New electrorheological fluids – characteristics and implementation in industrial and mobile applications

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Abstract. Various applications for controllable dampers in the industrial and automotive sector are demanding an improved ER-Fluid, concerning performance and long time behavior. The new ER-Fluid RheOil®3.0 developed by us and presented here overcomes the main disadvantages like sedimentation and re-dispersing behavior. Besides this, better ER-performance (control ratio, current-density, step response time) could also be achieved. During tests of the response to changing temperature and long time behavior no significant degradation of the fluid or abrasive wear in the components was found over a wide temperature range.

1. Introduction

The way to control movements of mechanisms or to realize vibration damping e.g. of critical components in large structures has changed since various so-called “smart materials” became available. For mechanisms, solid state actuators like piezo-ceramics or shape memory alloys are widely used, but for shock absorption in automotive or industrial applications the hydraulic principle is preferred. For this, two kinds of smart fluid technologies emerged in the last few years, relying on the magnetorheological (MR-Fluids) and electrorheological effect (ER-Fluids) respectively. Both technologies enable the construction of controllable dampers with a relatively simple design. Different damping characteristics are realized by modifying the fluid properties rather than by adjusting complex mechanical elements. Combining a direct, dynamic (<1 ms fluid reaction time), continuous and reversible manipulation of the apparent viscosity over a large control range with favorable basic hydraulic properties, ER-fluids are well suited for such intelligent hydraulic shock absorbers.

This article describes the development and testing of a new ER-Fluid (RheOil®3.0) with improved properties concerning the ER-behavior (max. shear strength, reduced current density and improved step response time), improved sedimentation and re-dispersing behavior and a wider usable temperature range. Therefore this fluid is particularly suited for use in dampers for the automotive sector and industrial applications. Together with improved system components (amplifiers, control algorithms and an advanced valve-design) the new ER-fluid was successfully implemented in standardized damper systems for industry and health-care [1] as well as a semi-active suspension system for off-road vehicles [2].
2. Experimental Results and discussion

2.1. Synthesis of ER Fluids and testing apparatus

The development was driven by the needs of industrial applications. For that, the ER-fluid of choice has to be based on LiCl or ZnCl$_2$ doped Polyurethane particles (PUR) dispersed in silicone-oil as base fluid. This type of ER-Fluid exhibits some outstanding properties: good ER-Properties, non abrasive behavior, low base-viscosity. It can be synthesized in a scalable process from standard raw-materials. The work, namely the optimization of polymer-composition and processing parameters, resulting in optimal particle morphology was carried out on a lab-scale production plant with the possibility to keep all relevant processing parameters under well-controlled conditions. Progress was checked with standard laboratory equipment as well as custom-made test rigs for measurement of ER-fluid-properties or testing the whole system. Part of the testing procedures is summarized in an industrial test-standard [3], some more data on the ERF-properties can be found in [4].

ER-specific tests were carried out on a custom-made test rig in flow-mode. Measurements were done under constant flow rate of 10000 s$^{-1}$ and defined temperatures in the range between 25°C and +80°C. The ER-behavior was recorded by two pressure sensors before (inlet) and behind (outlet) a cylindrical ER-valve with an electrode diameter of 40 mm, a length of 100 mm and a valve height of 0.5 mm. The electric field was applied via a voltage amplifier RheCon2 from FLUDICON, with a step response time of 0.3 ms, which was quite below the sampling rate of 1kS/s per channel of the recording system. The mean temperature of the fluid was determined from sensors at the in- and outlet of the ER valve.

Other rheological measurements were carried out with a commercially available Rheometer MCR300 from Anton Paar with a double gap cylinder (DG26.7) for base viscosity measurements and a cylindrical high voltage cylinder (CC17) for the shear behavior under electrical field influence. These rheometric measurements, used for characterization of the long term behavior under elevated temperatures were carried out in the lower shear rate range between 0…450 s$^{-1}$ under oscillating shear-mode in contrary to the measurements in flow-mode.

Re-dispersing measurements were carried out on the samples from the sedimentation tests (settling time 8 weeks). The remixing was done by a vortex-shaker (Type VV3, VWR International) which homogenizes the sample by circular motions of the glass tube. The remixing behavior was determined by the time needed for full homogenization while the vortex-shaker was set to a constant value.

2.2. Test results

2.2.1. Sedimentation / Re-dispersing: RheOil®3.0 shows improved sedimentation stability compared to the former commercially available ER-Fluid Rhe Oil®2.0 (also known as Rheobay 3566 developed by Bayer AG [5], [6], [7]) (Figure 1). More relevant for most applications is the re-dispersing behavior which could be improved by a factor of 25 for the new ERF. Compared to RheOil®2.0 the expended energy necessary for re-homogenization after settlement is a factor of 25 less for RheOil®3.0 which practically means that settlement becomes less critical for applications where fast access to the full performance of the damper is necessary even after a long term stand-by.

2.2.2. Improved ER-performance: Unique properties are constantly high shear stress of about 4000 Pa across a wide temperature range between 20°C and 80°C (Figure 2). Towards higher temperatures the current density increases starting at a very low level (Figure 2). Thus for an average operating temperature of 60°C the mean current density is in the range of 25 μA/cm$^2$, a factor of four less than for RheOil®2.0. The control ratio $(\sigma-\sigma_0)/\sigma_0$ is in the range of 18 (60°C, 10000 s$^{-1}$, 5 kV/mm) and can be increased to 25 (at 6 kV/mm). The field dependence of the shear force and current density can be approximated by a simple polynomial of the third degree (Figure 3). The higher standard deviation for the current density compared to the shear stress is due to the lower signal/noise ratio of the current monitor compared to the pressure signal.
Figure 1. Sedimentation behavior of RheOil® 2.0 and RheOil® 3.0. Starting point was 100%. The new ERF shows a 15% slower settlement.

Figure 2. Mean shear stress vs. temperature (left) and current density vs. temperature (right) for RheOil® 3.0 in flow-mode under applied high voltage (E = 5 kV/mm) and for voltage turned off (E = 0). Applied shear rate: 10000 s⁻¹.

Figure 4 shows an example of a shear stress step response in flow mode for a shear rate 10000 s⁻¹ at 60°C after a field step from zero to 5kV/mm. Within the first millisecond, 90% of the equilibrium shear stress (3700 Pa) is reached.

Figure 3. Mean shear stress vs. electric field strength (left) and mean current density vs. electric field strength (right) for RheOil® 3.0 in flow-mode at a temperature of 60°C. Applied shear rate: 10000 s⁻¹.

2.2.3. An extended usable temperature range of RheOil®3.0 was proved in a range between -40°C and 120°C. Within the whole range the performance with regard to shear forces and current were evaluated.
It has been observed that the ER-effect decreases rapidly between 5°C and -5°C and approaches the base viscosity caused shear stress slope asymptotically at the polymers glassy point of -17°C. The base viscosity at this temperature approaches 200 mPas increasing to 500 mPas towards -40°C.

**Figure 4.** Step response of the shear force after E-field step from 0 to 5 kV/mm. (T= 60°C; shear rate 10000 s⁻¹). The Flow-Rate Q remains constant at about 3.2 l/min due to the large pump of the system.

From DSC/TG measurements fluid decomposition was observed to be relevant above 140°C. The fluid performance does not suffer after a short term (< 2 h) temperature cure in air at 120°C. Regarding the long term stability of the ERF under elevated temperatures the ER-response of the ERF on a cure at various temperatures and time is shown in Figure 5.

**Figure 5.** Response of the ER-shear force, measured by a Rheometer in shear-mode after curing the ERF at elevated temperatures (60, 80 100, and 120 °C) for up to 1000 h. The view-graph shows the ER-shear stress at shear rates of 150 s⁻¹ and electric field strength of 5 kV/mm at 40°C cell temperature after a long term cure under air at above mentioned temperatures.

After a long term cure at 60°C no degradation was observed at all. The performance improved yet. For a long term temperature stress at 80°C the performance seems to change only slightly with time. Tempering at 100°C, however, leads to a measureable degradation of the shear stress as a function of time. The performance drop after 100 h at 100°C falls below 50 %. After a four hour cure at 120°C the ER-performance reveals a degradation of only 40 %.

In comparison, flow mode data measured under conditions comparable to Figure 2 suggest a degradation of about 10 - 15 % for the equally cured sample (Figure 6). The difference can be attributed to the different measuring conditions. Thus the above shown shear mode results give an upper range estimation for the thermal load capacity rather than an absolute behavior for a special application. Therefore, the MCR300 data might not be representative for the ER fluid under real application conditions, since neither air contact is expected nor a pure shear stress applies in common applications.
Figure 6. The graph shows shear stress measurements vs. operating temperature measured in the flow mode test rig under application relevant conditions.

The degradation of the ERF sample after a four hour cure at 120°C is in the range of 10-15 %. In contrast to the MCR 300, the flow mode test rig operates with larger fluid volume (> 2000 ccm) and at larger shear rates (10000 s⁻¹).

2.3. Testing in Applications

The new RheOil®3.0 was successfully tested in various applications. For industrial applications the ER-Fluid succeeded various performance and long-term tests in the now commercially available damper series RheDamp, where a total damping energy of up to $1.7 \times 10^7$ J was dissipated in about 200 ml of ER-fluid. Remarkably, neither the fluid nor the sealing of the damper was affected during the whole test with a total stroke of about 40 km, which can be awarded to the excellent non-abrasive behaviour of the Polyurethane-based ERF. For automotive applications RheOil®3.0 was successfully tested in a semi-active suspension system for a military off-road vehicle. The excellent response time and very low power consumption allowed for an outstanding field-test performance.

3. Conclusion

The new ER-Fluid RheOil®3.0 exhibits major advantages over former existing ER-Fluids or other controllable fluids. In laboratory measurements and practical testing under field-test conditions, advantages for the practical use could be proved: outstanding sedimentation and re-dispersing behaviour, improved ER-performance – short response time (< 1 ms), large control ratio (up to 25), low base viscosity (70 mPas@25°C) and current density, broad working temperature range (-20…+120°C) – and non-abrasive behaviour.

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