this paper, we use this latter definition. The change in the macroscopic properties as a function of time during the phase transition (which is the result of the temporal evolution of the microstructure) is usually approximated with a saturating exponential function. Thus the experimental response time can be characterized with the characteristic time constant of an exponential fitting function. Besides the physical properties of the components of an ER fluid, this response time is influenced by the external conditions (electric field strength, rate of deformation, etc.).

During the operation of a typical ER device the fluid is in pressure-driven flow, in drag flow, or in the combination of the two. Because the response time is influenced by the properties of the flow, it is measured mostly in the case where the fluid is under mechanical deformation. These measurements are based on the determination of time-dependent stress or pressure change of the fluid. The stress response based measurements are done mainly in shear mode with different geometries, while there are only a few compressive stress studies regarding the response time. The microstructural change can also be investigated with optical (transmittance, light scattering) methods, therefore, these experimental techniques are suitable for response time measurements even in the case of quiescent ER fluids. With dielectric spectroscopy the polarization process of the individual particles (relaxation time) can be investigated, but this gives only an estimate to the lower limit of the response time, because it does not includes the additional time needed for structure formation.

For accurate response time measurements it is important to take into consideration the error stemming from the instrumental response time of the employed experimental method. The stress response based techniques – especially when conventional rheometers are used – have a larger instrumental response time compared to other methods which use a purely electronic apparatus.

In a previous study, we employed a dielectric method to investigate the response time of quiescent ER fluids. The change in relative permittivity caused by the structure formation can be measured continuously with this technique and the response time is extracted from the time dependent permittivity as a characteristic time constant. We used this dielectric method to measure the response time of ER fluids in drag flow and in pressure-driven flow in addition to the quiescent state. In the case of fluids in drag flow, both the dielectric and rheological properties of the ER fluid were measured simultaneously with the improved experimental setup and the characteristic times were determined from the dielectric and rheological data.
Besides the response time measurements, the change in dielectric properties due to structure formation was compared to theoretical predictions. We used a simple theoretical model based on formulas derived from the Clausius-Mossotti equation to calculate the difference between the permittivity of isotropic and anisotropic ER fluids in equilibrium. The model was applied to quiescent and ER fluids under shear to evaluate the experimental dielectric results.

II. EXPERIMENT

A. Experimental setup

The block diagram of the dielectric measurement setup can be seen in Fig. 1. The concept of the dielectric permittivity measurement is based on the determination of the frequency change of an LC oscillator, where the capacitive element is a special, changeable dielectric cell (C_p). There is a direct relationship between the frequency of the sinusoidally varying ac measuring field and the relative permittivity of the fluid in the dielectric cell. The measuring ac field has a frequency of \( f = 2.3 \text{ MHz} \) (depending on the relative permittivity of the ER fluid), and the voltage across the electrodes is \( U_{\text{p-p}} = 4 \text{ V} \). The strength of the electric field created by the oscillator is below the limit needed to induce structure formation in the used ER fluid. The frequency is measured by a modulation domain (MD) analyzer (HP 53310A) with high time resolution. If the ER fluid is under the influence of strong electric field (\( E \approx 10^6 \text{ V/m} \)) the change in relative permittivity (caused by structure formation) can be continuously measured as a change in the frequency of the measuring field.

The strong electric field is created by rectangular high voltage (HV) pulses imposed to the cell. The HV pulse generator is a Trek 609E-6 HV amplifier and the input signal is supplied by the analog output of a data acquisition card (National Instruments PCI-6052E). The slew rate of the HV amplifier is greater than 150 V/\( \mu \text{s} \), therefore, even at the largest amplitude the rise time of the rectangular pulse is three orders of magnitude smaller than the measured response time of the ER fluids. The whole measuring system was controlled with a LabVIEW software running on a PC. The main tasks of this program were the acquisition and processing of raw data as well as to provide control functions (MD analyzer, HV pulse generator, syringe pump). Further technical details of the dielectric measurement setup can be found in [10]. The estimated error of the permittivity measurements is below 3%, while the characteristic times extracted from the dielectric data have an experimental error smaller than 14%.

In our experiments we used various dielectric cells: two shear cells with different geometries (parallel plates and concentric cylinders) for the drag flow, and one for the ER fluids in pressure-driven flow.

1. Dielectric shear and flow cells

The two different dielectric shear cells [Fig. 2(a) and 2(b)] were constructed using an Anton Paar Physica MCR301 rotational rheometer and its slightly modified accessories. The P-PTD200/E accessory and the PP50/E measuring tool is a plate-plate (PP) system (the electrode gap is 0.8 mm), while the C-PTD200/E accessory with the CC27/E tool has a concentric cylinders (CC) geometry (1.13 mm electrode gap). After small changes the measuring tools were connected as electrodes to the LC oscillator forming the frequency determining capacitive element. The electrical connection between the rotating tool and the oscillator was made by a spring loaded sliding wire. Both dielectric cells have a built-in Peltier device for temperature regulation.

The maximum shear rate was varied between 5 and 50 s^{-1} for both shear cells. The drag flow in the cells can be characterized as a steady, laminar flow. The torque exerted on the rotating electrode was measured with the Anton Paar rheometer parallel with the dielectric measurements. With this setup the dielectric permittivity and the shear stress in the ER fluid can be determined at the same time.

The pressure flow was realized as an axial annulus flow in the dielectric flow cell [Fig. 2(c)]. The cell is a coaxial cylinder type capacitor where the fluid flows between the two stainless steel electrodes. The diameter of the inner electrode is 34.0 mm and the electrode gap is 0.5 mm. The length of the outer electrode is 50 mm, which is equal to the length of the flow channel where the fluid is under the effect of high intensity electric field. Because of the asymmetry of the inner electrode, the direction of the fluid flow during the dielectric measurements was always from bottom to top of the cell.

A steady flow is necessary because the permittivity measurement is highly sensitive to variations in the flow...
rate. To achieve this we used a custom built, differential syringe pump to push the ER fluid through the dielectric cell. The measurements were carried out at various flow rates, but the flow was always laminar, even at the highest flow rate (the Reynolds number was Re < 0.06). The highest achievable flow velocity in the cell was 12 mm/s. The flow velocity is defined as the flow rate divided by the cross sectional area of the flow channel.

The printed circuit board of the LC oscillator was secured directly on the side of the flow cell. With this configuration the stray capacitance can be minimized and any variation of it is eliminated, which is crucial for the reproducibility of the permittivity measurements.

B. Materials

In our experiments we used dilute ER fluids containing nano-sized silica (SiO$_2$) particles dispersed in silicone oil (polydimethylsiloxane) with various viscosities. The diameter of the silica particles is between 10 and 20 nm. The dynamic viscosity of the silicone oils is 0.34 and 0.97 Pa s at 25°C. The relative permittivity of the carrier liquid is $\varepsilon_1 = 2.7$, while the particles have a permittivity of $\varepsilon_p = 4.0$. All materials were supplied by Sigma-Aldrich. Before preparing the suspensions, the silicone oil and the silica were vacuum-dried for six hours at a pressure of 300 Pa and a temperature of 50°C to remove any absorbed water. After mixing and homogenizing the two components, the suspensions were dried in vacuum again for 30 minutes to remove the air bubbles. The volume fractions of silica particles in the ER fluids were $\phi = 0.02$ and 0.04.

III. RESULTS AND DISCUSSION

A. Characteristic times

According to experimental and simulation studies [13, 14], the structure formation in ER fluids caused by an external electric field progresses as two distinct processes. First, there is a fast pair formation, which is followed by a slower aggregation of the particle pairs into longer chains and columns. The response time of the ER fluids is determined by the timescale of these two processes. Due to the microstructural change, the effective permittivity of the ER fluid measured parallel to the electric field also changes [15]. This gives the possibility to extract the characteristic time scales of the pair formation and aggregation into longer chains from the dielectric response of the ER fluid to a rectangular HV pulse. The change in the relative dielectric permittivity of the ER fluid can be approximated with a bi-exponential fitting function:

$$\Delta \varepsilon(t) = A \left(1 - e^{-\frac{t}{\tau_1}}\right) + B \left(1 - e^{-\frac{t}{\tau_2}}\right),$$

where the constant $\tau_1$ and $\tau_2$ are interpreted as the characteristic time scales for pair- and chain formation, respectively. $\Delta \varepsilon(t)$ is the change of the dielectric permittivity during the time period $t$ in which an external field is applied:

$$\Delta \varepsilon(t) = \varepsilon(t) - \varepsilon(0),$$

where $\varepsilon(0)$ is the relative permittivity of the isotropic ER fluid at $t = 0$ when the external electric field is turned on.

The $\tau_1$ characteristic time of sheared ER fluid (CC geometry) as a function of the electric field strength can be seen in Fig. 3. At a constant shear rate, the electric field strength dependence of the experimental characteristic times can be fitted with a $\tau_1 \propto 1/E^a$ function. In the case of quiescent ($\dot{\gamma} = 0 \text{ s}^{-1}$) ER fluids, the theoretical value of the exponent $a$ according to the polarization
model of the ER effect is 2 \[2\]. However, the experimental results show that for the ER fluid under investigation \(a\) has a value approximately 1.1. The experimental response time of other ER fluids shows similar (\(a < 2\)) electric field strength dependence. Rejón et al. \[16\] found that the exponent has a value between 0.41 and 1.05 in ER fluids containing polysaccharide particles. According to Abu-Jdayil \[6\], the response time determined by rheological measurements depends on the electric field strength with an exponent between 0.85 and 1.40 in ER fluids composed of polyurethane particles dispersed in silicone oil.

The experimental data show that the value of \(a\) is smaller if the ER fluid is subjected to shear. We found that \(a = 0.35\pm0.08\) at a shear rate of \(5\) s\(^{-1}\), while \(a = 1.13\pm0.06\) in the quiescent fluid. At a given field strength, \(\tau_1\) is decreasing with increasing shear rate. At higher shear rates (\(\dot{\gamma} > 10\) s\(^{-1}\)) \(\tau_1\) becomes independent of the electric field strength. This can be explained if we take into account the forces relevant to the structure formation in ER fluids.

The microstructure of ER fluids in steady shear flow is determined by the competition of the electrostatic forces between the particles and the viscous force. The relative importance of these forces can be described by the dimensionless Mason number \[17\]:

\[
Mn = \frac{\eta \dot{\gamma}}{2 \epsilon \epsilon_0 \beta^2 E^2},
\]

where \(\eta\) is the dynamic viscosity and \(\epsilon_1\) is the relative permittivity of the background fluid, \(\epsilon_0\) is the permittivity of free space, and \(\beta = (\epsilon_p - \epsilon_1)/(\epsilon_p + 2\epsilon_1)\). In the case of the ER fluid used in our experiments at \(\dot{\gamma} = 5\) s\(^{-1}\) shear rate and \(E = 2.0\) MV/m electric field strength, the Mason number is 1.32. This means that at this shear rate the viscous forces begin to become the dominant force to determine the microstructure. If the shear rate is greater than \(10\) s\(^{-1}\), the Mason number is \(2.05 < Mn < 10.6\) depending on the electric field strength. In this shear rate regime the viscous forces are clearly dominant, so \(\tau_1\) is independent of the electric field strength.

The electric field strength dependence of the characteristic times was measured with both dielectric shear cells (parallel plates and coaxial cylinders). By the comparison of the characteristic times measured with the PP and CC cells at the same conditions, we found that the difference between \(\tau_1\) is around 4-9%. This difference stems largely from the calibration error of the parallel plates cell. The characteristic times of the studied ER fluids, therefore, can be said to be independent of the geometry of the shearing surfaces.

The characteristic times were also determined from the rheological data that were measured simultaneously with the dielectric permittivity. The change in the measured shear stress during the high voltage pulse was fitted with a bi-exponential function similar to that used in processing the permittivity results [see Eq. (1)]. We found that the \(\tau_1\) characteristic times calculated from the shear stress response are almost two times greater (depending on shear rate) than the corresponding \(\tau_1\) determined from the permittivity response (Fig. 4). The significant difference between the characteristic times is the result of the different instrumental response times of the dielectric and rheological measurement methods. The rotational rheometer as a mechanical instrument has a much larger response time than the purely electronic dielectric measurement system, which introduces a significant systematic error. This means that the dielectric method has an advantage over mechanical methods for accurate dynamic measurements.

For the ER fluids in pressure flow, the electric field dependence of the \(\tau_1\) characteristic time is shown in Fig. 5.

FIG. 3. (Color online) The \(\tau_1\) characteristic time of ER fluids in drag flow (concentric cylinders) as a function of electric field strength at different shear rates (\(\eta = 0.97\) Pa s silicone oil, \(\phi = 0.94\), \(T = 25^\circ\)C).

FIG. 4. (Color online) The characteristic times as a function of shear rate determined with the rheological (diamonds) and dielectric (circles) methods. The lines are just guides to the eye.
At a given electric field strength, \( \tau_1 \) is smaller than in the quiescent state. In a system where the particles are moving with different velocities near each other, it can be expected that the time of pair formation is smaller compared to the static case. The exponent of the power function fitted to the experimental data in the case of flowing ER fluids is 1.02±0.01, 0.69±0.02, and 0.56±0.06 at a flow velocity of 0, 2, and 4 mm/s, respectively. The value of \( \alpha \) for the quiescent fluids derived from the data measured with the flow cell agrees well with the exponent determined with the shear cells (1.02 vs. 1.13). With increasing flow velocity in the range of 2-12 mm/s the characteristic times basically remain the same (within measurement error). In Fig. 5 the data for the flow velocities greater than 4 mm/s are omitted for clarity.

**B. The relationship between the permittivity and microstructure**

To estimate the permittivity change caused by the structural change in quiescent and in ER fluids under deformation we employed a simple theoretical model. The permittivity change is defined as the difference between the effective permittivities of isotropic and anisotropic ER fluids when the microstructure reached the new equilibrium state:

\[
\Delta \epsilon_s = \lim_{t \to \infty} \Delta \epsilon(t) .
\]

The ER fluid is treated as a two component system where the components are the single particles and the electrode spanning particle chains. It is assumed that the \( l \) particle long chains are one particle thick. The base fluid of the ER system is treated as a background continuum dielectric with a relative permittivity of \( \epsilon_f \). The effective permittivity (\( \epsilon_{eff} \)) of the two component system is given by the Clausius-Mossotti equation:

\[
\frac{\epsilon_{eff} - \epsilon_f}{\epsilon_{eff} + 2\epsilon_f} = \frac{1}{3\epsilon_0}\left(\rho_p\alpha_p + \rho_c\alpha_c\phi_c\right) ,
\]

where \( \rho_i \) is the number density and \( \alpha_i \) is the polarizability of component \( i \). The subscripts \( p \) and \( c \) represent the values for single particle and chains. The concentrations of the components can be given by volume fractions instead of number densities, so the \( \phi_c \) volume fraction of the chains is \( \phi_c = (1 - \phi_p)/l \).

The polarizability of the chains along the length is calculated using a dimensionless \( h \) "enhancement factor". This factor is defined as the ratio of the polarizability of the chains and the ideal additivity of the polarizability of single particles: \( h = \alpha_c/(l\alpha_p) \). If the total number density and the polarizability is reduced by \( \sigma^3 \) (the diameter of the particles is \( \sigma = 2r \)) Eq. \( \text{(5)} \) can be written as

\[
\frac{\epsilon_{eff} - \epsilon_f}{\epsilon_{eff} + 2\epsilon_f} = \frac{1}{3\epsilon_0}\rho^* \left[ \phi_p\alpha_p^* + (1 - \phi_p)\alpha_p^* h \right] ,
\]

where the reduced quantities are marked by the * superscript. The reduced polarizability of a single particle is

\[
\alpha_p^* = \frac{1}{2}\pi\beta\epsilon_f\epsilon_0 r^3 ,
\]

where \( r \) is the radius of the particle.

Kim and coworkers \[18\] derived analytical expressions for the \( h \) enhancement factor of different infinite-sized discrete clusters. The enhancement factor for infinitely long chains parallel with the electric field is

\[
h = \frac{1}{1 - \frac{\zeta(3)}{3\epsilon_0}\alpha_p^*} ,
\]

where \( \zeta(3) \) is the Riemann zeta function.

**FIG. 5.** (Color online) The \( \tau_1 \) characteristic time of ER fluids in pressure flow as a function of electric field strength at different flow velocities (\( \eta = 0.34 \text{ Pa s silicone oil, } \phi = 0.02, T = 25^\circ C \)).

**FIG. 6.** (Color online) The theoretical effective permittivity change relative to the permittivity of the isotropic (\( \phi_p = 1 \)) ER fluid as a function of the volume fraction of single particles [according to Eq. \( \text{(5)} \)].
where $\zeta(x)$ is the Riemann zeta function. The chains can be considered infinitely long if the $l$ number of particles in the chains is greater than 1000. In this case the asymptotic value of $h$ of a large cluster agrees well with the value determined from the analytical expression for an infinitely long chain. In the ER fluids under investigation, $l \approx 6000$ if the chains are spanning the whole electrode gap (which is true at sufficiently large electric field strength). This means that the chains in the ER fluid can be regarded as infinitely long and Eq. (5) is valid.

The theoretical effective permittivity of the ER fluids used in our experiments as a function of the $\theta$ tilt angle of slanted chains. The permittivity is given as a change relative to the field strength. This means that the chains in the ER electrode gap (which is true at sufficiently large electric field strength). In the ER fluids under investigation, $l \approx 6000$ if the chains are spanning the whole electrode gap (which is true at sufficiently large electric field strength). This means that the chains in the ER fluid can be regarded as infinitely long and Eq. (5) is valid.

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$\phi$ used in our experiments as a function of the valid.

The effective permittivity increases with decreasing particle volume fraction as the particles are aggregating into chains [see Eq. (6)]. The theoretical maximum of the permittivity increment is $\Delta \varepsilon_{\text{c}} = 0.0182$. According to the experimental data the permittivity increment saturates if the electric field strength is $E > 4 \text{ MV/m}$. Thus, in this electric field regime it can be assumed that every particle is part of the chainlike structures. The experimental maximum of $\Delta \varepsilon_{\text{c}}$ is 0.0210±0.0005, which agrees well with the value obtained from the theoretical model.

When the ER fluid is subjected to steady shear, the particle chains tilt due to hydrodynamic forces and are no longer parallel with the electric field. The parallel (with respect to $E$) component of the polarizability of the slanted chains becomes dependent on the $\theta$ tilt angle. Therefore, the formula for the enhancement factor takes the form. Eq. (9) has a physical meaning only in the $0^\circ < \theta < 54.7^\circ$ range, because if $\theta > 54.7^\circ$, the interaction between the particles in the chains becomes repulsive. The prediction of the model for the permittivity change as a function of the tilt angle is presented in Fig. 7. As the chains become more tilted, the effective permittivity decreases.

The measured permittivity change at various shear rates (Fig. 8) shows a similar behavior; as the shear rate is increased, the permittivity change caused by structure formation becomes smaller. In a sheared ER fluid, the chains are continually breaking up and reforming, so the microstructure attains a dynamic equilibrium state [19]. The tilt angle of a single chain increases until the chain breaks, after which the fragments tilt less. When the fragments form a complete chain again, the tilt angle is decreasing until breakage occurs. In general, the slant of the chains can be described with an average angle. From the experimental permittivity data we calculated the average tilt angle using the theoretical model outlined earlier. If the ER fluid is subjected to a steady shear of $\dot{\gamma} = 5 \text{ s}^{-1}$, the measured permittivity change is $\Delta \varepsilon_s = -0.0078 \pm 0.0002$. According to the employed model, this $\Delta \varepsilon_s$ corresponds to a tilt angle of $\theta = 30^\circ$, which is reasonable. At a higher $\dot{\gamma} = 50 \text{ s}^{-1}$ shear rate, $\Delta \varepsilon_s = -0.0105 \pm 0.0003$, which gives a value of $\theta = 36^\circ$ for the average tilt angle.

The measurement of the dielectric response of the ER fluid in drag flow to a 5 s long rectangular HV pulse at different shear rates ($\eta = 0.97 \text{ Pa s silicone oil, } \phi = 0.04$, $T = 25^\circ\text{C}$). The electric field was switched on at $t = 0 \text{s}$.
The electric field was switched on at $t = 0$ s. The flow velocities ($\eta = 0.34$ Pa $\text{s}$ silicone oil, $\phi = 0.02$, $T = 25^\circ\text{C}$). The electric field was switched on at $t = 0$ s.

The dielectric behavior of the ER fluids in pressure flow was similar to the fluids in drag flow. Under pressure flow the permittivity increment was smaller than in quiescent ER fluids. At a fixed electric field strength $\Delta \varepsilon$, decreased with increasing flow velocity (Fig. 9). The smaller permittivity of the flowing ER fluid can be explained by the deformation of the chains. Under pressure flow the chains are bent due to hydrodynamic forces acting on them, and the shape of the chains is near paraboloid corresponding to the velocity profile. The shape and the behavior of the bent chains in flowing ER fluids (containing $\mu$m sized particles) was visually confirmed using a videomicroscope setup.

As the polarizability of the chains (and hence the permittivity of the fluid) depends on the tilt angle of the chains in the case of shear flow, it depends on the curvature of the bent chains in the case of pressure flow. If the curvature becomes larger, the effective permittivity of the flowing ER fluid decreases. The curvature of the chains is a function of the electric field strength and the flow velocity. Increasing the electric field strength causes the chains to bend less, while increasing the flow velocity results in the increase of the curvature. This is in agreement with the electric field strength and flow velocity dependence of the measured permittivity increment of the ER fluids in pressure flow.

![Image of graph showing the dielectric response of the ER fluid](image_url)

**FIG. 9.** (Color online) The dielectric response of the ER fluid in pressure flow to a 5 s long rectangular HV pulse at different flow velocities ($\eta = 0.34$ Pa $\text{s}$ silicone oil, $\phi = 0.02$, $T = 25^\circ\text{C}$). The electric field was switched on at $t = 0$ s.

**IV. CONCLUSIONS**

The dielectric and the stress responses of ER fluids in shear and pressure flow were characterized by measuring the response time. The dielectric results confirm that the structural change is governed by two processes, a fast particle pair formation and the slower aggregation into longer chains and columns. Therefore, the response time of the ER fluids is determined by the timescale of these two processes. The dependence of the characteristic times on the electric field strength, the shear rate, and the flow velocity were determined. The electric field strength dependence of the characteristic time was fitted with a power function, and the exponent was found to be smaller than the value predicted by the polarization model of the ER effect. We found that in the case of shear flow above a certain shear rate, the characteristic time becomes independent of the electric field strength indicating that the viscous forces dominate the process of determining the microstructure. The time constants measured with different shearing surface geometries (parallel plates or concentric cylinders) were the same within measurement error. The characteristic time constants determined from the dielectric response of the sheared fluids were smaller than the corresponding ones determined on the basis of the shear stress behavior. This was attributed to the smaller instrumental response time of the dielectric apparatus due to the purely electronic nature. Therefore, for accurate dynamic measurements the dielectric method has an advantage over mechanical methods. The dielectric behavior of the ER fluids in pressure flow was similar to the fluids in drag flow. The characteristic time of ER fluids in pressure flow showed a power function dependence on the electric field strength, where the exponent was also smaller than the theoretical value of 2.

The measured change in the effective permittivity of the ER fluid was estimated on the basis of formulas derived from the Clausius-Mossotti equation. Despite the simple nature of the theoretical model, we found good agreement between the theoretical and experimental dielectric data.

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