APPROACHES TO THE APPLICATION OF MAGNETIC FLUIDS IN ELECTROMECHANICAL DRIVE SYSTEMS

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ABSTRACT

This paper shows the approach of applications of magnetic liquids in electromechanical drive systems. Magnetic fluids consist of colloidal ferromagnetic nanoparticles, a particle surfactant and carrier liquid. These fluids are divided into two groups called ferrofluids and magneto-rheological fluids (MRF). Both liquids are examined in two different kinds of electric motor prototypes. Following the ideas of Nethe [4], a ferrofluid is located in the air gap of an electrical drive. The influence on torque and especially heat transfer is shown by experiments. The system is also studied analytically as a classical Taylor-Couette-System. A second motor prototype is a novel and innovative magnetorheological assisted electrical machine. The construction and the functional principle are presented in this paper. In addition, some of first measurements are shown.

Index Terms **–** magnetic materials, ferrofluid, electric drive systems, thermal conductivity

1. INTRODUCTION

Magnetic fluids are stable colloidal suspensions of nanoparticles in an oily or watery carrier liquid. Commonly, they are divided into two groups with respect to their particle size. Ferrofluids are made of a particle diameter from 2 nm up to 20 nm. Each tiny particle is coated with a surfactant to inhibit clumping and sedimentation of particles in a gravitational field and agglomeration in a strong magnetic field. A uniform size of particles characterizes a high-quality ferrofluid. With a particle size above 20 nm, the magnetic fluids enter the group of magnetorheological fluids (MRF). While ferrofluids remain liquid in strong magnetic fields, magnetorheological fluids show a dependence of the viscoelastic properties as a result external magnetic fields.

An electric machine has two important components, a rotor and a stator. Between these parts is the so called air gap, which is necessary for rotating and is normally chosen small enough. Ferrofluids in the air gap and/or the stator coils of an electric machine reduce the magnetic and thermal resistance [3]. Especially heating can be a problem in an electrical machine, because the insulation of stator coils can be damaged. Furthermore, the permanent magnets in permanent magnet synchronous machines (PMSM), for example, will be demagnetized at a critical high temperature and destroy the machine completely. In this case, ferrofluids can improve the heat transfer to an electric machine and increase torque. Incidentally, reducing magnetic material and rare earth elements in electric drive systems is an actual field of investigations, especially in the automotive sector. A torque increase due to a ferrofluid in the air gap means less magnetic material, merge to less rare earth elements, with the same space of installation and the same machine power. All investigations on this machine are transferred to a mechanical model. An electric motor is similar to the Taylor-Couette-System (TCS) due to the technical design of rotor and stator. Therefore, an electric drive system is also a classical TCS. A TCS is well known [5,6]. First, it was a test system for fluid dynamics and hydrodynamic structures. The construction consists of a solid cylinder in a hollow cylinder, see Fig. 1. In the gap between two rotating cylinders, a viscous fluid can be used to measure the viscosity, for example. For low angular velocities, the flow is laminar and only azimuthal.

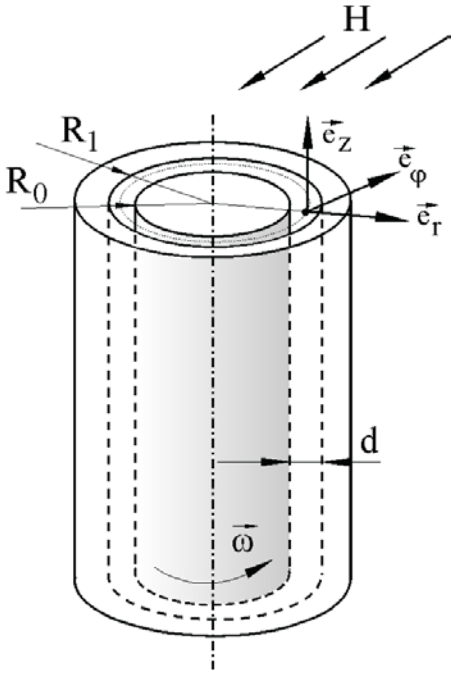

Fig. 1. Schematic sketch of the TCS

The second part of the article considers a new type of electric motor. This motor is a magnetorheological assisted electric machine, which transforms a harmonic and mechanical oscillating motion into a constant direction rotating movement. The modification of some parameters allows a change in the angular velocity, the direction of rotation and the torque at the motor shaft.

The investigations in this paper show the potential of magnetic fluids in automotive engineering.

2. MATHEMATICAL-MECHANICAL MODELING

In reference [3] the Navier-Stokes equations were shown in vector format and their transformation into cylinder coordinates. Conditions like e.g. no convection and stationary temperature were given and the dependence of fluid velocity v inside the air gap to the radius r could be shown. The velocity of the fluid in a point within the air gap ($R_0 > R_1$) could be plotted.

Furthermore, the thermal conductivity equation for an incompressible viscous fluid is given and has the following form:

$$c_p \frac{dT}{dt} = \frac{\lambda}{\rho} \Delta T + \frac{\eta}{\rho} e_{ij} e^{ij}. \tag{1}$$

In this case, c_p is the specific heat capacity, $T = T(r)$ is the temperature, λ is the thermal conductivity, e_{ij} and e^{ij} are the components of the strain-rate tensor. The non-zero components of it are $e_{r\varphi} = e_{\varphi r} = -\omega R_0^2 R_1^2/((R_1^2 - R_0^2)r^2)$.
As already stated, we assume that the temperature is stationary ($\partial T/\partial t = 0$). In addition, two other assumptions are notated:

1) If the dynamic viscosity is constant (η = const.), the thermal conductivity equation (1) is linear.
2) If the dynamic viscosity depends on temperature $\left(\eta = \eta(T, H)\right)$, the thermal conductivity equation (1) is nonlinear.

In the following, we assume that the viscosity is constant:

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + 2\frac{\eta}{\lambda} \frac{\omega^2 R_0^4 R_1^4}{(R_1^2 - R_0^2)^2} \frac{1}{r^4} = 0. \tag{2}$$

As shown in reference [3], this leads to the solution of the temperature:

$$T = T_{R0} - \frac{1}{\lambda}\left(\frac{\eta\, \omega^2 R_1^2 R_0^4}{(R_1^2 - R_0^2)^2} + q_{R1} R_1\right) \ln\left(\frac{r}{R_0}\right) + \frac{\eta\, \omega^2 R_0^4 R_1^4}{2\lambda (R_1^2 - R_0^2)^2}\left(\frac{1}{R_0^2} - \frac{1}{r^2}\right), \tag{3}$$

with the boundary conditions:

$$T|_{r=R_0} = T_{R0}, \qquad \lambda \frac{dT}{dr}\bigg|_{r=R_1} = -q_{R1}. \tag{4}$$

In equation (4), q_{R1} is the heat flow flowing through the wall of the outer cylinder.
If the viscosity η is constant, the profile to the temperature T on the distance r with R_0 = 5 cm, d = 0.25 cm, ω = 10 rad/s, T_{R0} = 293 K, η = 2.0·10^{-3} Pa·s, and λ = 64 W/(m·K) can be seen in Figure 2.

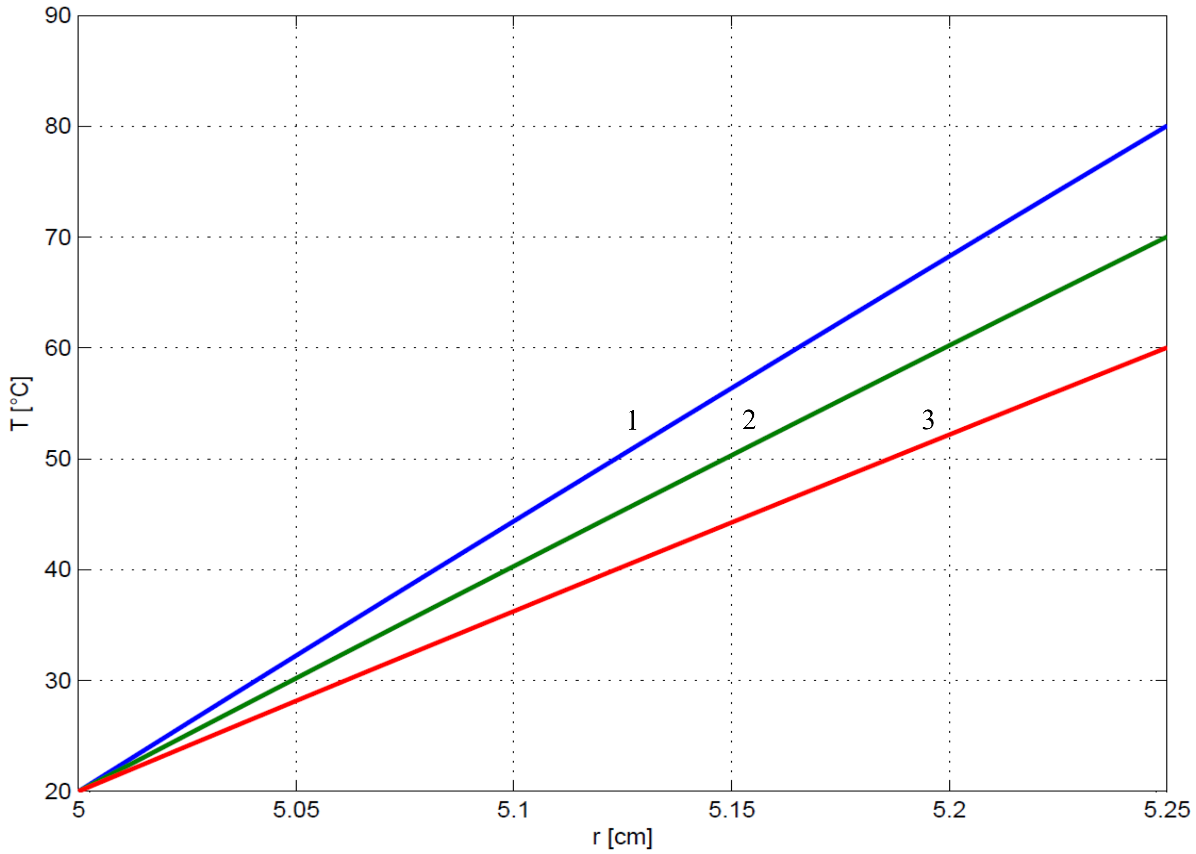

Fig. 2. Representation of the thermal flow $T = T(r)$ in the air gap for:
1) q_{R1} = 1.5·10[4] W/m[2], 2) q_{R1} = 1.25·10[4] W/m[2], and 3) q_{R1} = 1.0·10[4] W/m[2]

Case 2, if the dynamic viscosity depends on temperature and thermal conductivity equation is nonlinear; we do not always have a solution to the temperature equation. In this case, Matlab is a useful tool to solve the boundary value problem easily. The temperature equation must be brought into the dimensionless form before.

After insert $\kappa = 2\,\eta/\lambda$, we obtain from (2):

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \kappa \frac{\omega^2\, R_0^4\, R_1^4}{(R_1^2 - R_0^2)^2}\frac{1}{r^4} = 0. \tag{5}$$

Then we define dimensionless variables and characterize them by an asterisk (*). By introducing the characteristic temperature T_C, the dimensionless variables can be written as follows:

$$T^* = \frac{T}{T_C} \quad , \quad r^* = \frac{r - R_0}{R_1 - R_0} \; . \tag{6}$$

The radius of the outer cylinder R_1, the radius of the inner cylinder R_0, and the length of the air gap d are related as follows:

$$R_1 = R_0 + d. \tag{7}$$

After introducing the parameter $\varepsilon = d/R_0$ and the new variable x as:

$$r = R_0(1 + \varepsilon\, x), \quad \text{with} \quad 0 \le x \le 1, \quad R_1 = R_0(1 + \varepsilon)\,, \tag{8}$$

and with $r^* \equiv x$ we obtain from (8):

$$r = R_0 \left(1 + \frac{R_1 - R_0}{R_0} \cdot r^*\right). \tag{9}$$

From $\kappa = \kappa(T) = \kappa_0\, f(T^*)$ and $\kappa_0 = 2\,\eta_0/\lambda$ we get the stationary temperature equation in dimensionless form:

$$\frac{d^2T^*}{dx^2} + \frac{\epsilon}{1+\epsilon x} \cdot \frac{dT^*}{dx} + \alpha\, f(T^*) \frac{1}{(1+\epsilon x)^4} = 0\ , \tag{10}$$

with

$$\alpha = \kappa_0 \frac{\omega^2 R_1^4}{T_C (R_1 + R_0)^2}\ . \tag{11}$$

The corresponding boundary condition in dimensionless form is:

$$\left.\frac{dT^*}{dr}\right|_{x=1} = -\frac{q_{R_1}\, R_0\, \epsilon}{\lambda\, T_C} = -\beta \qquad , \qquad T^*|_{x=0} = \frac{T_{R_0}}{T_C} = \gamma\,. \tag{12}$$

After a substitution of

$$\Theta = T - T_{R_0}\ , \tag{13}$$

and an introduction of the characteristic temperature follows for Θ in the dimensionless form:

$$\Theta^* = \frac{T}{T_C} - \frac{T_{R_0}}{T_C} = T^* - \gamma\,. \tag{14}$$

This leads to the boundary condition in the form:

$$\left.\frac{d\Theta^*}{dx}\right|_{x=1} = -\beta \qquad , \qquad \Theta^*|_{x=0} = 0\,. \tag{15}$$

If the characteristic temperature T_C is defined as

$$T_C = \frac{q_{R_1}\, R_0\, \varepsilon}{\lambda}\ , \tag{16}$$

then the parameter $\beta = 1$. For the temperature dependence of the dynamic viscosity η of Newtonian liquids, according to [4] three approaches are given in the literature. One of them is shown here:

$$\eta = \eta_0 \cdot \exp\left(\frac{C\rho}{T}\right) \quad , \quad \eta_0 = 10^{-6} \cdot A \cdot \rho^{1/3}\ , \tag{17}$$

where A and C are constant at preassigned value H.

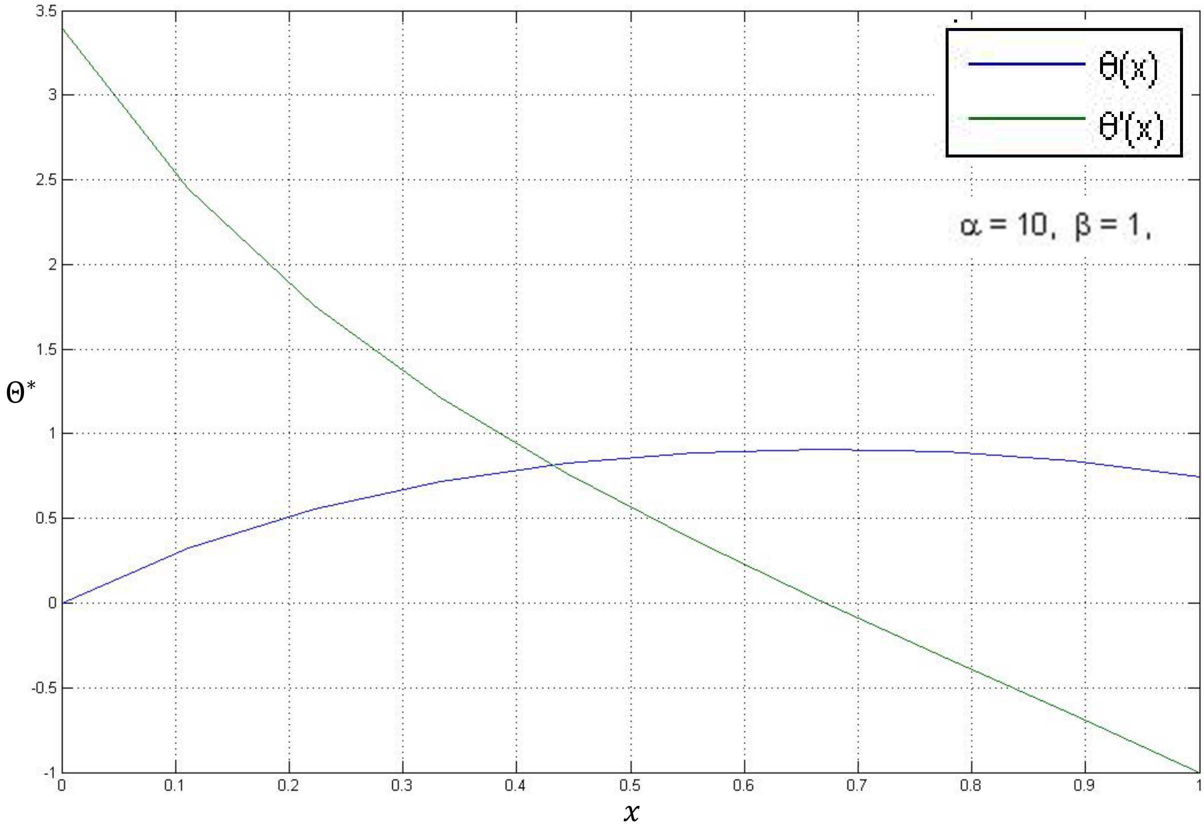

Fig. 3. Representation of the dimensionless thermal flow $\Theta^* = \Theta^*(x)$ in the air gap

The solution of the boundary value problem for a nonlinear equation (10) not always exists. It means that the stationary solution of the equation exists only under certain values of the parameter α. Figure 3 shows the stationary thermal flow (temperature and its gradient) in the air gap in dimensionless values as result of the numerical solution of the equation (10) with Matlab for $\alpha = 10$. This value of the dimensionless parameter α is according to actual dimensional physical parameters of the ferrofluid.

3. MAGNETIC FLUID PROTOTYPE-MACHINES

Within the scope of the investigations, two different types of electrical machines were developed to investigate the influence of magnetic liquids in electromechanical drives. Both, the functional principle as well the fluid used, is different for the machines.

3.1 Ferrofluid supported electrical drive system

The first prototype is a permanent magnet synchronous machine developed at Volkswagen, Department of Development Electric Power Steering. The choice fell on this type of motor because it can be found in many electric power steering systems.

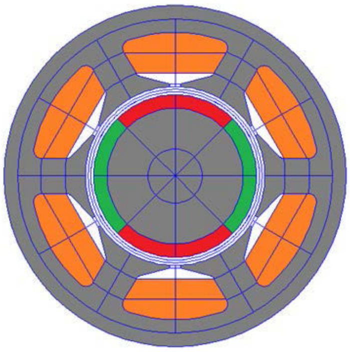

Fig. 4. Sheet cut of the permanent magnet synchronous machine

In Fig. 5, the complete motor test bench is presented. It consists of an iron powder brake on the left side, a torque sensor in the middle, and the ferrofluid supported experimental motor on the right. The setup is based on a grooved panel. The electronics of the brake and the sensor is not shown in Fig. 5. The motor control is also not part of the picture. With this kind of the motor, we can evaluate our calculation and the influence of the magnetic fluid inside the motor. A ferrofluid flow is diagonal through the stator coils (see Fig. 6 filler in/out) and also diagonal through the air gap. Eight temperature sensors are installed in the motor.

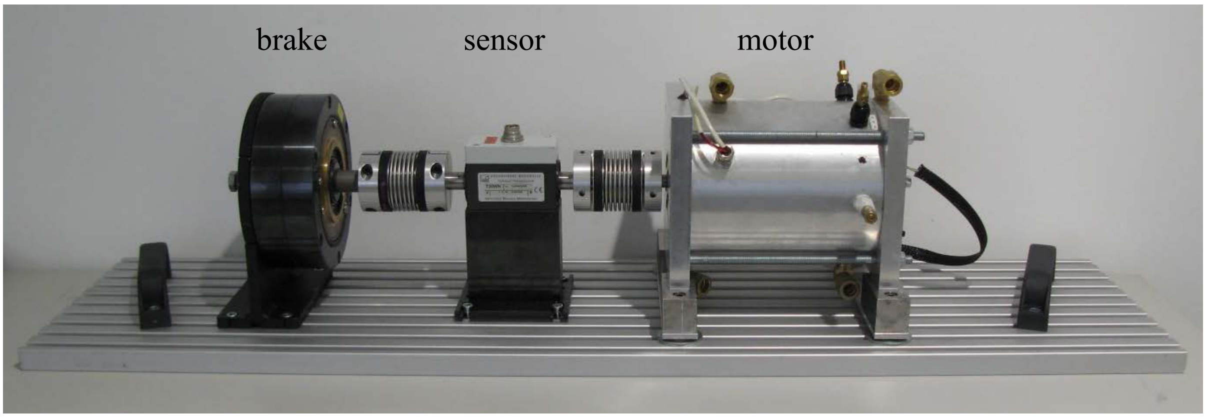

Fig. 5. Ferrofluid supported experimental motor with iron powder brake and torque sensor

The main goal by using ferrofluids in electrical drive systems is the torque increase, a better thermal conductivity and a lower current consumption. Due to the separation of the fluid between the stator coils and the air gap through a glass fiber pipe, the prototype has a larger air gap than conventional motors (less than 1 mm). Due to type of construction and by sealing the motor, the motor has a high friction and an air gap of 3 mm with a ferrofluid effect of 2 mm.

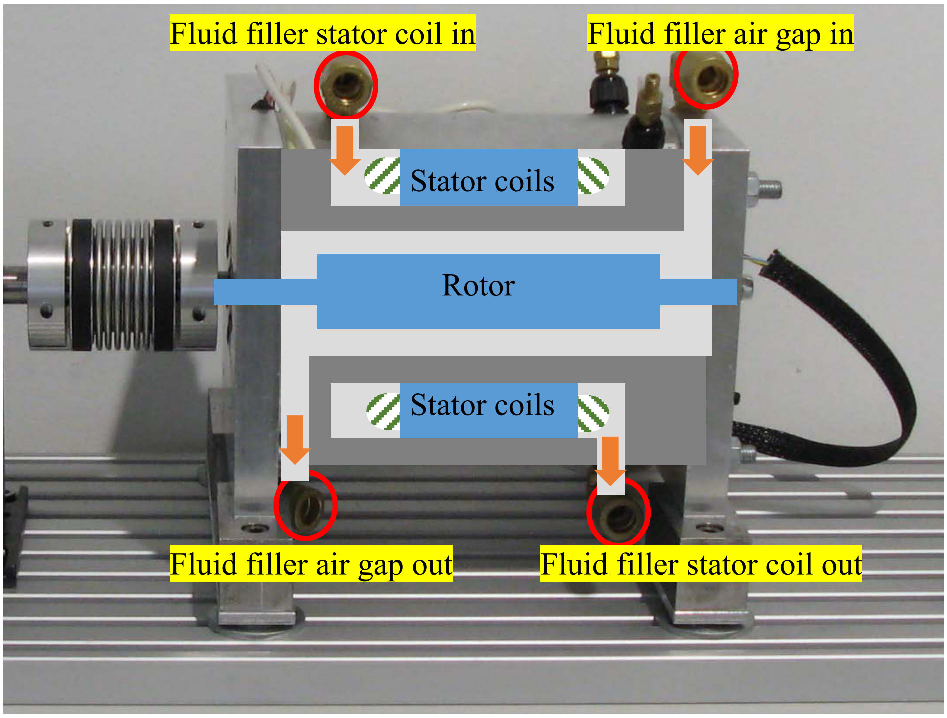

Fig. 6. Ferrofluid flow through the experimental motor

3.2 Magnetorheological fluid assisted electrical machine

The second part considers an electromagnetic motor based on the controllable mechanical properties of an MRF (Fig. 7). The system consists of two identical units that forward the drive shaft half-period phase-shifted. A single unit consists of three parts: a system that creates a harmonic mechanical oscillation (linear solenoid with spring and rocker arm), two toothed disks with an MRF filled gap in between and a system of three electromagnetic coils to create the external magnetic field to control the viscosity of the MRF. The oscillation system produces an alternating rotational motion of the first toothed disk with the amplitude of five degrees. The electromagnetic coils are switched ON and OFF synchronous to harden or soften the MRF, which influences the moment transmission between the input disk and the output disk. The drive shaft is forwarded incrementally by the disk transmitted torque. Changing the amplitudes and synchronization of the control signals, the motor can change the rotation direction, angular velocity and output torque. The drive shaft can be rotated freely if all coils are switched OFF. Applications lie e. g. in torque vectoring systems and torque control.

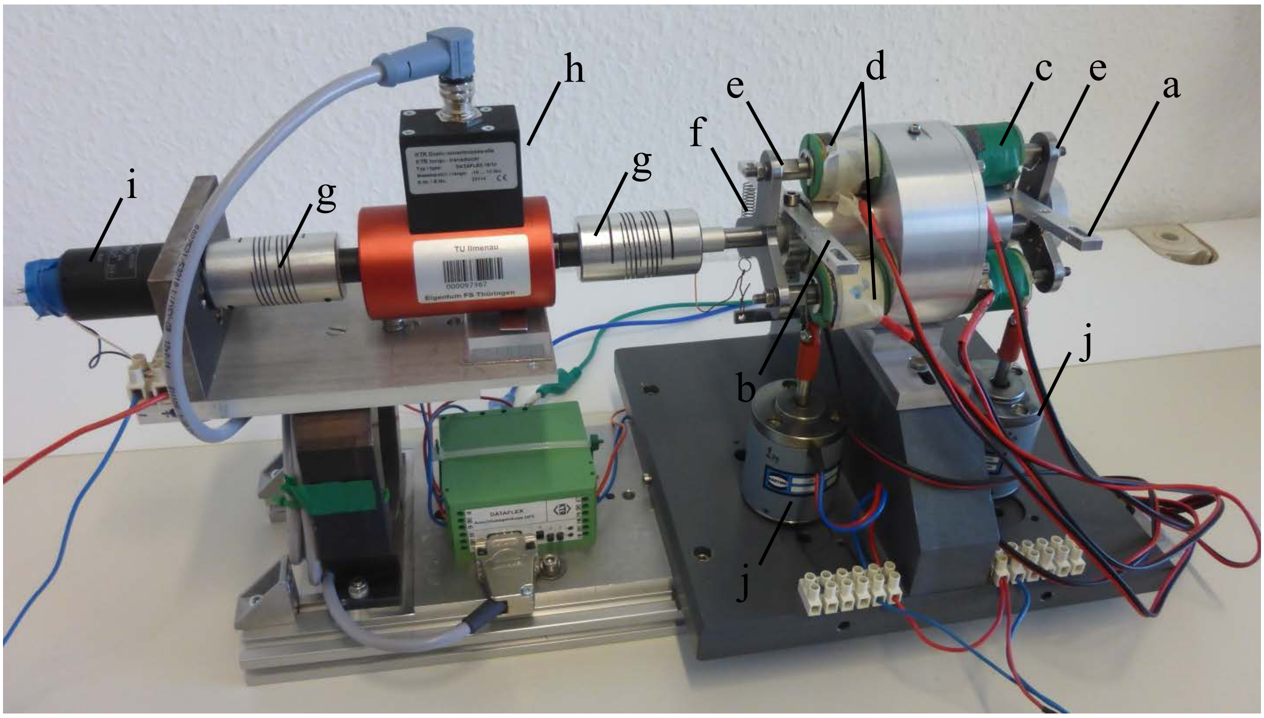

Fig. 7. Magnetorheological assisted electrical machine (test bench)
a) rocker arm right, b) rocker arm left, c) electromagnetic coil right, d) electromagnetic coil left, e) iron back-circuit, f) spring, g) coupling, h) torque sensor, i) brake, j) linear solenoid

4. EXPERIMENTAL INVESTIGATION

In the following chapter, the measurements of both electromechanical prototypes will be shown. First, the results of the ferrofluid supported PMSM are presented. Once with unfilled engine and then with ferrofluid-filled engine. Subsequently, measurements are made on the MRF motor. The torque is to be measured.

4.1 Ferrofluid supported electrical drive system

The ferrofluid supported PMSM is operated at a speed of 500 r pm. The current I_{STR} is increased in certain intervals and held for a certain time. The temperature in the air gap, the stator coils, the stator groove and the winding head is recorded and shown in the following. As can be seen, the temperature within the engine increases more slowly, which is due to the ferrorfluid and the better thermal conductance (Fig. 8 and Fig. 9).

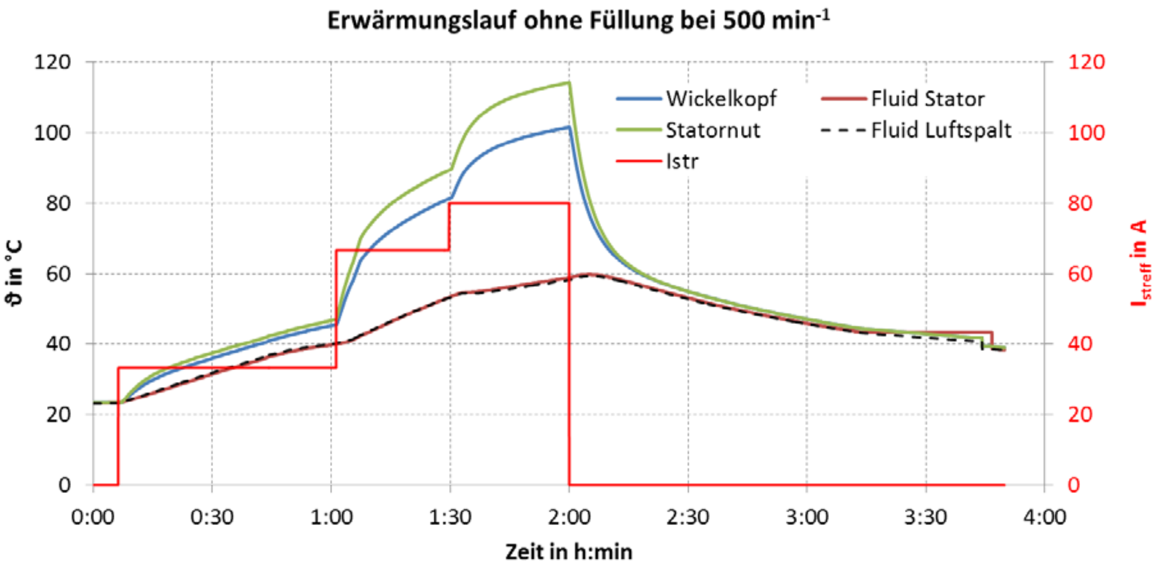

Fig. 8. Heat run with the unfilled experimental motor

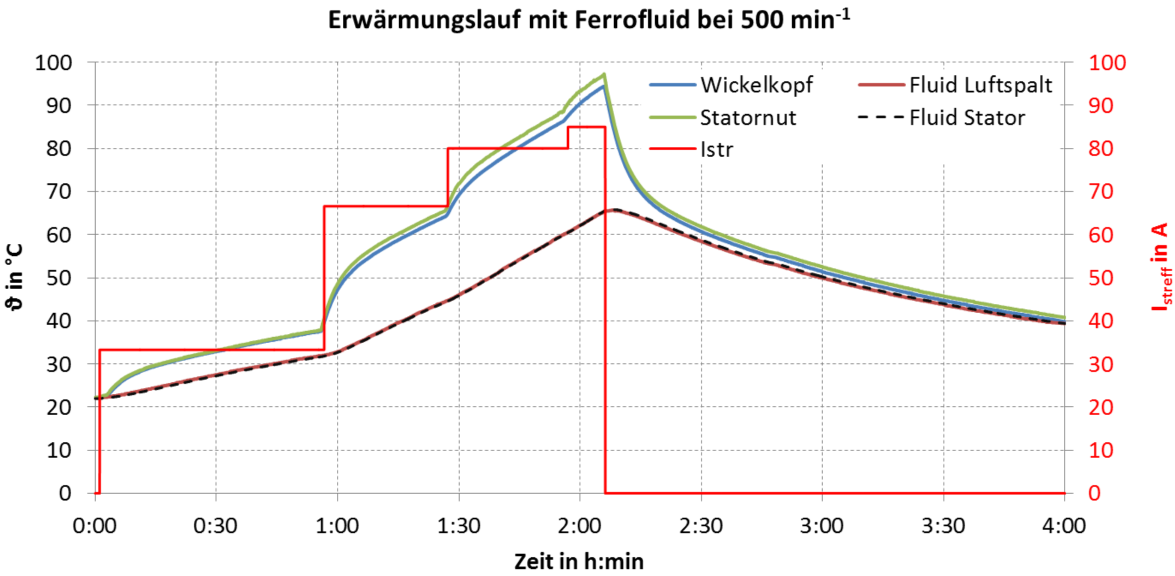

Fig. 9. Heat run with the ferrofluid filled experimental motor

4.2 Magnetorheological fluid assisted electrical machine

Figure 10 shows the torque measurement of the MRF motor. The torque was recorded while the load motor was stationary and shows a maximum torque of 0,8 Nm. In addition, the control signal for the coils of one side can be seen, which alternately has a periodic high signal with an amplitude of 22 V and a duration of 400 ms as well as a low signal with a duration of 400 ms.

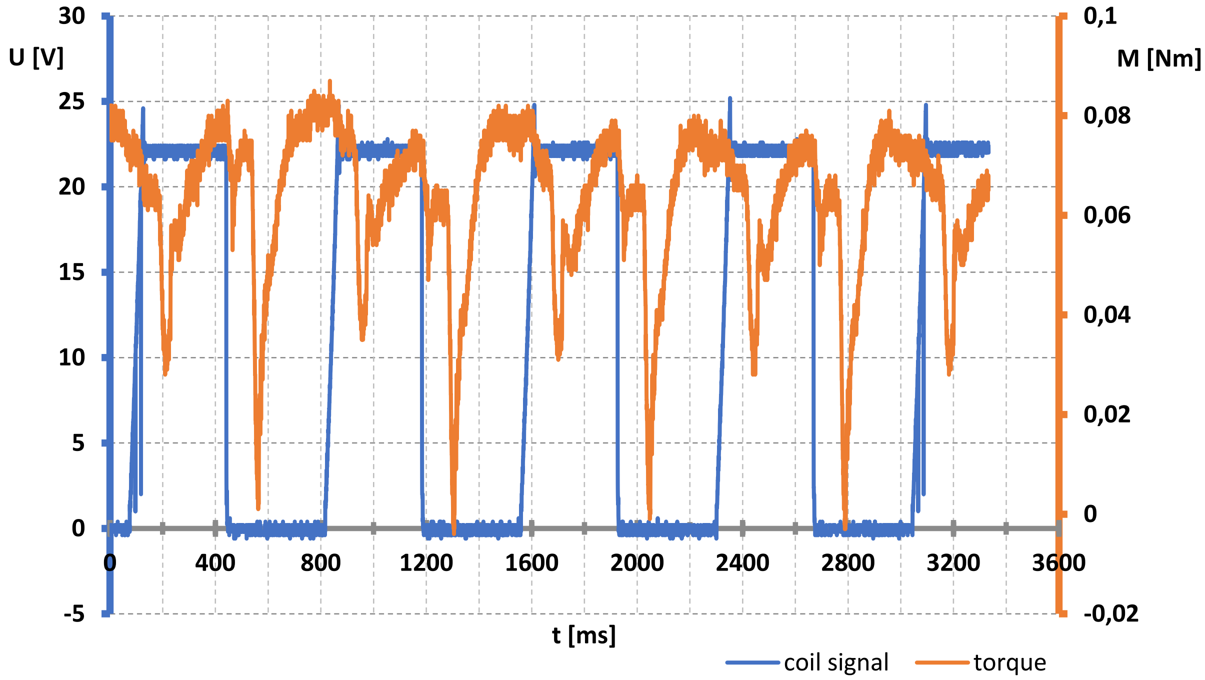

Fig. 10. Torque measurement of the magnetorheological electrical drive

5. CONCLUSION AND OUTLOOK

The measurements have shown that ferrofluid supported electric drives favor heat transfer, increase efficiency and torque. Ferrofluids in electrical drive systems are particularly suitable when the electrical machine has to deliver high power for a short time. For example, an airplane takes off. If the prototype had more realistic values with respect to the air gap and the seals are optimized, ferrofluids in electric drive systems are a good way.
Magnetorheological Motors, which transform a harmonic and mechanical oscillating motion into a rotating movement, can exploit the wave movement of the sea. The optimization of the measurement setup, the stabilization of the components and the choice of suitable measuring equipment still provide high potential.
The investigations in this paper show the potential of magnetic fluids in automotive engineering. Future work will be subjected to increase the efficiency of the motor designs. Analytical and numerical methods will be applied.

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