Temperature induced effects on the durability of MR fluids

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Abstract. Although commercial MR fluids exist for quite some time now and the feasibility as well as the advantages of the MR technology have been demonstrated for several applications by a variety of MR actuator prototypes, a sustainable market break-through of brake and clutch applications utilizing the shear mode is still missing. Essential impediments are the marginal knowledge about the durability of the MR technology. To overcome this situation, a long-term measurement system was developed for the durability analysis of MR fluid formulations within a technical relevant scale with respect to the volume of MR fluid and the transmitted torque. The focus of the presented series of measurements is given to the analysis of temperature induced effects on the durability. In this context four different failure indicators can be distinguished, namely an apparent negative viscosity, deviations in torque data obtained from different measurements as well as a pressure increase and a drop in the on-state torque. The measurement data of the present durability experiments indicate a significant dependency of the attainable energy intake density on the temperature. The aim of such durability tests is to establish a reliable data base for the industry to estimate the life-time of MR devices.

1. Introduction
The measurement of the durability is complex and often takes long periods of time. This situation becomes even more difficult, as the wear behavior of MR fluids has been rarely investigated so far, especially for the shear mode utilized in clutches and brakes. Durability tests have been performed with an MR clutch utilized as fan drive for trucks, [1]. Subsequently, the MR fluid was extracted from the MR fan drive after the durability test and analyzed in detail afterwards. The organics analysis [2] showed a degradation of the poly-alpha-olefin based fluid. Iron oxidation was also detected [3], which most likely caused the decrease of the MR effect during the durability test. The degradation of the base oil, in combination with an increasing pressure and a continuously decreased on-state torque, and in-use-thickening (IUT) [4] are important effects that were observed in some MR fluid formulation tests [5]. Lifetime dissipated energies (LDE) [4] of up to 5 MJ/mL were also achieved with optimized high shear stress MR fluid formulations for clutch and brake applications [6] using a rheometer-sized test cell.

To overcome this situation, a long-term measurement system was developed, which is suitable to analyze the durability of different MR fluid formulations within a technical relevant scale with respect to the volume of MR fluid and the transmitted torque. This system was initially presented in [7] and therefore only a brief description is given in section 2. Previous measurements with the commercial

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MR fluid Basonetic® 5030 from BASF SE showed basic effects on the durability of MR fluids: A variation of the load cycle profile from constant to a square wave shaped power dissipation yielded no effects on the durability. This indicates that the life time dissipated energy (LDE) determined by the proposed durability tests can be extrapolated to real life MR brakes. Further measurements indicate a significant effect of the dissipated power per volume on the LDE, which decreases in the case of an increasing dissipated power resulting from increasing rotational speed and constant braking torque.

In the present contribution, the focus of a new series of measurements is given to the analysis of temperature induced effects on the durability. Life cycle test were performed by varying temperatures in the range from 20°C to 80°C, each with duration of several weeks. The potential thermal expansion of the MR fluid has to be taken into account when changing the temperature in a higher range. The analysis of the thermal expansion of the MR fluid is described in section 3 and the accordingly modified measurement process is presented in section 4. The experimental results of the new series of experiments are discussed in section 5.

2. Experimental

2.1. Long-term measurement system

The utilized torque test bench is equipped with a specially developed MR actuator for continuous loads (continuous load actuator, CLA) [7]. For this purpose, a cylindrical, horizontally oriented double shear gap (drum type) design was chosen to avoid the mass force induced phenomena of centrifugation and sedimentation (Figure 1). Homogenous shear conditions throughout the shear gap are an additional advantage of this design, which improves the transferability of the results. An easy and reproducible extraction of the MR fluid after the experiment is considered, which ensures a quick disassembling of the CLA and an easy cleaning of the shear gaps.

The lifetime of MR devices is affected by both, the durability of the MR fluid and in particular by the wear resistance of the utilized seals. Increased leakage due to worn seals almost inevitably causes a breakdown of MR devices. Thus, the choice of the seal type was one of the main aspects in the design phase of the CLA. Different kinds of seals were evaluated in extensive durability experiments described in [7]. The finally chosen combination of a spring steel seal and a RSS combines a good sealing capacity with comparably low friction and cost.

The influencing quantities temperature, rotational speed, and excitation current of the CLA are controlled in a closed-loop. The measured quantity is the torque generated by the CLA. Additionally, the pressure in the area of the outer seal can be assessed. A half section schematic of the CLA and the system structure of the long-term measurement system are shown in figure 1.

Figure 1. (a) Half section schematic of the Continuous Load Actuator (CLA), (b) detail view of the shear gap, and (c) system structure of the long-term measurement system [7].
2.2. Thermal expansion of MR fluids

In contrast to the previous experiments published in [7], the present series deals with the effect of the temperature on the LDE. Therefore greater changes in the MR fluid’s temperature occur especially during the preparation phase of the durability experiment. The effect of the MR fluid’s thermal expansion was analyzed in a preliminary study. In general, the density of the MR fluid is reduced by a temperature rise due to the thermal expansion effect. A free volume of MR fluid, which is not limited by external boundaries, would grow. The cubic expansion coefficient $\beta$ is the relation between the volume expansion and the change in the temperature, e.g. [8]. The change in volume $\Delta V$ due to the change in temperature $\Delta T$ is calculated usually assuming a constant cubic expansion coefficient $\beta$, which is independent from the temperature. In the case of chemical mixtures, the expansion coefficient is not independent from the volume, which leads to the following expression:

$$\Delta T \approx \frac{1}{\beta_{\text{cf}}} \int_{V_{0}}^{V_{0} + \Delta V} \frac{1}{V} \, dV \rightarrow \Delta V = V_{0} \left[ \exp\left( \beta_{\text{cf}} \cdot \Delta T \right) - 1 \right] \approx V_{0} \cdot \beta_{\text{cf}} \cdot \Delta T \tag{1}$$

For suspensions like MR fluids, the volumes of the single phases can be treated separately. Considering the values given in Table 1, it becomes obvious that the expansion $\beta_{\text{Fe}}$ of the iron particles can be neglected compared with the carrier fluid $\beta_{\text{cf}}$. For small changes in temperature a linear approximation can be found, which leads to an expression easy to handle. In the relevant range of temperature the approximation error is small in relation to the assumptions already made.

$$\Delta T \approx \frac{1}{\beta_{\text{cf}}} \frac{V_{0} + \Delta V}{V_{0}} \int_{V_{0}}^{V_{0} + \Delta V} \frac{1}{V} \, dV \rightarrow \Delta V = V_{0} \left[ \exp\left( \beta_{\text{cf}} \cdot \Delta T \right) - 1 \right] \approx V_{0} \cdot \beta_{\text{cf}} \cdot \Delta T \tag{2}$$

Since the shear gaps of the CLA have to be treated as a confined volume the expansion of the MR fluid volume is impossible. An increase in the temperature leads to an increase in the pressure of the MR fluid instead. This pressure increase is related to the compressibility of the MR fluid. Based on the definition of the compressibility factor (e.g. [8]) a simple expression for the pressure change $\Delta p$ can be found in a comparable way as used for equation 2. The compressibility of the iron $\kappa_{\text{Fe}}$ can be neglected, in this case too.

$$\kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_{T=\text{const.}} \rightarrow \Delta p \approx \frac{\Delta V}{\kappa_{\text{cf}} \cdot V_{0}} \tag{3}$$

The expression for the temperature induced pressure increase can be obtained from equations 2 and 3 substituting the change in volume $\Delta V$.

$$\Delta p \approx \frac{\beta_{\text{cf}}}{\kappa_{\text{cf}}} \cdot \Delta T \tag{4}$$

Using the values given in Table 1 and assuming a temperature increase of 80 K leads to a change in volume of approximately 9% based on equation 2 and a theoretical pressure increase of 900 bar (13e3 psi) using equation 4. This theoretical pressure value cannot be observed in reality due to the seals’ elasticity and leakage occurring inevitably. But it shows that the thermal expansion of an MR fluid cannot be neglected when changing the temperature in such a range. A measurement is shown in figure 2 indicating the pressure increase due to the thermal expansion of the MR fluid.
Figure 2. Measurement data indicating the pressure increase due to thermal expansion. The measured pressure is significantly smaller than the theoretical estimated value by equation 4. This deviation occurs due to the elasticity of the seals and leakage. The pressure drops occurring in the phases of a constant temperature are caused by leakage, too. Both effects are contrary with the assumption of a confined volume initially stated for equation 4.

| Parameter       | Symbol | Unit        | Iron (Fe) | Cyclohexane (C_{10}H_{12}) |
|-----------------|--------|-------------|-----------|-----------------------------|
| thermal expansion | $\beta$ | °C$^{-1}$   | 35.4e-6   | 1.15e-3                     |
| compressibility  | $\kappa$ | Pa$^{-1}$   | 16e-12    | 1.13e-9                     |
| typical for      | -      | particles   | -         | carrier fluid               |
| assumed volume fraction | $V$ | %           | 50        | 50                          |

2.3. Modified measurement process for the examination of the temperature effect
The aim of the utilized testing process is the durability analysis of MR fluids by ensuring reproducible conditions, while the whole characteristic is observed in relation to the influencing quantities. The measurement process described in [7] was modified to regard the thermal expansion of the MR fluid when investigating the temperature effect on the durability.

At the preparation and the start of a durability experiment disturbing influences resulting from the assembly and filling process, from the bedding-in of the seals, and from the thermal expansion should be minimized. A flow chart of the modified measurement process is shown in figure 3. The parameters used for the present series of experiments are stated in table 2.

Figure 3. Modified measurement process.
The modified measurement process can be divided into three phases. The aim of the initial phase is to guarantee consistent conditions for each experiment. At the beginning, an initial characterization is performed by measuring the torque in relation to the current (On-State) and the rotational speed (Off-State). All characterizations are performed following the same principle: At first the off-state torque behavior is measured by changing the rotational speed and maintaining a current of 0 A and second the on-state torque behavior is measured by changing the current and maintaining a constant rotational speed. All characterizations during the experiments are performed with the same set of parameters except for the temperature, which is 20°C during the initialization phase. In the main phase, the characterizations are performed at the temperature defined by the load case.

Table 2. Parameters utilized for the examination of the temperature effect on the durability of MR fluids.

| Sub-procedure                  | Parameter | Value  | Unit | Comment                        |
|-------------------------------|-----------|--------|------|--------------------------------|
| Characterization              | Current $I$ | 0      | A    |                                 |
| Characterization - Off-State  | Speed $n$ | 10 : 20 : 70 | rpm  | Min. : Inc. : Max.            |
|                               | Temperature $\vartheta$ | 20 / Load Cycle | °C    | Initialization Phase / Main Phase |
| Characterization              | Current $I$ | 0 : 0.25 : 2 | A    | Min. : Inc. : Max.            |
| Characterization - On-State   | Speed $n$ | 5 rpm    |      |                                 |
|                               | Temperature $\vartheta$ | 20 / Load Cycle | °C    | Initialization Phase / Main Phase |
| Bedding-In Seals              | Current $I$ | 0 A     |      |                                 |
|                               | Speed $n$ | 40 rpm   |      |                                 |
|                               | Temperature $\vartheta$ | 20 °C   | |                                 |
| Change Temperature to Load Case | Current $I$ | 0 A     |      |                                 |
|                               | Speed $n$ | 5 rpm    |      |                                 |
|                               | Initial Temperature $\vartheta$ | 20 °C   | |                                 |
|                               | Final Temperature $\vartheta$ | Load Cycle | °C  |                                 |
|                               | Change Rate | 10 °C / h | |                                 |
| Load Cycle                    | Current $I$ | 0.7 A   |      |                                 |
|                               | Speed $n$ | 15 rpm   |      |                                 |
|                               | Temperature $\vartheta$ | 20 / 40 / 60 / 80 °C | present series of experiments |
|                               | Load Profile | Constant | |                                 |
|                               | max. Duration | 16 h    | |                                 |

The data of the unstressed MR fluid obtained during the first characterization can be utilized for the estimation of variations, which can result from the assembly and filling process. The bedding-in of the seal contact surfaces is performed afterwards. The parameters were chosen to enable a quick bedding-in and to minimize the load of the MR fluid. The seals do not provide the full sealing capacity before the sealing surfaces are bedded-in. Because of the higher viscosity of the carrier liquid the bedding-in is performed at room temperature to minimize leakage. After the seals’ bedding-in, a
second characterization is performed. Afterwards, the temperature is changed according to the load case maintaining a defined change rate to prevent high temperature gradients and resulting thermal stresses within the CLA. During this phase a volume compensation of the shear gaps is established to prevent a pressure increase and leakage by thermal expansion (section 3). The change to the temperature defined by the load case typically takes several hours. To prevent the sedimentation of the particles the rotor of the CLA is moved at a low rational speed. When the desired temperature is achieved the volume compensation is disabled so that the shear gaps are nearly a confined volume and the pressure increase due to the chemical degradation of the MR fluid becomes measureable.

In the first step of the main experimental phase a further characterization of the torque behavior in the on- and off-state is performed. A load cycle is started afterwards causing defined wear of the MR fluid. During this load cycle, a pre-defined workload profile is repeated (Table 2) and the time behavior of the torque and the influencing quantities is recorded until a desired energy intake or period of time is achieved. An additional characterization of the on- and off-state behavior is performed after every load cycle. This alternating procedure is repeated until the overall energy intake (LDE) is reached, indicated by an improper change of the MR fluid characteristics. A final performance characterization is carried out in the end. In the post-processing phase the temperature of the CLA is changed to 20°C maintaining a defined change rate prior to the extraction of the MR fluid. For the calculation of the energy intake density $w$ during the data post-processing phase the time integral of the power dissipation per volume is calculated, [7]:

$$w(t) = \int_0^t \tau(t) \cdot \gamma(t) \cdot dt = \frac{2 \cdot \pi}{60 \cdot \nu_{MRF}} \int_0^t (T_m - T_p) \cdot n \cdot dt$$

(5)

The measured torque $T_m$ must be corrected by the parasitic torques $T_p$, which mainly result from the seals and can be estimated based on the characterization data. Further quantities are the volume of the shear gaps $V_{MRF}$ and the rotational speed $n$.

3. Results and discussion

The objective of the presented experiments was the examination of the temperature effect on the durability of MR Fluids. The measurement process (figure 3, table 2) was used for all experiments presented in this section.

3.1. Results of a single experiment

At first, the measurement data of a single, exemplary experiment are described in detail. Already in the initialization phase, measurement results are obtained. The torque behavior over time shown in figure 4(a) represents the bedding-in process of the seals. The measured torque decreases while the surfaces of the seal point contact are adapting on each other. Afterwards the torque remains constant at a low level. The seal’s bedding-in has a potential effect on the torque behavior of the CLA. So the on- and off-state torque was characterized before and after the bedding-in process showing the effect of the seals’ bedding-in. The torque behavior remains stable apart from the seals’ friction, which is reduced by the bedding-in. After bedding-in, the torque behavior in the off-state shows a clear viscous component superimposed by coulomb friction. The torque behavior regarding to the current shows a quite linear relation. The MR effect, which can be defined as the relation of the maximum to the minimum torque of an MR actuator, is remarkably enhanced by the low off-state friction of the utilized RSS-Nilos seal system [7].

The main phase is the essential part of the durability experiment, which is following the initialization phase. The torque data obtained during the load cycles and the on-state characterizations (by variation of the current) is compared in figure 5. The decrease in torque after reaching a certain energy intake density is caused by leakage of the MR fluid (particles and carrier liquid). This drop in the on-state torque is a distinct failure indicator preventing further proper operation of an MR device and hence of reaching the LDE. Before the drop in the on-state torque begins, a slight difference
between the torque obtained during the load cycle and the characterizations can be observed. This indicating effect is caused by the MR fluid partly solidifying in the shear gap over time during the load cycle and the subsequent homogenization by mixing during the characterizations. “Solidifying” in this context is used for certain fluid volumes that suffer a loss of base fluid, that show strongly increased viscosity. Such an ambiguous behavior is undesirable for MR actuators and occurs only after a certain energy intake. Therefore, the deviation in the torque data can be used as an early indicator of reaching the LDE of the MR fluid.

The formation of solidifying structures of the MR fluid leads to a further effect. The torque curves of the off-state characterizations obtained at different rotational speeds are crossing. This suggests that an apparent negative viscosity – assuming a Newtonian flow behavior of the MR fluid in off-state mode – occurs. In fact, however, the solidified structure of the MR fluid was destroyed between the first measurement at the lower velocity and the second at the higher velocity by simple remixing. The apparent negative viscosity is a further early indicator.

An abrupt rise in the off-state torque occurs at a higher energy intake density, which is caused by the pressure increase also shown in figure 5. The pressure increase indicates the chemical degradation of the carrier fluid. Gases resulting from the degradation reaction can be the reason for the pressure increase. The abrupt change in pressure at approximately 3 MJ/mL is resulting from MR particles blocking the channel of the pressure sensor firstly and then suddenly breaking. Probably the pressure increase has begun earlier at approximately 2 MJ/mL. This increase in pressure leads to a larger contact pressing force of the seals and thus to a higher friction. From that point on typically a leakage of the MR fluid (particles and carrier fluid) can be observed. The leakage of the MR fluid is most often indicated by the drop in the on-state torque as stated before. Improving the seal capacity to minimize...
the leakage due to the pressure increase caused by a chemical degradation would result in a high seal friction, which would deteriorate the torque quality of an MR actuator in a not acceptable range.

In conclusion the following indicators of the degradation of the MF fluid can be stated:
- apparent negative viscosity (if our specific method of assessment is used)
- deviation in torque data obtained from different measurements
- pressure increase caused by a chemical degradation of the carrier fluid
- drop in the on-state torque

3.2. Temperature effect on the lifetime dissipated energy
Experiments with different temperatures are performed to investigate the effect on the durability of the MR fluid. The data of the bedding-in procedure as well as of the first main phase characterization are depicted in figure 6. The comparison of the different experiments does not result in significant differences. Varying the rotational speed the off-state torque shows only the typical temperature dependency of the viscosity. The data depicted in figure 6 show that there were equal conditions at the start of the main phase for all conducted experiments.

The data obtained during the main phases of the several experiments are presented in figure 7. In all the experiments a similar behavior of the MR fluid is observed, but the failure indicators appear at different energy intake densities regarding to the temperature. The mentioned effects on the durability are indicated by the measured torque $T_m$ and pressure $p$ obtained during the load cycles, as well as the MR torque $T_{mr}$ and the parasitic torque $T_p$, which are calculated based on the characterization data.

The attainable LDE is decreasing in the case of an increasing temperature from 20°C to 60°C. Thus, an increased degradation of the MR fluid is caused at a higher temperature. The increase in the
LDE when changing the temperature from 60°C to 80°C is remarkable, which could be reproduced for several times. A fluctuation of the measurement thus appears implausible. The reason has to be clarified within further studies in detail. Reasons could be different degradation reactions at this temperatures as well as the temperature behavior of the used surfactants.

The characterizations were performed at a representative speed $n$ according to table 2. Every durability experiment presented in this section took several weeks. The torques was calculated as follows [7]:

\[ T_p = T_m (i) \mid_{i=0} \]  \hspace{1cm} (6)

\[ T_{mr}(i) = T_m (i) - T_p \]  \hspace{1cm} (7)

In figure 8 the energy intake densities are compared at which the failure indicators (see subsection 5.1) occur. The dependency of the attainable energy intake density on the temperature becomes obvious with this depiction, too. The early indicators apparent negative viscosity and deviation in torque data occur portending the solidification of the MR fluid before a significant drop in the on-state torque states the final failure. Besides this, a pressure increase results due to the chemical degradation of the MR fluid.
4. Conclusions
The aim of this contribution was the investigation of the temperature effect on the durability of MR fluids to enable engineers to calculate the lifetime of MR devices from the scratch. An essential aspect for temperature durability experiments is the consideration of the thermal expansion of the MR fluid. The existing measurement process was modified accordingly. It can be divided into three phases: Initialization, main and post-processing phase.

When investigating the durability, four indicators of an occurring failure can be distinguished, namely an apparent negative viscosity, the deviation in torque data from different measurements, a
pressure increase within the confined shear gaps and a drop in the on-state torque caused by leakage of the MR fluid. The deviation in torque data and the apparent negative viscosity are caused by a solidification of the MR fluid during the load cycle. Both can be used as early indicators of the degradation of the MR fluid as well as the pressure increase.

Durability experiments were performed by varying temperatures in the range from 20°C to 80°C, each with a duration of several weeks. The measurement data of the durability experiments indicate a significant dependency of the attainable energy intake density on the temperature. Lifetime dissipated energy decreases with increasing operating temperature. Thus, an increased degradation of the MR fluid is caused at a higher temperature. The increase in the attainable energy intake density when changing the temperature from 60°C to 80°C is remarkable. Its cause has to be clarified within further studies in detail.

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