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HIGH PRESSURE CAPABILITIES OF SLENDER SQUEEZE GAPS OF MAGNETO-RHEOLOGICAL FLUIDS

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Abstract

In the last decade ample of academic and industrial research work in the area of magneto-rheological fluids (MRF's) has been done. Most of the concepts and products developed in this time period (e.g. MRF brakes and clutches) feature a shear mode operation. Hence a majority of the published work is addressing this mode. Nevertheless, the MRF squeeze mode becomes more and more attractive (for damping applications for instance) due to its higher reachable force densities compared to the other modes. In this paper attainable MRF squeeze mode pressures for very small squeeze gaps are experimentally investigated. For squeeze gaps down to few hundredth of a millimetre the mean squeeze pressure reaches nearly 100bar. On the other hand, especially in the squeeze mode, the problem of MRF segregation occurs. In this work three different methods to avoid or to reduce this phenomenon are experimentally tested and discussed. Finally, a simplified analytical relation for the MRF squeeze mode pressure characteristics is presented and compared to experiments. This comparison shows that the analytical model predicts the MRF squeeze pressures with a satisfactory accuracy such that it can be used for dimensioning purposes.

Keywords: magneto-rheological fluid (MRF), squeeze mode, segregation effect, load carrying capacity, analytical model, squeeze flow paradox

1 Introduction

Magneto-rheological fluids are mixtures of a carrier fluid and embedded micron sized ferromagnetic particles and can change their material properties by an applied magnetic field. In the absence of a magnetic field they constitute a Newtonian fluid but they become an elasto-plastic material if exposed to a magnetic field. The yield stress depends monotonically on the magnetic flux density. In case of a well mixed and homogenous MRF the response of the material behaviour to a changing field is nearly immediate and mainly limited by the dynamical properties of the magnetic circuit that generates the magnetic field. The segregation phenomenon is a separate process that follows different time scales.

The immediate response and the absence of any moving mechanical parts stimulate the application of MRF's in various fields. Currently, the main practical application area of MRF's is car industry for dampers (Sassi et al., 2005; Dogruer et al., 2008; Zschunke, 2005; Lange, 2004) or for clutches and brakes (Huang et al., 2005; Park et al., 2006; Karakoc et al., 2008; Kavlicoglu et al., 2002; Benetti and Dragoni, 2006).

In most realized as well as proposed practical applications the so called shear mode is exploited in which the MRF is generating shear forces in a shear gap between two bodies with a relative motion parallel to this gap. This mode is quite well understood and technically matured. In the valve mode the MRF passes a narrow channel in which a transversal magnetic field adjusts the pressure drop. In combination with a cylinder, a dissipative linear force can be generated. The current and practical by far least important operation mode is the squeeze mode where MRF is placed between narrowing plates and generates a magnetically controllable force opposing the plate motion.

In several papers the authors' working group has dealt theoretically and experimentally with the MRF squeeze mode and has proposed novel applications (Gstöttenbauer et al., 2004; Gstöttenbauer et al., 2005; Gstöttenbauer, 2007; Resch and Scheidl, 2009). Its main advantages are the large pressures that can be achieved and the small amount of needed MRF. These are contrasted by a high complexity and nonlinearity of

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the MRF material behaviour in the squeeze mode in relation to the shear mode.

The adaptive MRF bearing proposed in Gstöttenbauer et al. (2007) and investigated in Gstöttenbauer (2007) and Gstöttenbauer et al. (2006) has been seriously evaluated for applications in metal rolling technology. The intended application was the control of the line pressure at the edges of the rolls for which the currently used actuation principles in rolling technology do not offer sufficient control capability. The requirement characteristics for this special actuation function favour in principle the squeeze mode since very high forces (line loads in the order of 5 kN/mm) and very small displacements (order of 50 μm) are required. In the course of a quantitative feasibility study of an application of the adaptive MRF bearing a main question was what squeeze pressures can be produced for extremely narrow squeeze gaps with gap to width ratios < 10^{-2}. To the best knowledge of the authors no experimental results for such extreme gap proportions have been published so far.

A second question related to this is if the danger of a separation of the carrier fluid from the particles can be avoided by proper measures. This so called segregation effect leads to a loss of controllability of the MRF and has been observed in several experiments (Gstöttenbauer, 2007; Resch and Scheidl, 2009; Tang et al., 1997; Lopez-Lopez et al., 2006; Farjoud et al., 2009; Ciocanel et al., 2006). It is explained by a squeezing out of mainly carrier fluid if a magnetic field is present but a refilling with fluid and more particles during gap widening. This gradually enriches the gap with particles at a loss of fluid share. In this way the MRF is drying-out and adopts increasingly granular media material properties.

In a series of experiments, answers to the following two questions have been sought:

- which squeeze pressures can be achieved and
- how can the segregation effect be avoided

In this paper these experiments are reported and rules for the dimensioning are presented. The experimental facility is presented in the next section. Section 3 reports about the experimental procedures and the experimental results. Additionally, proposals to achieve a remixing of the MRF are presented. Section 4 deals with an analytical study of a MRF in squeeze mode and compares it to the measurements.

2 Test Rig and Procedure of Squeeze Mode Tests

The basic structure of the MRF squeeze test rig is shown in Fig. 1. The bottom plate of a squeeze pot and a die (ø25mm) form the squeeze gap (size 0-3mm). A hydraulic cylinder attached to the die generates the closing and opening motion. The squeeze force is measured via a quartz force link on the rear side of the squeeze pot. A direct MRF gap distance measurement hardly can be realized due to the MRF surrounding. Therefore, a double rod cylinder is used and the gap distance is measured indirectly on the opposite piston rod side via an eddy current position sensor. Such a sensor seems to be appropriate because of the hands-on experience of the authors' working group using this sensor at similar experiments (Resch and Scheidl, 2008; Resch and Scheidl, 2009). Likewise, a direct measurement of the magnetic flux density in the MRF zone (e.g. via a hall-effect-sensor) is impracticable due to the significant mechanical load acting on the sensor device in case of squeezing. Hence, the magnetic flux density in the squeeze area is calculated from the magnetic force instead measuring the flux density. In chapter 3.1 the calculation procedure of the magnetic flux density is explained in detail.

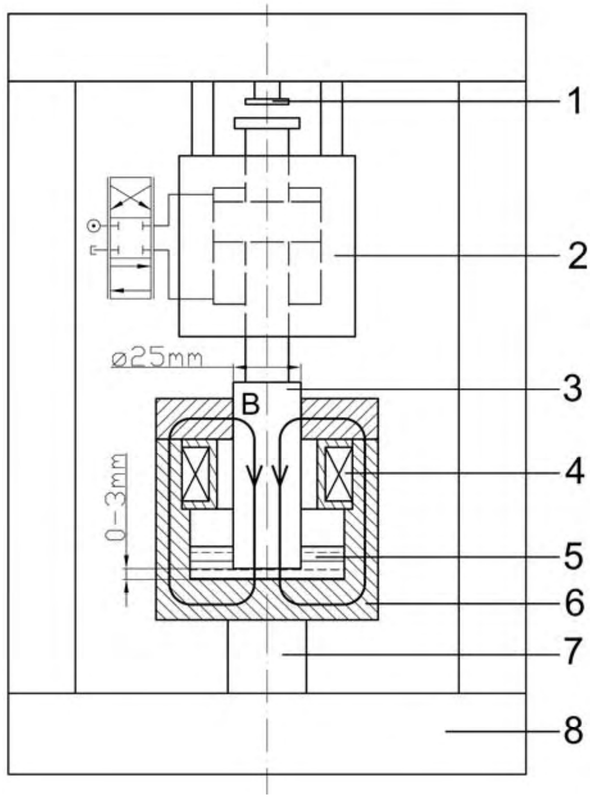


Fig. 1: *Basic test rig structure (1 eddy current pos. sensor; 2 hydraulic cylinder; 3 squeeze die (ø25mm); 4 coil (70 turns); 5 MRF (Lord 132LD); 6 squeeze pot; 7 quartz force link; 8 frame)*

3 Experimental Results

All experiments presented in this paper were done with the following MRF: Hydrocarbon-Based MR Fluid MRF-132LD supplied by LORD (www.lord.com).

3.1 Calculation of the Magnetic Flux Density B

The identification of the magnetic flux density B is done by the following procedure: the hydraulic cylinder is mechanically fixed at different gap distances; variable coil currents are applied and the magnetic reaction force F_{mag} is measured. The effective magnetic flux density B in the MRF zone can be calculated from the equation:

$$B = \sqrt{\frac{2F_{\text{mag}}\ \mu_0\ \mu_{\text{rMRF}}(B)}{A_{\text{MRF}}}} \tag{1}$$

A_{MRF} stands for the cross section area of the squeeze die, μ_0 for the permeability constant and $\mu_{\text{rMRF}}(B)$ for the relative permeability of the MRF-132LD which is not known initially. In Gstöttenbauer (2007) a linearised $\mu_{\text{rMRF}}(B)$ relation of the MRF-132LD is derived which is used here also. The combination of this linearised relative permeability relation and Eq. 1 leads to a quadratic equation for B which can be solved explicitly to obtain a gap distance – coil current – flux density – correlation as visualized in Fig. 2. The uncertainty of this result due to force measurement errors is indicated in the right hand side diagram of Fig. 2 using the specified sensor accuracy (0.5 % of the rated maximum force) and the usual error propagation techniques. The reason for the fluctuation of the B curves for small gaps (< 0.5 mm) is not known so far.

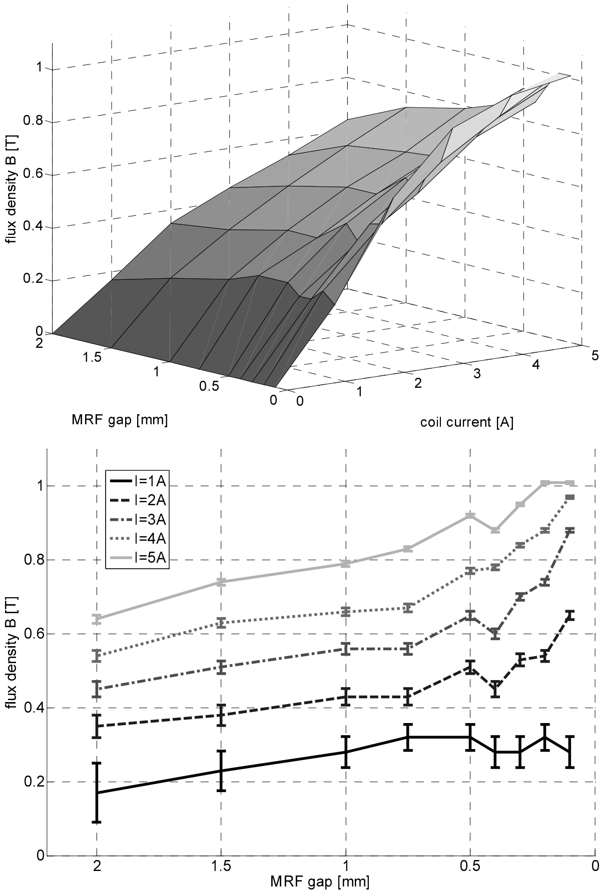


Fig. 2: *Gap – coil current – flux density – correlation (top); including the uncertainties of the flux density information due to the limited accuracy of the force measurement (bottom)*

In order to compare the results with different MRF squeeze measurements (e.g. Mazlan et al., 2007; Mazlan et al., 2008a; Mazlan et al., 2008b) the mean squeeze pressure p_{squeeze} is calculated from the measured squeeze force F_{squeeze}:

$$p_{\text{squeeze}} = \frac{F_{\text{squeeze}}}{A_{\text{MRF}}} \tag{2}$$

3.2 Investigation of the Achievable MRF Squeeze Pressure

3.2.1 Testing Procedure

The experiments presented in sections 3.2.2 and 3.2.3 are done in the following way: first, the squeeze die is positioned at the desired initial squeeze gap. This is done by closed loop cylinder position control. Afterwards the squeeze action is performed. The squeeze motion is open loop controlled in order to avoid stick-slip effects of the cylinder, which occurred in case of a closed loop controlled squeeze action and led to unfeasible results. This simple open loop approach could avoid stick-slip effects in all experiments presented in this paper. During the squeeze motion the actual value of the squeeze gap and the squeeze force are recorded via a dSPACE system. This squeeze test is repeated several times for various coil currents (section 3.2.2) and various magnetic flux densities (section 3.2.3) to analyze the influence of these parameters on the squeeze mode behaviour of a certain MR fluid.

3.2.2 Squeeze Experiments with Constant Coil Currents

For the first series of squeeze tests as described in chapter 3.2.1. the coil current is held constant.

The mean squeeze pressure increases for higher coil currents and smaller squeeze gaps. For a squeeze gap of 0.15mm and relatively high coil currents the compressive stress is roughly 30bar, which has been published by the authors' working group (Resch and Scheidl, 2009). For very small squeeze gaps, down to few hundredth of a millimetre the mean compressive stress rises up to nearly 100bar. To the best knowledge of the authors no such high measured compressive stresses of a MRF in squeeze mode have been reported before.

It is worth mentioning that the flux density in this case of experiments is not constant. Due to a decreasing MRF gap and a constant coil current the flux density increases during the squeeze motion.

It should be also noted that the results shown in Fig. 3 and Fig. 4 are only valid for the very first squeeze motion of a well mixed MRF. Repeated squeeze cycles lead to higher pressures (section 3.4).

Fig. 4 shows that the initial gap distance has no significant influence on the MRF compressive stress. The high squeeze pressures are mainly caused by the extremely small squeeze gaps. Thus, the mean pressure is just a function of the actual gap and the current; there is no influence of the gap history.

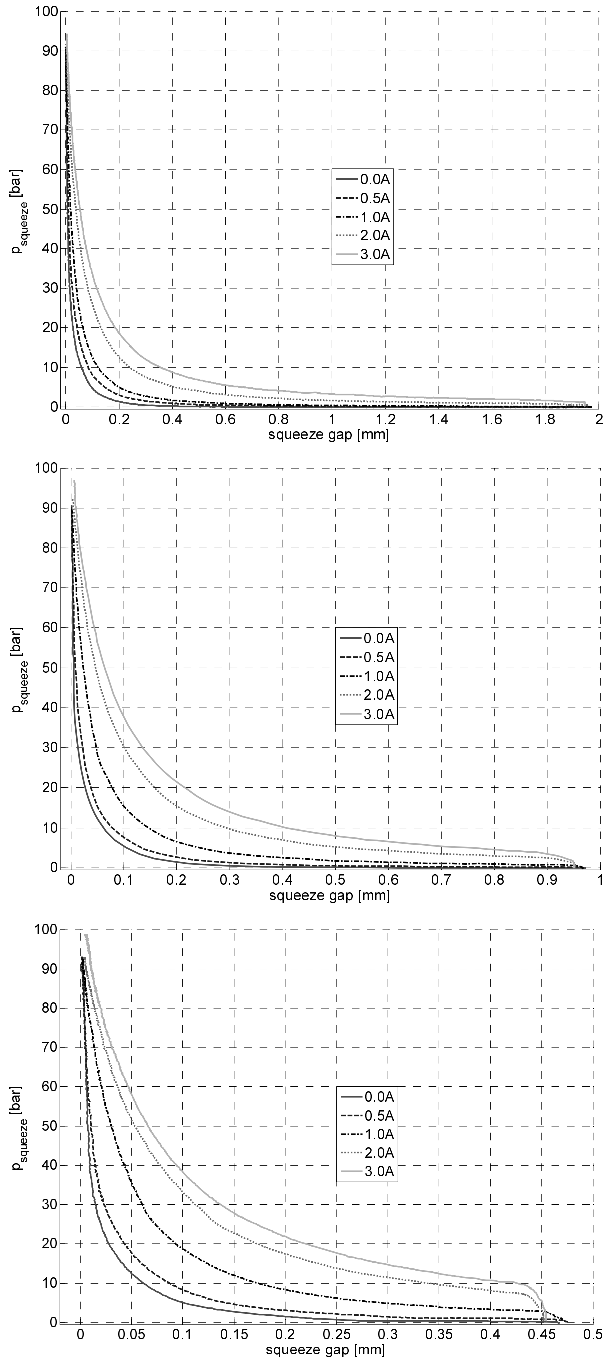


Fig. 3: *Influence of the coil current @ initial gap of approx. 1.95mm (top), @ initial gap of approx. 0.95mm (middel), @ initial gap of approx. 0.45mm (bottom)*

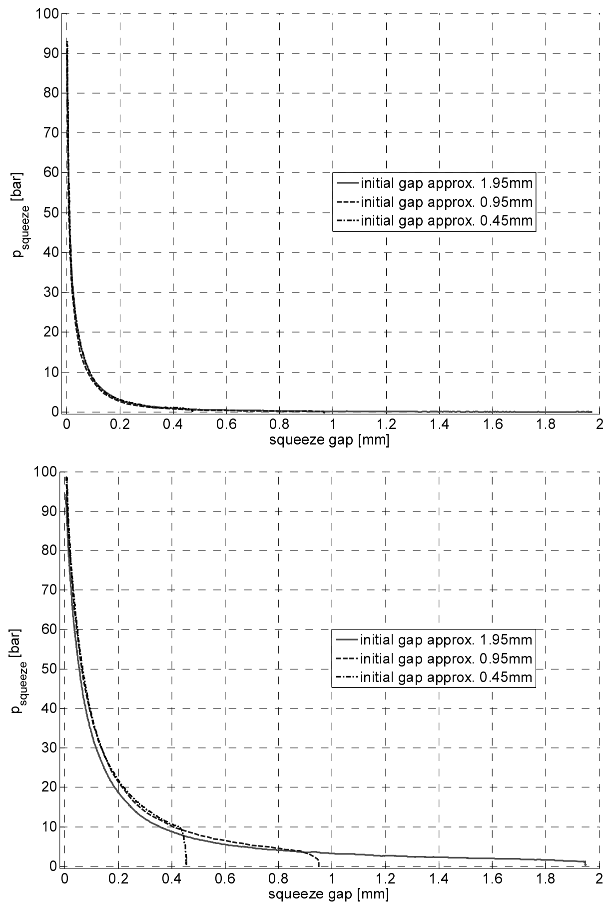


Fig. 4: *Influence of the initial gap @ 0.5A (top) and @ 3.0A (bottom)*

3.2.3 Squeeze Experiments with Constant Magnetic Flux Densities

In order to obtain a constant flux density during the squeeze action the coil current is adjusted according to the relation represented by Fig. 2.

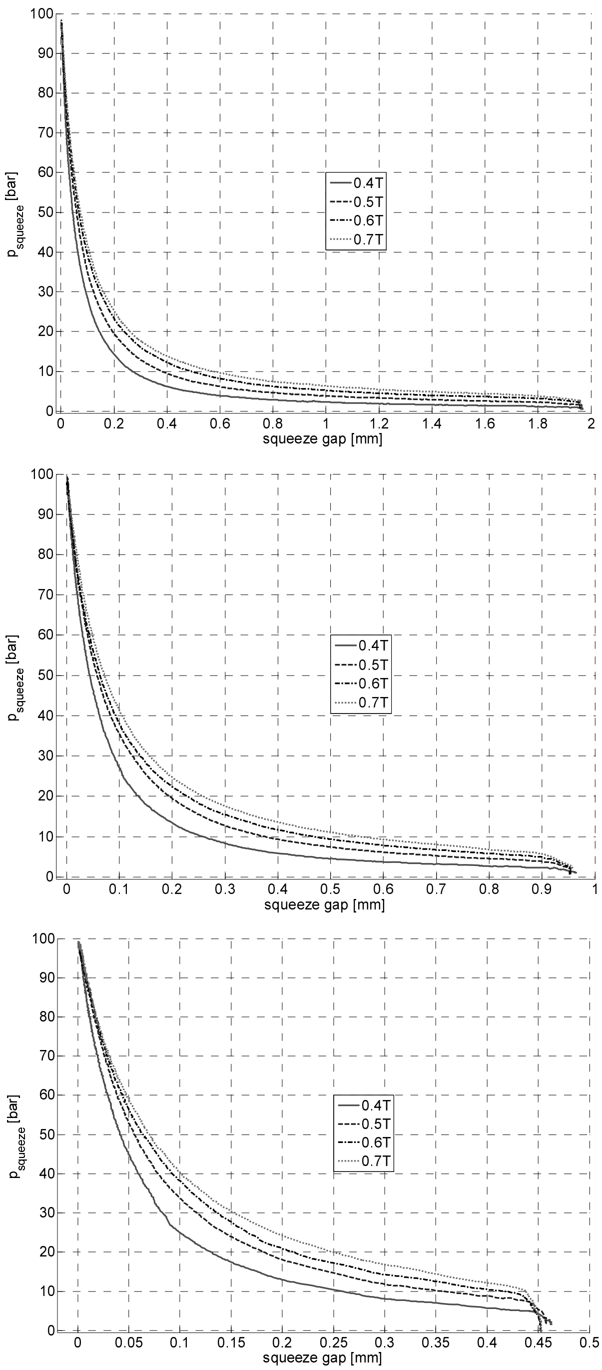


Fig. 5: *Influence of the flux density @ initial gap of approx. 1.95mm (top), @ initial gap of approx. 0.95mm (middel), @ initial gap of approx. 0.45mm (bottom)*

In principle, the same results as in case of constant coil current are achieved. Likewise the compressive stress reaches nearly 100bar.

As in section 3.2.2 the results shown in Fig. 5 and Fig. 6 are only valid for a well mixed MRF for the very first squeeze motions.

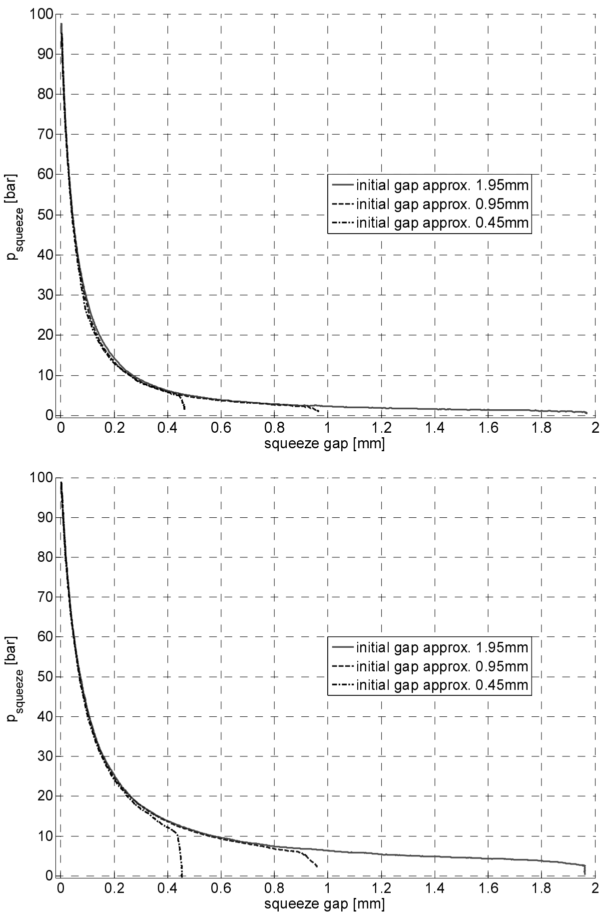


Fig. 6: *Influence of the initial gap @ 0.4T (top) and @ 0.7T (bottom)*

3.3 Conclusion of the Squeeze Experiments

The experiments showed that the mean squeeze pressure rises with coil current or magnetic flux, respectively. Extreme pressures occur for very small squeeze gaps, in the range of few hundredth of a millimetre. The maximum measured pressures nearly reach 100 bar, which is approximately three times higher than published so far (Resch and Scheidl, 2009). There is no noticeable influence of the initial squeeze gap. The pressure depends only on the actual squeeze gap and coil current or magnetic flux density, respectively.

3.4 Segregation Effect

In case of repeated squeezing without an intermediate MRF mixing remarkable increase of the mean squeeze pressure from squeeze cycle to squeeze cycle shows up in most cases. This effect occurs in the constant coil current experiments (section 3.2.2) as well as in the constant flux density experiments (section 3.2.3). Only for very small coil currents and very small magnetic flux densities, respectively, no such pressure increase from cycle to cycle appears.

This rising of the compressive stress is related to segregation effects. Due to the magnetic field forces the non-magnetic carrier fluid is easier squeezed out than the magnetic MRF-particles. Thus, the carrier fluid separates from the particles from cycle to cycle and the particles concentrate successively in the squeeze area. This segregation phenomenon is a self-amplifying effect. Due to the increase of the particle concentration in the squeeze area the magnetic flux density increases in this area also. Because of the raised flux density the magnetic forces get higher too, which tend to hold the particles in the squeeze zone even stronger. In Fig. 7 this unstable characteristic can be seen. The segregated MRF in the squeeze area more and more tends to behave like a granular media (such as sand) rather than a fluid.

3.4.1 Testing Procedure of the Segregation Experiments

In order to analyse this segregation effect the testing routine is changed in the following way:

The squeeze motion of the segregation experiments becomes a closed loop controlled sinusoidal curve with a frequency of 2 Hz and an amplitude of 1 mm (peak-peak). The offset position is modified in order to get different minimum squeeze gap distances.

3.4.2 Exemplary Segregation Effect Measurements

For higher coil currents and higher magnetic flux densities, respectively, there is a remarkable unstable segregation tendency, which is indicated by the rising compressive stress from squeeze cycle to squeeze cycle.

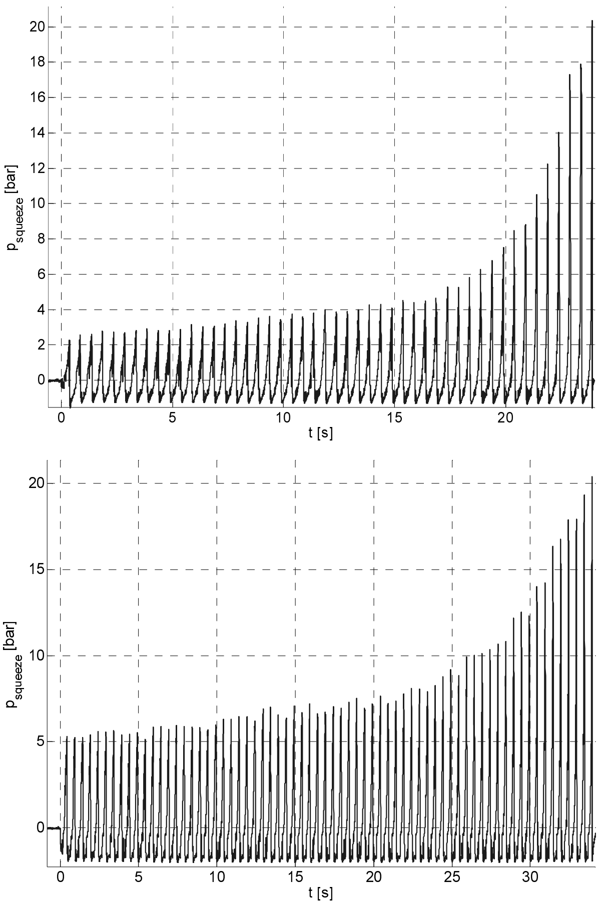


Fig. 7: *Segregation effect; min. gap 0.5mm; coil current 1A (top); flux density 0.4T (bottom)*

Several authors (e.g. Gstöttenbauer, 2007; Tang et al., 1997; Farjoud et al., 2009) mentioned problems with the segregation phenomenon in the MRF squeeze mode but no investigations were published to eliminate this effect.

3.5 Experimental Tests of Three Anti-Segregation methods

The high measured MRF compressive stresses in the pure squeeze mode (section 3.2.2 and 3.2.3) make this mode very interesting for certain industrial applications (as mentioned in section 1), provided the segregation can be avoided. Three of such anti-segregation methods and their experimental test are reported in the sequel.

3.5.1 Mechanical Wiper Approach

To wipe out the MRF squeeze zone by a mechanical wiper in the expansion phases following each squeeze cycle and to provide a sufficient remixing in this way, is the main idea of this approach. A very simple copper wire, which is moved through the squeeze zone manually after each squeeze cycle, acts as wiper. To do so, the squeeze cycle has to be adapted slightly. It is a periodic movement as explained in section 3.4.1 but it is halted after each squeeze cycle to do the wiping. The other parameters of the squeeze motion are unaltered.

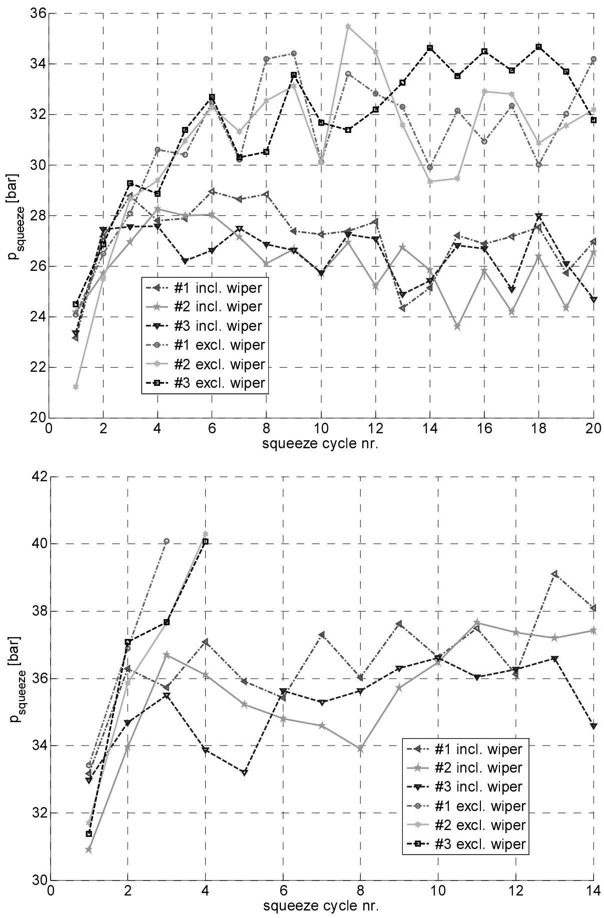


Fig. 8: *Wipe experiment; min. gap 0.15mm; coil current 2A (top); coil current 3A (bottom)*

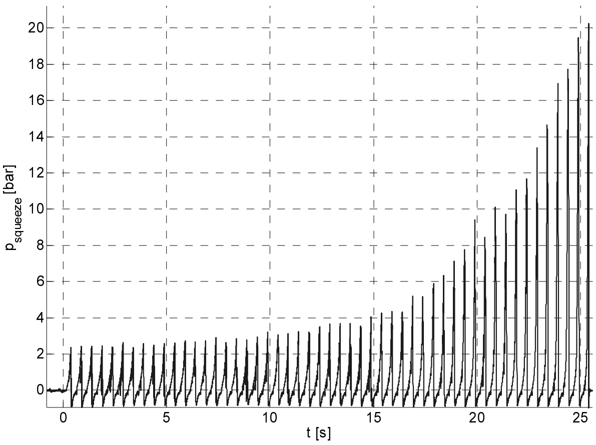
At a moderate coil current of 2 A there is a remarkable difference between the wiping and non-wiping experiments (Fig. 8 top). With wiping the squeeze zone after every squeeze cycle the squeeze pressure is much lower than without and does not show the strongly increasing trend, thus indicates a reasonable mixed MRF.

Without wiping the MRF zone the mean squeeze pressure at a coil current of 3 A gets very high already after 3 or 4 squeeze cycles which is a sign of massive segregation of the MRF (Fig. 8 bottom). Using the mechanical wiper leads to stable mean squeeze pressure. The level of the compressive stress in case of wiping is a little increased after some squeeze cycles in relation to the very first squeeze motion. This is probably due to the relatively poor quality of the wiping and remixing processes.

It is obvious that the design of an adequate mechanical wiper for practical applications (especially for very small gaps down to few hundredths of a millimetre) would be a challenging task that's asking fore some cute new design idea.

3.5.2 Zero Coil Current Approach

The second approach to reduce the segregation phenomenon is to turn off the coil current in every gap expansions phase and to have a magnetic field only during the squeeze motion itself. The idea was that in this way the MRF has the chance to homogenize in the opening phase since no magnetic field affects the particle flow.



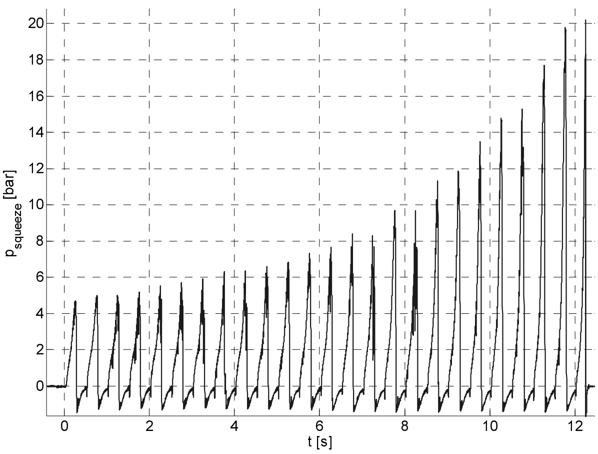


Fig. 9: *Min. gap 0.5 mm; coil current 1 A at closing gap and 0 A at opening gap (top); flux density 0.4 T at closing gap and 0 T at opening gap (bottom)*

In all tested cases there is no reduction of the segregation behaviour (Fig. 9). The ineffectiveness of this approach results either from the magnetic remanence of the MRF (Lopez-Lopez, 2006) or from its missing tendency to homogenize by itself. For a more detailed explanation of the inefficiency of this anti-segregation strategy and of the segregation effect itself, modified experiments with an observation of the radial segregation distribution are currently under investigation.

3.5.3 Elastic MRF Reservoir Approach

As explained in section 3.4 the reason for the increasing compressive stress from squeeze cycle to squeeze cycle is the accumulation of the MRF particles in the inner gap zones. For continuity reasons this must lead to a carrier fluid enrichment in the outer zones. This suggests avoiding segregation by reducing the amount of MRF to a minimum, just what is needed for the widest gap (Kulkarni et. al, 2003; Resch and Scheidl, 2009). An elastic reservoir absorbs the MRF squeezed out. This possibly pre-pressurized reservoir forces the MRF back into the squeeze gap when it is expanding. The conjecture behind this solution idea is that the chance of segregation is smaller for a reduced MRF volume and that the forced backflow causes some mixing. A simple technical realization of such a reservoir is shown in Fig. 10. The MRF is encapsulated in a pad and the volume is reduced from 12 ml (= reservoir in all other experiments) to approximately 3 ml.

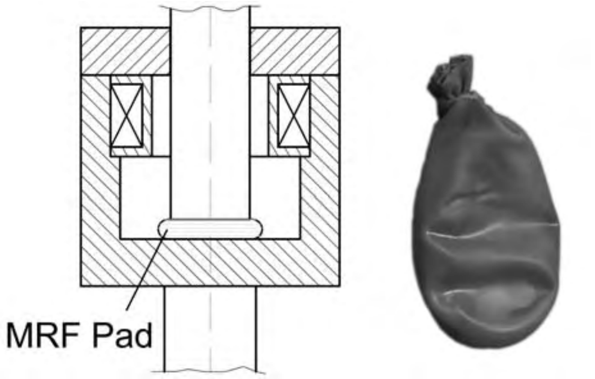


Fig. 10: *Sketch of the MRF reduction strategy and photo of the MRF pad*

Pad squeeze tests show, that there is still an increasing compressive stress (Fig. 11), which indicates segregation, but the segregating process is much slower than in all other comparable experiments. Also the increasing of the compressive stress has a more linear behaviour than the unstable growth in the conventional tests (cf. Fig. 7 with Fig. 11).

The main problem of this approach is the destruction of the pads after several minutes of squeezing. Thus, further development has to be done to find an adequate MRF pad solution in order to achieve appropriate durability of this anti segregation device.

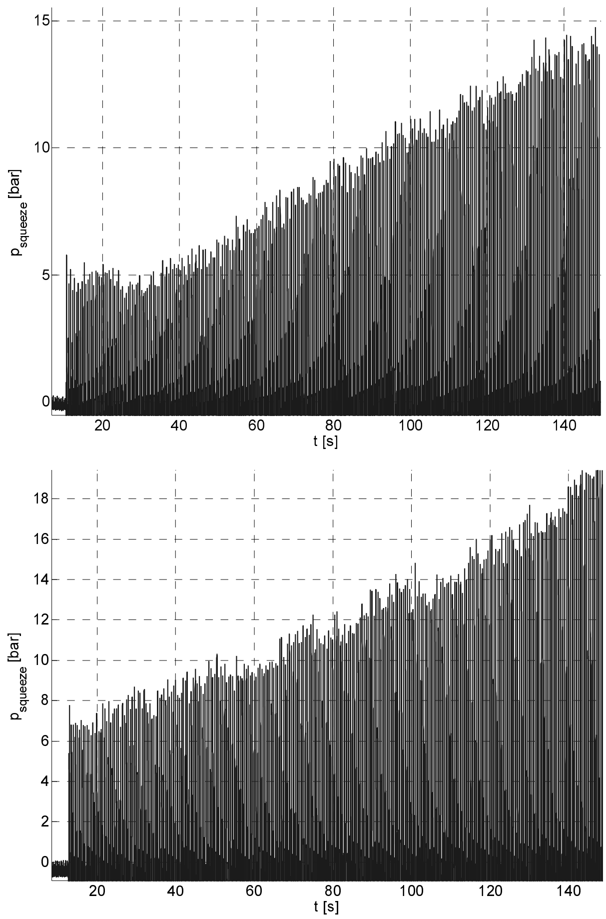


Fig. 11: *Pad squeeze experiments, min. gap 0.5mm; coil current 7A; pad 1 (top); pad 2 (bottom)*

3.5.4 Conclusive Assessment of the Investigated Anti-Segregation Methods

The wiper approach seems to work adequately. The design of a reliable non-manual wiper for practical applications especially for very small squeeze gaps is a challenging design task. The zero coil current approach shows no improvement of the segregation phenomenon. This is most likely due the distinctive remanence of the MRF. More investigations need to be done in the topic of the MRF volume reduction approach in combination with an elastic reservoir. First measurements show that the segregation behaviour is improved by using a MRF pad. It also needs to be clarified if the main segregation problem results mainly from a global particle accumulation (particles concentrate in the squeeze area, fluid in the outside reservoir), or if there is also a local particle accumulation problem in the squeeze zone itself.

4 Analytical Studies of the MRF Squeeze Mode

The aim of this section is to derive an analytical approximate dimensioning rule for MRF squeeze mode systems for an effective assessment of practical applications. This description should yield the MRF squeeze pressures as a compact function of the MRF material properties, the gap distance and the magnetic field.

4.1 Literature Survey – Phillips Approach

A common approach to describe the rheological properties of a MRF is to use a Bingham model (Zschunke, 2005; Lange, 2004; Benetti and Dragoni, 2006; Farjoud et al., 2009):

$$\tau(B,\dot{\gamma}) = \tau_Y(B)\,\mathrm{sgn}(\dot{\gamma}) + \eta\,\dot{\gamma} \tag{3}$$

where $\tau(B,\dot{\gamma})$ is the shear stress, $\tau_Y(B)$ the yield stress, η the viscosity and $\dot{\gamma}$ the shear rate.

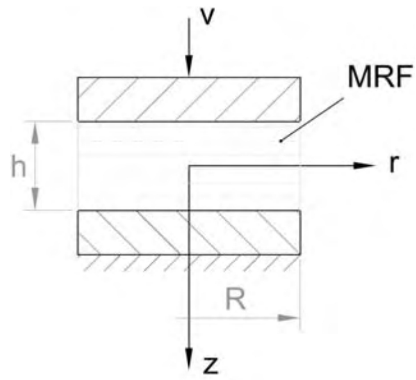


Fig. 12: *Squeeze model geometry*

In the work of Phillips (1969) the classical lubrication theory for Newtonian fluids (Reynolds equation) is extended for fluids with variable yield stresses. Following the derivation of Phillips for a Bingham fluid in squeeze mode using circular squeeze plates, the squeeze pressure is divided into a field and yield stress independent viscous component $p_\eta(r)$ and an applied field dependent induced yield stress component $p_{\tau Y}(r)$:

$$p_\eta(r) = \frac{3\eta r^2 v}{h^3} \tag{4}$$

$$p_{\tau_Y}(r) = \frac{2r\tau_Y}{h}\,\mathrm{sgn}(v) \tag{5}$$

where h denotes the gap distance and v stands for the squeezing speed (Fig. 12). Adding up the two components yields the total pressure $p(r)$. Integration of the pressure $p(r)$ finally gives the squeeze force F_{Phillips}:

$$F_{\mathrm{Phillips}} = \frac{3\eta R^4 \pi v}{2h^3} + \frac{4\pi R^3 \tau_Y}{3h}\,\mathrm{sgn}(v) \tag{6}$$

In Eq. 6, R stands for the radius of the squeeze plates.

It is worth mentioning that Eq. 6 reduces to the Stefan's law (Stefan, 1874) in case of $\tau_Y = 0$ (Newtonian fluid).

$$F_{\mathrm{Stefan}} = F_{\mathrm{Phillips}}\Big|_{\tau_Y=0} = \frac{3\eta R^4 \pi v}{2h^3} \tag{7}$$

The approach of Phillips (Eq. 6) is also suggested by Jolly and Carlson (1996) and in agreement with first measurements done by Farjoud et al. (2009).

4.1.1 Bingham Squeeze Flow Paradox

The extension of the classical lubrication theory for Bingham fluids yields to a paradox as mentioned in the work of Covey and Stanmore (1981) and several subsequent publications. Because of the symmetry of the problem ($\dot{\gamma} = \frac{\partial v_r}{\partial z} = 0\big|_{z=0}$) the shear stress τ vanishes in the mid-plane z = 0 (Fig. 12). According to the model of a Bingham medium, this fact requires that the material behaves as a rigid plug in the mid-plane. But on the other hand, the radial momentum balance and material conservation for a decreased squeeze gap demand a MRF velocity that increases with the radial coordinate even for the mid-plane. Therefore, the rigid plug has to deform which contradicts the "rigid plug" hypothesis. This inconsistency is based on the one-dimensional yield condition of the lubrication theory and is known as the "Bingham squeeze flow paradox" in the literature.

It needs to be pointed out, that such a paradox does not appear if an adequate multidimensional plasticity theory is used to describe the MRF squeeze mode (Gstöttenbauer, 2007). The outcome of such a plasticity approach are rather complex and do not yield to a simple analytical description which can be easy used for dimensioning of a MRF squeeze mode application. Due to this, the focus of this work is on the approach of Phillips (Eq. 6).

4.2 Comparison with Measurements

For comparing the measurements to the Phillips theory one needs to know the viscosity η and the yield stress $\tau_Y(B)$ of the concrete MRF. The yield stress values of the MRF can be found in the product bulletin (www.lord.com) but no adequate viscosity values are provided. However, Lange (2004) did several viscosity measurements for the MRF-132LD, and his results are used here.

Table 1: Used yield stress and viscosity data of the MRF-132LD

$\tau_Y = 17\,kPa$ @ $B = 0.4\,T$	$\tau_Y = 25\,kPa$ @ $B = 0.5\,T$
$\tau_Y = 30\,kPa$ @ $B = 0.6\,T$	$\tau_Y = 37\,kPa$ @ $B = 0.7\,T$
$\eta = 0.17\,Pas$	

The mean theoretical squeeze pressure is built in analogy to Eq. 2:

$$p_{\text{Phillips}} = \frac{F_{\text{Phillips}}}{A_{\text{MRF}}} \tag{8}$$

As shown in Fig. 13 there is a good accordance between the experiments and the Phillips approach. Only for very small gap distances a discrepancy exists. According to Eq. 6 the squeeze force, and the mean squeeze pressure respectively, get infinite for $h \to 0$ but the measurements are limited by a mean squeeze pressure of approximately 100 bar. For very small squeeze gaps (in the range of few particle diameters) the MRF particles itself might be squeezed and deformed. The limited mechanical strength of the particles, in case of squeezing the particles and not the MRF suspension, can explain the finite measured squeeze pressure. Nevertheless, down to a squeeze gap of $h > 0.25$ mm (plate diameter - gap distance ratio $D/h < 100$) the agreement is satisfying.

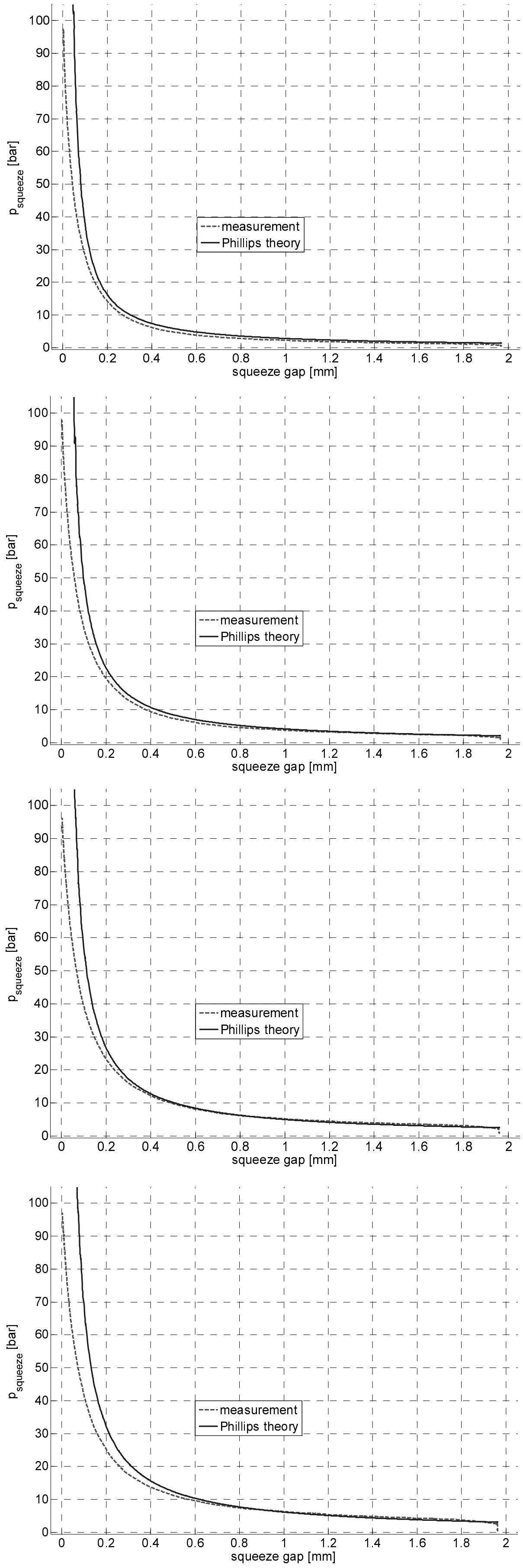


Fig. 13: *Theory vs. measurement @ 0.4T (top); @ 0.5T (top second); @ 0.6T (top third); @ 0.7T (bottom)*

4.3 Conclusion Concerning the Phillips Approach

The mathematical model according to Phillips is in reasonable agreement with the experiments as long as $h > 0.25$ mm despite the paradox in this approach as outlined in 4.1.1. For $h > 0.25$ mm this simple theory may be used for design purposes of MRF squeeze mode applications. For very small squeeze gaps the Phillips approach, which is based on the lubrication theory, fails. In this case a more sophisticated theory needs to be considered.

5 Conclusion

Measurements showed that the mean squeeze pressure in the MRF squeeze mode rises to extreme values for very small squeeze gaps. A mean squeeze pressure of nearly 100 bar was measured, which is approximately three times higher as published so far and roughly hundred times higher than the maximum MRF shear stress in shear mode applications.

In case of repeated squeezing the problem of segregation is faced. Even though the MRF squeeze mode is passively unstable it has some potential for new technical applications because of the high squeeze force densities. That's why three different anti-segregation methods were tested experimentally. Two of these approaches have the capability to avoid or to reduce the segregation phenomenon but for practical usage further investigations (based on the published ideas) need to be done.

For dimensioning of MRF squeeze mode applications a simple MRF squeeze pressure equation (based on Phillips) is derived. This equation is in satisfying agreement with experiments as long as $h > 0.25$ mm.

All experimental results presented in this publication are based on the squeeze die diameter of $D = 25$ mm. It needs to be clarified if there is a significant influence of the squeeze die diameter on the mean squeeze pressure (especially for very small squeeze gaps). This investigation will be subject of further work.

Nomenclature

A_{MRF}	cross section area squeeze die	[m^2]
B	magnetic flux density	[T]
D	diameter of the squeeze die	[m]
F_{mag}	magnetic force	[N]
$F_{Phillips}$	squeeze force according to Phillips (1969)	[N]
$F_{squeeze}$	measured squeeze force	[N]
F_{Stefan}	squeeze force according to Stefan (1874)	[N]
h	gap distance	[m]
p	squeeze pressure	[Pa]
$p_{Phillips}$	mean squeeze pressure – Phillips approach	[Pa]
$p_{squeeze}$	mean squeeze pressure	[Pa]
p_{η}	squeeze pressure (viscous component)	[Pa]
p_{τ_Y}	squeeze pressure (yield stress component)	[Pa]
R	radius of the squeeze die	[m]
v	squeezing speed	[m/s]
$\dot{\gamma}$	shear rate	[1/s]
η	dynamic viscosity	[Pas]
μ_0	permeability constant	[Vs/Am]
μ_{rMRF}	relative permeability of the MRF	[-]
τ	shear stress	[Pa]
τ_Y	yield stress	[Pa]

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