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Scale effects of the rheological properties of electrorheological suspensions

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Abstract

The knowledge about the rheological behavior of electrorheological suspensions in all prevalent conditions is essential for the design process of applications. Of particular importance is the dependence of fluid viscosity on the electric field strength, the temperature, and the shear rate. Previous research has pointed out the difficulties in determining the relevant rheological parameters independent from the geometry and flow conditions. For example, experimental results obtained using a capillary rheometer are different from the results gained in flow channel experiments. Even the results from one flow channel could not easily be used to predict the performance of a channel with, for example, a different distance between the electrodes. Some possible effects such as wall slip, interactions of the particles with the surface of the electrodes, or scale effects based on the particle size distribution in relation to the dimension of the flow channel may complicate the determination of the rheological parameters. To investigate these effects, a flow channel test rig that allows systematic changes to the flow conditions was developed. The distance of the electrodes can continuously be changed from 0.02 to 1 mm with an apparent shear rate from 100 to 10,000 s^{-1}. The electrodes can easily be replaced to determine the influence of surface structure. This article will first discuss the design of the flow channel followed by the experimental results obtained under different test conditions. The aim of this research is to gain insight into the scale effects of electrorheological suspensions in order to develop microfluidic applications.

Keywords

Rheology, electrorheology, electrorheological suspension, RheOil, microgap, microvalve, scale effect, electrode surface, electrode topography

The flow channel

Typical electrorheological (ER) valves for particle-type electrorheological fluids (ERFs) are realized with a gap height of about 1 mm (Schneider, 2012). They can be divided into two different types: concentric versus parallel gaps. The circular gap is formed by positioning a rod electrode inside a metal pipe electrode. The electrical field is generated between these two main elements.

The flow channel with adjustable gap height discussed in this article has a rectangular gap. The channel is created by planar parallel electrodes which are integrated into a housing material with a very high dielectric strength. One electrode is integrated into the header, while the second is located at the bottom of the flow channel (Figure 1).

Two wedges form the adjustment mechanism for the gap height. One of the wedges is screwed directly to the slide and the other one to the header. By shifting the wedges horizontally, the upper electrode is moved vertically the desired distance. For example, moving the wedge 1 mm in the flow direction changes the gap height by 20 μm. By using this system, it is possible to obtain every gap height between 0.02 and 1 mm. Over this height range, shear rates from 100 to 10,000 s^{-1} can be realized, depending on the volume flow and inlet pressure.

The electrode in the housing has direct contact with the high-voltage supply. The other one in the piston is grounded. Establishing an electric field between the two

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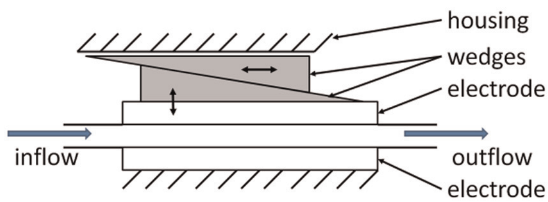

Figure 1. Schematic representation of the flow channel with geometric dimensions of the electrode surface of 50×50 mm^2.

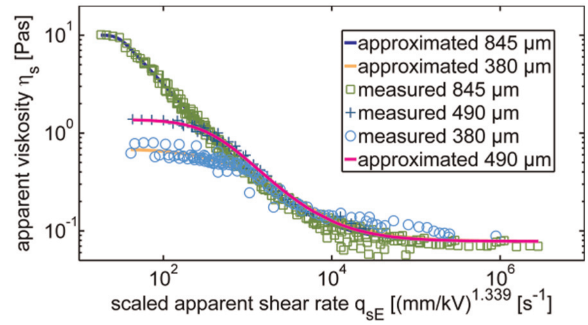

Figure 2. Approximation of the flow curves with the Carreau–Yasuda model for different gap heights at a temperature of 25°C.

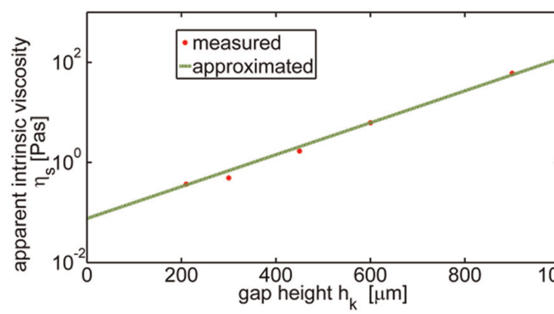

Figure 3. Apparent intrinsic viscosity as a function of the flow channel gap height at a fluid temperature of 25°C.

electrodes causes a change in fluid viscosity. This flow channel allows one to investigate the influence of the gap height and, by changing the electrodes, the influence of the surface as well as the electrode material.

To characterize the behavior of an ER suspension, the fluid is forced to flow through the rectangular-shaped gap. The gap height, the flow rate, the voltage at the electrode, and the surface of the electrode were changed in order to get a complete understanding of the influence of these different parameters on fluid flow and behavior.

Influence of the gap height

The apparent shear rate and the electric field strength can be calculated based upon the flow rate, the voltage, and the geometry of the flow channel. These parameters are used to compare the influence of the different gap heights.

Without an electric field, the ERF shows even at a gap height of 120 µm a Newtonian behavior with a linear relation between the shear rate and the shear stress. The pressure difference increases with a rising electric field strength and apparent shear rate.

To compare and to define the influence of the gap height, the scaled apparent shear rate needs to be introduced (Ulrich et al., 2010).

Using the scaled apparent shear rate, the non-proportional behavior of the ER suspension RheOil 4.0 can be defined as a function of the field strength using the existing potency law and available viscosity curves. RheOil 4.0 can be specified as a silicon oil–based ER suspension with 50 vol% polyurethane particle with an average particle diameter of 3.5 µm.

Figure 2 shows the similar behavior of the approximated flow curves. Of course, all the fluids start at the same apparent viscosity. The fluid viscosity then increases until it reaches a Newtonian plateau. In this section, the apparent viscosity maintains a constant level and thus defines the apparent intrinsic viscosity. This intrinsic effect, which is based on the gap height, can be calculated using data measured at different gap heights (h_k).

By using the experimental data, the influence of the gap height (Figure 3) on the intrinsic effect depending on the gap height can be approximated by

$$\eta_0(h_K) = 2*(\eta_\infty)^{(\beta * h_K)}$$

Thereby, η_0 defines the apparent intrinsic viscosity, η_∞ the base viscosity of the RheOil 4.0, h_k the gap height between the electrodes, and β a not more detailed fluid characterization parameter—in this case, $\beta = 7.34 \times 10^3 (1/\text{m})$.

This relationship is limited to a minimum gap height of 118 µm. Below this gap height, electric breakdowns (or flash-overs), even at very low electric field strengths, disturbed the measurement. Flash-overs were observed to occur more often at higher fluid temperatures, for example, 60°C. One explanation is that the polarizability of the particles increases with rising temperature. In addition, the peaks of the roughness profile come closer together as the gap height is lowered. Therefore, measurements have to be carried out at a minimum gap height of 118 µm or higher.

All experiments were conducted using aluminum electrodes with a polished surface and an average surface roughness below Rz 1. In the case of constant temperature, measurements collected at different gap heights clearly indicate that surface roughness has an effect on the reachable apparent viscosity. Specifically, the ratio of the height of the surface peaks to the gap height itself is of importance.

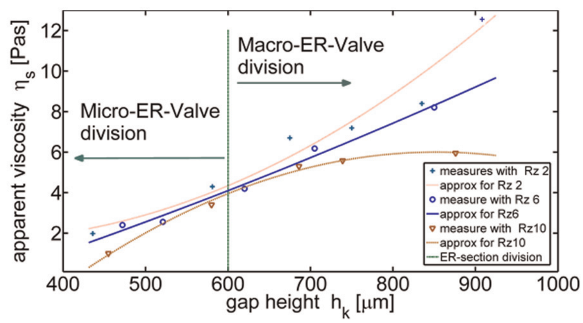

Figure 4. Apparent viscosity at different gap heights at an electric field strength of 4 kV mm^{-1}, a fluid temperature of 25°C, and a shear rate of 7000 s^{-1}.

Influence of the surface roughness

The influence of the surface roughness has been analyzed by changing the electrodes in the flow channels. The new aluminum electrodes have been manufactured with the same procedure as the polished ones. In the first step, they have been milled 100 μm thicker than they were needed. In the second step, the electrodes were clamped next to each other and polished to the precise thickness which was needed. Several different granulations of sandpaper have been used during the finishing process, such that an average surface roughness between Rz 1 and 20 μm has been obtained. The actual surface roughness was subsequently measured by a Perthometer at several points of the electrode.

A comparison of the apparent viscosity obtained under a constant electric field strength as a function of gap height clearly indicates that the surface roughness of the electrodes has a significant influence on the apparent viscosity.

The highest apparent viscosity was measured with an electrode having a surface roughness of Rz 1. The influence of the surface condition becomes more pronounced for surface roughness values between Rz 2 and 10. Figure 4 shows the apparent viscosity for three different surface roughness values as a function of the gap height.

First, at low gap heights and a surface roughness of Rz 10, the influence of the surface roughness is very striking. Especially at a gap height of 420 μm, it is not possible to generate a static measurement because of electric breakdowns. Turbulences in the flow which result from the surface roughness are the probable cause for the breakdown even at low Reynolds numbers below 2. For gap heights above 600 μm, the apparent viscosity stays at a constant level.

In contrast, the approximation curve for the apparent viscosity increases for the electrodes with a surface roughness of Rz 2. Even at very low gap heights, the reachable apparent viscosity at a surface roughness of Rz 2 is higher than that of electrodes with a surface roughness of Rz 6.

Experimental results indicate that a surface roughness of Rz 6 has little influence on fluid behavior. These previously discussed results demonstrate that the smoother the surface (e.g. beyond Rz 6), the better the performance with regard to the possible switchable pressure difference and in fact the apparent viscosity.

By focusing on the influence of the surface roughness, the shape of the curves offers the option to divide the different gap heights into a macro- and a micro-division. The micro-division can be defined until a gap height of 600 μm; gap heights above 600 μm define the macro-division of ER valves.

Summing up the influence of the surface roughness, it is obvious that in micro-ER valves the surface roughness should be smoother than Rz 6. At gap heights above 600 μm, the surface does not have a negative influence on breakdowns, but does in regard to the reachable apparent viscosity.

Against first expectations that the influence of the surface roughness stops at electrode distances above the surface peak heights, at low distances the boundary layer flow influences the ER effect between the two electrodes extremely (Qian et al., 2013).

It is important to note that our examination regarding the influence of the different surface roughnesses assumes that differences in the thickness of the boundary layer have an influence on the wall slip-effect. This should be evaluated by further research of structured electrode surfaces.

Influence of defined structures on the surface

Not only the surface roughness but also the topography of the electrodes can have an influence on the ER effect. To measure the influence of grooves in the electrodes, several electrodes with 100 μm deep grooves were manufactured. These grooves have different spacings and can be used to measure the effect in both the flow direction and perpendicular to the flow direction.

These electrodes have been manufactured using a "Kugler" micromilling machine and were measured afterward using a confocal microscope.

One of the most important points of the confocal measurements is the ability to measure the surface profile between grooves as well as at the bottom of the grooves in the electrode. The black parts seen in Figure 5 are the radii from the wall to the bottom of the groove which cannot be detected due to the reflective property of the electrode material and the measurement technique of the confocal microscope.

The influence of the grooves vertical to the flow direction is similar to that which is offered by a high surface roughness. However, these grooves generate breakdowns even at an electric field strength of only 500 V mm^{-1} at gap heights beyond 600 μm. Above

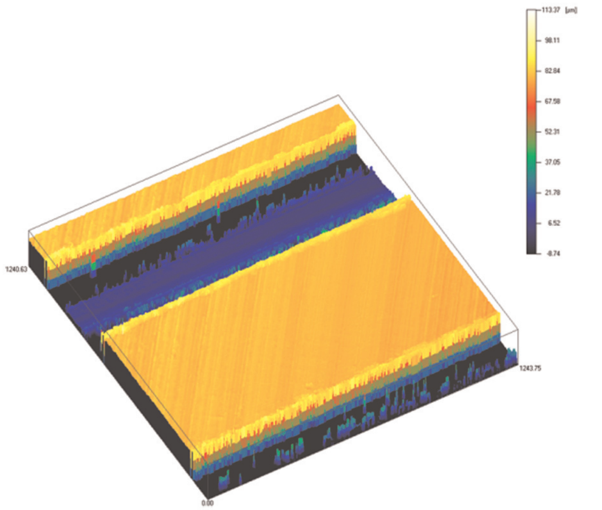

Figure 5. Confocal measurement of the structured electrode with a groove deepness of 100 μm and a groove distance of 2 mm.

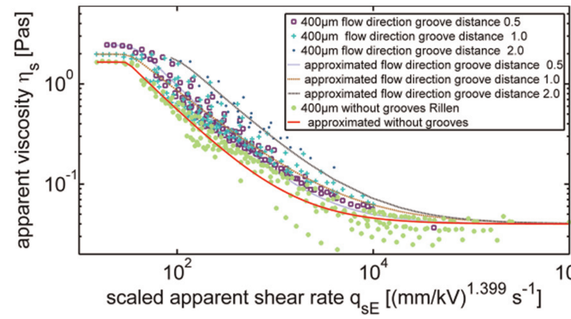

Figure 6. Influence of grooves in the flow direction at a gap height of 400 μm and a fluid temperature of 25°C, approximated with Carreau–Yasuda.

this height, the vertical grooves have little, if any, influence on the measurable apparent viscosity.

This effect is similar to the effect of grooves in the flow direction. Therefore, several measurements with different gap heights and groove distances have been performed.

Figure 6 shows the approximated curves according to Carreau–Yasuda, showing the influence of different groove distances at a gap height of 400 μm. This results in a ratio of gap height to groove distance of 2.

A very impressive fact is that grooves in the flow direction show only a deviation of 0.6%, as demonstrated by the difference in the base viscosity to the total difference in the apparent viscosity.

These results have been confirmed in several other measurements. Especially important in this case is that with an increasing ratio of gap height to groove distance, the difference between the reachable apparent viscosity with grooves and without grooves gets lower than it is at a gap height of 400 μm. For example, at a gap height of 600 μm (the maximum gap height of ER microvalves), the difference in the ratio between reachable apparent viscosity and base viscosity with and without grooves is less than 0.01%. Therefore, the orientation of structured electrodes is insignificant for the use of ER suspensions.

This effect underlines the results presented in the earlier section "Influence of the surface roughness," in which the effect of the surface roughness transitions from a positive effect on the reachable apparent viscosity for gap heights up to 600 μm to a negative influence at gap heights above 600 μm. Especially, the variation of the boundary layer thickness depending on the shear rate and the change of the boundary layer to the underlaminar layer at gap heights of 600 μm influence the ER effect.

Conclusion

All the described static measurements of apparent viscosity were done with a commercially available ER suspension called RheOil 4.0. First, an ER effect of this suspension in microfluidic systems was measured down to gap heights of 117 μm.

Second, a division of the gap heights into regions appropriate for ER microvalve and macrovalve technology was introduced. An examination of the influence of surface roughness and groove orientation indicated that the subdivision should be set at a gap height of 600 μm. Above this gap height, neither the surface roughness nor groove orientation had any appreciable influence on the observed behavior.

Below 600 μm, the influence of grooves in the flow direction can be neglected. However, the surface of the electrodes should be as smooth as possible. The optimal solution is a surface roughness better than Rz 6 for microvalves designed for the ER suspension RheOil 4.0.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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