Efforts to establish standardized methods to characterize electrorheological suspensions – An interim report focusing on flow mode characterization

S Schneider¹, K Holzmann² and S Ulrich³
¹ Bundeswehr Research Institute for Materials, Fuels and Lubricants, Institutsweg 1, 85435 Erding, Germany
² FLUDICON GmbH, Landwehrstrasse 55, 64293 Darmstadt, Germany
³ Helmut-Schmidt-Universität Hamburg - University of the German Armed Forces, Holstenhofweg 85, 22043 Hamburg, Germany

E-mail: steffenschneider@bwb.org

Abstract. Intensive research, project development, and success in industrial applications based on electrorheological (ER) technology lead to considerations to develop standardized methods to characterize ER suspensions. Some independent work was completed in earlier projects and in 2006 a working group was founded in Germany consisting of seven different partners: FLUDICON GmbH, Darmstadt, Germany; Institute for Fluid Power Drives and Controls (IFAS), RWTH Aachen University, Germany; Fraunhofer-Institut für Silicatforschung, Würzburg, Germany; NMW Neue Materialien Würzburg GmbH, Würzburg, Germany; Automation and Control Institute (ACIN), Vienna University of Technology, Austria; Bundeswehr Research Institute for Materials, Fuels and Lubricants, Erding, Germany; Helmut-Schmidt-Universität - University of the German Armed Forces, Hamburg, Germany.

In April 2011, the first part of DIN 51480 was issued addressing “Electrorheological suspensions – Requirements, testing and application – Part 1: Basics and field strength independent properties”. In the future, two additional parts are planned to be released. Part 2 will describe methods to determine field strength dependent properties under laboratory conditions. Part 3 will describe methods to determine field strength dependent properties under application-like conditions. The majority of the work has already been completed for the development of Parts 2 and 3. However, some efforts still need to be completed before these two parts can be released.

1. Introduction

Intensive research, project development, and success in industrial applications based on electrorheological (ER) technology lead to considerations to develop standardized methods to characterize ER suspensions.

Some independent work was completed in earlier projects and in 2006 a working group was founded in Germany consisting of seven different partners:

- FLUDICON GmbH, Darmstadt, Germany
- Institute for Fluid Power Drives and Controls (IFAS), RWTH Aachen University, Germany
- Fraunhofer-Institut für Silicatforschung, Würzburg, Germany
- NMW Neue Materialien Würzburg GmbH, Würzburg, Germany
- Automation and Control Institute (ACIN), Vienna University of Technology, Austria
- Bundeswehr Research Institute for Materials, Fuels and Lubricants, Erding, Germany
- Helmut-Schmidt-Universität - University of the German Armed Forces, Hamburg, Germany.

⁴ Corresponding author.
In April 2011 the first part of DIN 51480 was issued addressing “Electrorheological suspensions – Requirements, testing and application – Part 1: Basics and field strength independent properties” [1].

In the future two, additional parts are planned to be released. Part 2 will describe methods to determine field strength dependent properties under laboratory conditions. Part 3 will describe methods to determine field strength dependent properties under application-like conditions.

2. The new DIN 51480 specification

2.1. Part 1 of DIN 51480: Basics and field strength independent properties
One purpose of Part 1 is to give an introduction into ER technology. Furthermore, it gives advice on how to determine field strength independent properties using standardized and non-standardized test procedures.

The outline of Part 1 is as follows:
- Fundamentals, terms and definitions of typical properties of ER suspensions
- Determination of the dynamic base viscosity depending upon the shear rate
- Determination of the dynamic base viscosity depending upon the temperature
- Determination of the mean particle size and the particle size distribution according to DIN EN 725-5
- Determination of the density of an ER suspension according to DIN 51757 and DIN EN ISO 3838
- Determination of the relative solid content and the density of the solid particles following DIN EN ISO 3838
- Determination of the sedimentation
- Determination of the re-dispersing behaviour

2.2. Part 2 of DIN 51480: Field strength dependent properties
The purpose of Part 2 is to characterize ER suspensions with regard to their field dependent behaviour using laboratory equipment and standardized methods if available.

The outline of Part 2 is as follows:
- Determination of the shear stress at constant shear rate depending upon the electric field strength in rotational motion
- Determination of the yield stress depending upon the electric field strength in oscillatory motion
- Determination of the electric breakdown voltage following DIN EN 60156 (Figure 1)
- Determination of the relative permittivity $\varepsilon_r$, dielectric dissipation factor $\tan\delta$ and the d.c. resistivity $\rho$ following DIN EN 60247

In the current state, an attempt will be made to determine the yield stress using already approved, standardized methods. Therefore, we will try to adopt one of the following specifications:
- DIN 51810-2: Testing of lubricants – Testing rheological properties of lubricating greases – Part 2: Determination of flow point using an oscillatory rheometer with a parallel-plate measuring system.
- DIN 54458 (Draft): Structural adhesives – Determination of the flowability and application behaviour of viscoelastic adhesives using the oscillation rheometry.

If both are not applicable than it becomes necessary to develop a new test procedure capable of determining the yield stress using an oscillatory rheometer with a parallel-plate measuring system.

The electric strength of an insulator is the maximum electric field strength which the material can withstand without experiencing an electric breakdown (spark). The electric strength $E$ of an insulating material is expressed in the same unit as field strength (specified in kV/mm or V/mm). Therefore, electric strength is also referred to as breakdown field strength and is calculated by using equation 1.
\[ E = \frac{U}{l} \]  

where \( U \) is the breakdown voltage in V or kV and \( l \) is the insulator thickness in mm.

Figure 1. Determination of the electric breakdown voltage.

Figure 1 shows the test setup according to DIN EN 60156. The DIN specification requires a series of ten tests without interruption. In deviation from the specification, the ten measurements need to be carried out as single tests. Due to chain formation in each single test the material between the gap needs to be homogenized after each single test.

2.3. Part 3 of DIN 51480: Determination of field strength dependent, application-like properties

ER suspensions experience higher shear rates than obtainable with rheometer setups in dampers and other industrial applications. Depending upon the rheometer geometries for bob and rotor, shear rates are typically possible up to 2,000 s\(^{-1}\). At higher shear rates turbulent flow, like Taylor vortices, may occur. In dampers ER suspensions often experience shear rates higher than 10,000 s\(^{-1}\), a fact which led to considerations to design a hydraulic test bench. With this equipment, the field strength dependent behaviour of ER suspensions under application-like conditions could be tested.

The outline of Part 3 is as follows:
- Requirements to the hydraulic test bench (Figure 2, Figure 3).
- Measurement of field strength dependent stationary pressure differences, calculation of the dynamic base viscosity, and calculation of the field strength dependent yield stress \([4]\).
- Determination of the field strength dependent step response behaviour \([5, 6]\).

In principle, a distinction is made between the two design types of electrorheological valves, the annular gap design and the rectangular gap design. Both types will be considered in part 3 of DIN 51480. However, since all measurements described in this paper are carried out with an annular gap valve, this type is subject of further descriptions here.

A design concept for the development of cylinder drives based on electrorheological fluids was introduced by WOLFF-JESSE, FEES, and ZAUN \([2, 3]\). The design of an annular gap was used in the cylinder drives itself as well as in electrorheological valves to evaluate the rheological behaviour under laboratory conditions. Such an annular gap is shown in Figure 2 and Figure 3. It is composed of an outer electrode (cylinder of radius \( R_a \)) connected to earth and an inner electrode (cylinder of radius \( R_i \)) connected to the voltage \( U \), forming an annular gap. Since the height \( H = R_a - R_i \) of the gap is small compared to the mean radius \( R_m = (R_a + R_i) / 2 \), the ER valve can be approximated by an equivalent flat channel with the length \( L \) and the width \( W = 2R_m \pi \). The ER valve can be considered as a hydraulic throttle with a pressure difference \( \Delta p \) calculated from the pressures \( p_1 \) and \( p_2 \) before and behind the gap (equation 2).

\[ \Delta p = |p_1 - p_2| \]  

(2)
3. Determination of the field strength dependent yield stress

3.1. Assumption

The yield stress $\tau_0(E, T)$ is the lowest shear stress beyond which plastic material shows the rheological behaviour of a liquid (see DIN 1342-1). For ER suspensions, this electrorheological yield stress $\tau_0(E, T)$ depends, among others, on the electric field strength $E$ and the temperature $T$.

Under the assumptions that (i) the flow in the gap remains laminar, (ii) the fluid in the gap is incompressible and (iii) the temperature is constant, the constitutive equations of many ER fluids can be simplified to a “Bingham-like” material model (3)

$$\sigma_{12} = \tau_0(E) \text{sign}(\dot{\gamma}) + \eta \dot{\gamma} \quad \text{for} \quad \dot{\gamma} \neq 0$$

with the shear stress $\sigma_{12}$, the dynamic viscosity $\eta$, the electric field strength $E$, the field dependent yield stress $\tau_0(E)$ and the shear rate $\dot{\gamma}$.

3.2. Test procedure

The stationary pressure difference $\Delta p$ will be measured at constant volume flow $q$ under variation of the applied electric voltage $U$.

With the pressure difference $\Delta p_1$ from measurements without applied electrical field ($U = 0$ V) the dynamic base viscosity will be derived according to equation 4.
\[ \eta = \frac{W H^3 \Delta p_i}{12 L q} \]  \hspace{1cm} (4)

From the voltages \( U_i \), the corresponding field strength \( E_i \) will be calculated according to equation 1:

\[ E_i = \frac{U_i}{H} \]  \hspace{1cm} (5)

In the following steps, the pressure gradient \( P_i \) is calculated according to equation 6. Furthermore, an assistant variable \( \Phi_i \) is introduced according to equation 7. In a final step, the field dependent yield stress \( \tau_{0,i} \) is calculated according to equation 8.

\[ P_i = \frac{\Delta p_i}{L} \]  \hspace{1cm} (6)

\[ \Phi_i = \arccos \left( \frac{12 \eta q}{W P H^3} - 1 \right) \]  \hspace{1cm} (7)

\[ \tau_{0,i} = P_i H \cos \left( \frac{\Phi_i + 4\pi}{3} \right) \]  \hspace{1cm} (8)

As a result, the measurements were visualized in a diagram showing the dependence between electrical field strength and yield stress. The entire algorithm is shown in Figure 4. The complete derivation is described in [4].

\[ \text{Figure 4. Algorithm to identify the field strength dependent yield stress.} \]
3.3. Reproducibility
The acceptance of a test procedure depends on repeatability and reproducibility. The reproducibility is the difference between two single and independent results obtained by different operators working in different laboratories on identical test method. The measurements shown in Figure 5 and Figure 6 were carried out by three different operators working in the same laboratory with the same apparatus under constant operating conditions on the same ER fluid. The tests were carried out at constant volume flows \( q \) of 5 and 10 litres per minute. The geometry used was version V105 (Table 1).

The repeatability is the difference between successive results obtained by the same operator with the same apparatus under constant operating conditions on identical test material. The repeatability of test carried out by operator 2 is shown in Figure 7 and for test carried out by operator 4 in Figure 8.

These measurements are evidence that this test procedure shows an acceptable reproducibility when carried out in the same laboratory. Comparisons between other laboratories are planned but not available yet.

3.4. Influence of the volume flow
The test was carried double each at two different volume flows \( q \), 5 and 10 litres per minute, and geometry version V105. Calculating the shear rate out of the volume flow and the geometry data according to Table 1 shear rates are 13,893 and 27,785 s\(^{-1}\), respectively. The measurements were carried out by operator 2.

As one can see in Figure 7, there is an influence of the volume flow to the yield stress which can not be eliminated by the test procedure.

![Figure 5. Reproducibility between three operators at 5 L/min.](image)

![Figure 6. Reproducibility between three operators at 10 L/min.](image)

![Figure 7. Influence of the volume flow.](image)

![Figure 8. Influence of the gap geometry.](image)
3.5. Influence of the gap geometry
As there are different flow channel geometries available, it was of interest if there is also an influence by the geometries. The measures of the geometries used are listed in Table 1. The measurements were carried out by operator 4 at a constant volume flow q of 10 litres per minute.

| Geometry Version | V105 | V107 | V110 | V112 | V207 | V212 |
|------------------|------|------|------|------|------|------|
| Mean Diameter Dm [mm] / B [mm] | 40.025 | 30.05 | 40.05 | 30.02 | 30.025 | 30.02 |
| Gap Height H [mm] | 0.535 | 0.73 | 1.01 | 1.20 | 0.705 | 1.20 |
| Gap Length L [mm] | 100 | 100 | 100 | 100 | 200 | 200 |
| Gap Cross Section Area A [mm²] | 67.3 | 68.9 | 127.1 | 113.2 | 66.5 | 113.2 |
| Inner Electrode Diameter Di [mm] | 39.49 | 29.32 | 39.04 | 28.82 | 29.32 | 28.82 |
| Outer Electrode Diameter Da [mm] | 40.56 | 30.78 | 41.06 | 31.22 | 30.73 | 31.22 |
| Shear Rate @ volume flow 10 litres per minute | 4629 | 4521 | 2451 | 2752 | 4685 | 2752 |

It can be seen that the yield stress, whose calculation is described above, is also dependent on the geometry especially from the height of the channel. The simple Bingham model where the yield stress is only dependent on the electric field strength seems not to be sufficient to describe the flow behaviour of the ER suspension accurately. Other influences, like wall slip or non-Newtonian flow behaviour, have to be taken into account, which are known for these complex suspensions [7].

But a standardisation method has to be applicable for fluid investigators as well as for application engineers. Therefore, it has to be as simple as possible but reproducible and clear. For this reason it seems necessary to define the flow channel geometry and the conditions to gain the electric dependent rheological parameters of ER suspensions. The chosen geometry and conditions should be similar to typical application of ER systems.

4. Summary
Much effort was put in to develop and release Part 1 of the specification. The majority of the work has already been completed for the development of Parts 2 and 3. However, some efforts still need to be completed before these two parts can be released. Especially a standard flow channel to measure the electrical dependent rheological parameters has to be defined in Part 3.

References
[1] DIN 51480 2011 Electrorheological suspensions – Requirements, testing and application – Part 1: Basics and field strength independent properties
[2] Wolff-Jesse C and Fees G 1998 Examination of flow behaviour of electrorheological fluids in the flow mode Proc. Instrn. Mech. Engrs. vol 212 part I
[3] Zaun M 2006 Design concept for the development of electrorheological cylinder drives J. Intell. Mater. Syst. Struct 17 303-7
[4] Holzmann K 2011 Modellierung und Regelung von elektroforheologischen Dämpfern, Technical University Vienna, PhD thesis
[5] Ulrich S, Böhme G and Bruns R 2009 Measuring the response time and static rheological properties of electrorheological fluids with regard to the design of valves and their controllers Journal of Physics: Conference Series 149 012031
[6] Gurka M, Petricevic R, Schneider S, and Ulrich S 2011 Characterization of step response time and bandwidth of electrorheological fluids *J. Intell. Mater. Syst. Struct.* **22** 1745-48

[7] Schneider S 2012 Wall slip effects measuring the rheological behaviour of electrorheological (ER) suspensions *Int. J. Mod. Phys. B* **26** 1250006.