frontiers in Materials

ORIGINAL RESEARCH
published: 20 June 2019
doi: 10.3389/fmats.2019.00139

Selection of Materials Used in Viscous Clutch With ER Fluid Working in Special Conditions

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Specialty section:
This article was submitted to
Smart Materials,
a section of the journal
Frontiers in Materials

Received: 30 October 2018
Accepted: 29 May 2019
Published: 20 June 2019

Citation:
Olszak A, Osowski K, Motyl P, Mędrek G, Zwolak J, Kęsy A, Kęsy Z and Choi S-B (2019) Selection of Materials Used in Viscous Clutch With ER Fluid Working in Special Conditions. Front. Mater. 6:139. doi: 10.3389/fmats.2019.00139

This article presents considerations regarding materials used to fabricate a hydraulic clutch with an ER fluid operating in non-standard working conditions. The hydraulic clutch was a subassembly of the device used for exerting a controlled force on the stationary object. This clutch was driven by an electric motor. The force was controlled by changing the shear stresses in the ER fluid. Shear stresses were changed in two ways: by changing the angular velocity of the electric motor and by changing the high voltage applied to the electrodes located on the driving part and the driven part of the clutch. The increase in these stresses caused an increase in the torque transmitted and an increase in the pressure force. In order to construct the clutch, mathematical models based on the Bingham model were developed, which took into account the influence of temperature and humidity on the shear stress in the ER fluid, allowing calculation of the clutch performance. In addition, numerical calculations of the temperature distribution inside the clutch were carried out using the ANSYS program because of the intense heat generation during the clutch operation. The developed mathematical models were used to optimize the clutch. The aim of the optimization was to obtain a high transmitted torque with small dimensions of the clutch, taking into account the thermal capacity of the clutch. Based on the optimization results, a prototype of a hydraulic clutch with an ER fluid was designed and made, assuming that for metal materials their anti-corrosion properties are the most important, since the presence of conductive metal oxides causes electrical breakdowns. The plastics used in the clutch prototype were mainly evaluated for insulating properties and high temperature resistance. When choosing the ER fluid, its sensitivity to temperature and humidity as well as durability were taken into account. The clutch prototype has been tested on a specially built test rig. The test results confirmed the proper selection of both construction materials and ER fluids. Based on the results of these tests, guidelines for the construction of clutches with ER fluids were formulated.

Keywords: viscous clutch, smart fluids, ER fluids, optimization, numerical calculations

INTRODUCTION

The most important factors that have recently contributed to mechanical devices' better results and which have increased the devices' reliability are the implementation of new materials and integration with digital electronics. In viscous clutches and brakes, both of these factors are combined by using new construction materials and hydraulic working fluids of a new type, i.e., smart fluids which react to a physical field by altering their rheological properties.

Two types of smart fluids are in use: electrorheological fluids (ER) and magnetorheological fluids (MR), activated, respectively with an electrical or magnetic field. ER and MR fluids are divided into two groups, according to their composition: monophasic and biphasic. Monophasic fluids are homogeneous while biphasic fluids consist of two phases: solid and liquid.

Viscous clutches consist of the driving part connected to input shaft and the driven part connected to the output shaft. Immobilizing the driven part causes the clutch to become a brake. In these clutches the torque is transmitted as a result of friction caused by shear stress in the working fluid between the driving part and the driven part. Two main types of viscous clutches can be distinguished, according to the shape of driving and driven part: cylindrical and disc clutches.

Due to the necessity to create an electric or magnetic field in the gap containing working fluid, building clutches and brakes with smart fluids proves much more complex than building clutches and brakes with typical working fluids. In viscous clutches with ER fluids, the electric field is usually created between two electrodes, one of which is situated in the driving part and the other in the driven part of the clutch. In such clutches, in order to convey the voltage to electrodes connected with the movable part of the clutches, additional electrical wires and sliding rings are used. However, in the viscous clutches with MR fluid, electromagnet cores and coils must be installed in addition to electrical wires and sliding rings. Due to these reasons, viscous clutches with MR fluids weigh more, and there is consequently more inertia of the rotating parts, which is unfavorable for the control of the clutches. The complicated structure of the clutches and brakes with smart fluids makes it necessary to select materials with proper properties as well as to choose design methods based on mathematical modeling and numerical calculations.

So far, to control the torque, a vital feature of viscous clutches and brakes was used: the dependence of torque on angular velocity of the input shaft. Altering the angular velocity enables the control of the transmitted torque. The torque can also be controlled by changing temperature, pressure or volume of the working fluid within the clutch. For viscous clutches and brakes built with new materials such as smart fluids, the control is achieved by causing changes in shear stress, influencing the ER or MR fluid with an appropriate field with regulated voltage. The change in electric or magnetic field is achieved by changing voltage or current with electronically controlled electric power supplies. Increase in shear stress within the working fluid causes increase in the torque transmitted by viscous clutches or brakes.

The paper presents the results of design optimization and experimental research of a viscous disc clutch with an ER fluid, working in unusual thermal conditions. The aim of the design optimization was to achieve a large torque of the clutch, with a small size of the clutch, and at the same time a small area of heat dissipation. However, the working fluid temperature of the clutch was kept close to the temperature of the surroundings. The multi-objective optimization was carried out based on mathematical models of the ER fluids and a disc viscous clutch. The multi-objective optimization of the viscous clutch with the ER fluid including the quality of materials had not been conducted in this way before. Subsequently, a prototype of a viscous clutch with the ER fluid was made and tested on a specially built test rig. The obtained results allowed the compilation of principles for constructing viscous clutches with ER fluid, including choice of materials.

LITERATURE STUDY

In the practically used biphasic ER and MR fluids, the solid phase is comprised of particles of polymer or iron, respectively, of diameter ranging from 5 to 10 μm, and the liquid phase—silicon oil (Fertman, 1990; Conrad, 1993; Weiss, 1993; Mikkelsen et al., 2017). The biphasic fluids also contain additives (up to 3%) that prevent sedimentation and aggregation of the solid phase and increase the electrorheological or magnetorheological effect. A percentage of contents of the solid phase in biphasic ER and MR fluids is, according to weight, 60–80% and according to volume, 20–30%. One limitation in the use of the ER fluid is its sensitivity to temperature changes and air humidity. MR fluid use is limited by the magnetic saturation phenomenon.

ER and MR fluids are used or predicted to use mainly as materials with controlled rheological properties in a variety of devices, such as haptic devices (Liu et al., 2006), energy absorbers (Milecki et al., 2005; Choi and Wereley, 2015), dampers (Sapiński et al., 2016), cantilever beams (Lara-Prieto et al., 2010), hydrodynamic clutches (Madeja et al., 2011; Olszak et al., 2018), discharge machines (Kim et al., 2002), or even robots (Saito and Ikeda, 2007; Jing et al., 2018) and seismic isolators (Li et al., 2013).

The most frequent uses of ER and MR fluids are in devices such as clutches and brakes (Olszak et al., 2016a; Raju et al., 2016; Gao et al., 2017). To achieve the assumed characteristics of clutches and brakes with ER and MR fluids, their architectures are taken into consideration by analyzing the shape and position of working space (Avraam et al., 2010), the way of producing the electric or magnetic field (Takesue et al., 2003; Böse et al., 2013; Sohn et al., 2018) as well as thermal working conditions (Chen et al., 2015; Song et al., 2018). Additionally taken into consideration are the smart fluids used for construction of clutches and brakes with ER and MR, mainly their composition (Sarkar and Hirani, 2013; Kumbhar et al., 2015; Mangal et al., 2016) and durability (Olszak et al., 2016b; Kim et al., 2017; Ziabska et al., 2017). Examples of design solutions for clutches and brakes with smart fluids can be found in publications (Papadopoulos, 1998; Kavlicoglu et al., 2002; Smith et al., 2007; Fernández and Chang, 2016).

The next vital step on the way to improving the construction of clutches and brakes with smart fluids is using the optimization methods. In the publications concerning this subject, the geometric dimensions are optimized while the authors assume different objective functions and different optimization methods.

The optimization objects are usually devices with the MR fluid, used in vehicles. In previous works (Park et al., 2006, 2008) the construction process involved multidisciplinary design optimization; the objective function takes into consideration brake weight as well-braking torque and uses scalar weighting factors. In these works the assumption was that in a car, the brake weight is more important than braking torque. To decrease calculation time, three optimization methods were used, the first two being less effective: built-in capabilities of ANSYS and then a random-search method, which gave the lowest objective function values. During the optimization, CFD analysis was also conducted and magnetic field intensity distribution along with steady-state temperature distribution were evaluated. Nguyen and Choi (2010), in the process of a car brake optimization and while defining the objective function, took into consideration the following aspects: required braking torque, temperature due to zero-field friction of MR fluid, mass of the brake system and geometric dimensions. The optimization method used there was based on finite element analysis. In the work (Assadsangabi et al., 2011), the objective function was assumed in a way which allowed the largest possible braking torque with the smallest possible weight of the car brake. The optimization was conducted with the use of finite element analysis and Genetic Algorithm. The aim of the work (Sohn et al., 2015) was the optimization of a motorcycle brake. In the objective function, factors taken into consideration were braking torque, weight and temperature. In the optimization process a tool based on finite element analysis was used. In research (Nguyen and Choi, 2010) concerning a passenger vehicle magnetorheological damper, the objective function included damping force, dynamic range and inductive time constant of the damper. In the optimization method based on finite element analysis, a golden-section analysis algorithm and a local quadratic fitting technique were used.

Dimension optimization of the clutches with MR fluid can be found in two previous articles (Horvath and Torőcsik, 2011; Bucchi et al., 2017). In both, the optimization was aimed to achieve the largest possible transmitted torque of the clutch, while in Bucchi et al. (2017) emphasis was put on the magnetorheological fluid gap shape, and the optimization was conducted while using the finite element method. However, in Horvath and Torőcsik (2011) the inner radius was emphasized, while the optimization was based on the simple analytical method and a simulation procedure. The article (Gao et al., 2017) depicts the optimization of a MR damper designed for smart prosthetic knees. In the objective function, factors taken into consideration were total energy consumption during one gait cycle and weight of the MR damper. The optimization was conducted based on the particle swarm optimization algorithm. The original optimization method called the Taguchi Method was used to optimize the magnetorheological brake actuator (Erol and Gurocak, 2011). In the objective function, torque-to-volume ratio was taken into consideration.

MATHEMATICAL MODEL

While defining the mathematical model of the ER fluid, it was assumed that rheological properties of the fluid can be described by the Bingham model:

$$\tau = \mu_p \dot{\gamma} + \tau_0 \tag{1}$$

while for $U = 0$, $\tau = \mu_0 \dot{\gamma}$, and the electric properties of the ER fluid can be described with the equation:

$$I = i_g S \tag{2}$$

where μ_p is plastic viscosity, τ_0 is electric field-dependent yield stress of ER fluid, μ_0 is the ratio of dynamic viscosity of fluid without an electric field, and i_g is the density of current leakage.

The relation of τ_0, μ_0, i_g to electric field E was described by formulas, in which temperature T, relative air humidity w and shear rate $\dot{\gamma}$ were taken into consideration:

$$\begin{aligned} \tau_0 &= a_0 \cdot a_1 \cdot a_2 \cdot a_3 \cdot E^2 \\ \mu_0 &= b_0 \cdot b_1 + b_2 E^2 \\ i_g &= c_0 \cdot c_1 \cdot c_2 \cdot c_3 \cdot E^{1,7} \end{aligned} \tag{3}$$

where a_0, b_0, c_0, a_2, b_2 are numerical coefficients; a_1, b_1, c_1 are coefficients depending linearly on temperature T; a_3, c_2 is coefficients depending linearly on relative air humidity w; and c_3 is coefficients depending linearly on shear rate $\dot{\gamma}$.

It was assumed that radiuses r in the mathematical model of the viscous clutch with ER fluid are described by a proportional enlargement of the model clutch whose geometry was determined based on the analysis of already existing clutches and brakes with smart fluid (Papadopoulos, 1998; Kavlicoglu et al., 2002; Smith et al., 2007; Nguyen and Choi, 2010; Erol and Gurocak, 2011) using the magnification factor s_k. The width of the model clutch is calculated depending on the number of discs n with a constant width of the gap h between discs. **Figure 1** shows a construction scheme of a model viscous clutch with ER fluid, and **Table 1** shows juxtaposed dimensions of the clutch, dependent on magnification factor s_k and number of working gaps n.

During the optimization process of the clutch, the following calculations were made: torque transmitted through the clutch M, the clutch's power P, the clutch's volume O, temperature of the ER fluid in clutch T_Z, and centripetal acceleration a_d. Calculations were made based on the following formulas:

$$\begin{aligned} M &= n\frac{\pi \mu_p}{2h}\omega\left({r_2}^4 - {r_1}^4\right) + n\frac{2\pi\tau_0}{3}\left({r_2}^3 - {r_1}^3\right) \\ P &= n\frac{\pi \mu_p}{2h}\omega^2\left({r_2}^4 - {r_1}^4\right) + n\frac{2\pi\tau_0}{3}\omega\left({r_2}^3 - {r_1}^3\right) \\ O &= \pi {r_z}^2 S_z \\ a_d &= \omega^2 r_z \\ T_z &= \frac{P}{\alpha S_z} + T \\ i_c &= n \cdot i_g \cdot S \end{aligned} \tag{4}$$

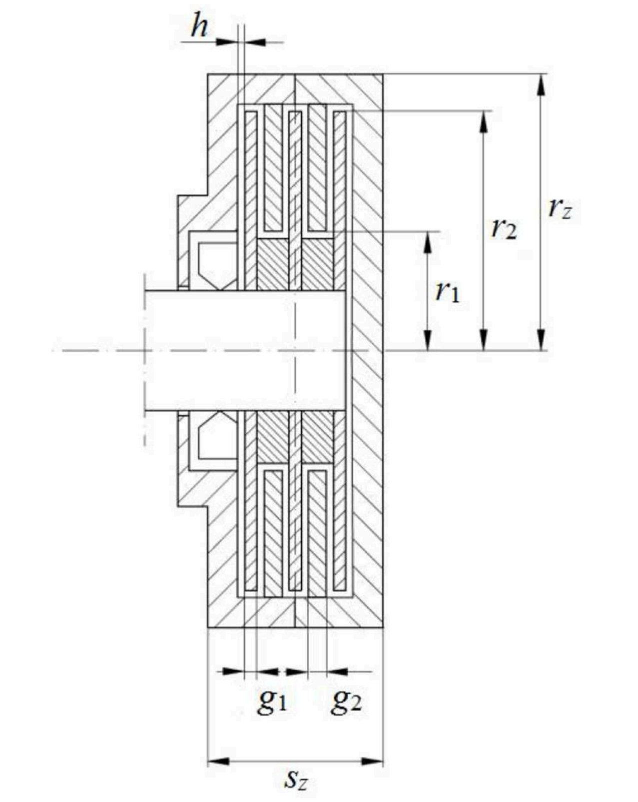

FIGURE 1 | Construction scheme of a model viscous clutch with ER fluid with 5 discs.

where T is the temperature of the surroundings and $S = \pi(r_2^2 - r_1^2)$ is the surface of the electrode's side.

The torque M transmitted through the viscous clutch with the ER fluid was calculated by integration of unit force occurring on the radius r, with the simplifying assumption that the shear stress τ does not change—neither along the disc radius nor along the gap height. The result was the following equation:

$$M = \int_{r_1}^{r_2} r\, dF = 2\pi \int_{r_1}^{r_2} \tau\, r^2 dr \tag{5}$$

where, subsequently, the formula (1) (Park et al., 2008; Erol and Gurocak, 2011) was taken into consideration.

The temperature T_Z was calculated from an equation describing heat Θ released into the surroundings in the moment Δt assuming that the clutch works with a constant power P in set conditions:

$$\Theta = P\,\Delta t = \alpha\, S_s\,(T_z - T)\,\Delta t \tag{6}$$

where α -is the heat transfer coefficient and T is the temperature of the surroundings.

TABLE 1 | Dimensions of the clutch with ER fluid assumed for optimization.

Dimension	Denomination	Unit	Formula
The inner radius of the friction surface	r_1	cm	$r_1 = 1{\cdot}s_k$
The outer radius of the friction surface	r_2	cm	$r_2 = 2.25{\cdot}s_k$
The inner radius of the clutch	r_z	cm	$r_z = r_2 + 1.75{\cdot}s_k$
The width of the working gap	h	cm	$h = 0.15$
The thickness of the inner disc	g_1	cm	$g_1 = 0.1{\cdot}s_k$
The thickness of the outer disc	g_2	cm	$g_2 = 0.1{\cdot}s_k$
The width of the clutch	s_z	cm	$s_z = n{\cdot}h + g_1(n\text{-}1) + 1.25{\cdot}\, s_k$
The volume of the clutch	O	cm^3	$O = \pi\, r_z^2{\cdot}s_z$
The side surface of the clutch	S_z	cm^2	$S_z = 2\pi\, r_z^2 + 2\pi\, r_z{\cdot}\, s_z$

The quantities described by formulas (4) are construction indicators of the viscous clutch with ER fluids, depicting its characteristic features, such as performance (P, M), dimensions (O) and working conditions (T, T_Z, a_d).

OPTIMIZATION OF THE VISCOUS CLUTCH WITH ER FLUID

The Way of Conducting the Optimization Calculations

The main goal of the optimization was to receive a viscous clutch with ER fluid with the smallest possible dimensions, transmitting the largest possible torque, but at the same time the amount of dissipated heat, dependent on the side surface of the clutch, ensured a possibly low temperature of the ER fluid during the constant work of the clutch.

Two objective functions were created, containing relations M/O and T_Z/T. Relation M/O should be as large as possible to receive the largest possible torque M from a construction with the smallest possible volume O. However, the relation T_Z/T should generate possibly small values to reduce temperature change, and consequently the temperature's influence on the ER fluid's attributes. The assumed limitations were the values of power P, centripetal acceleration a_d and current i_c.

The objective functions were as follows:

$$F_c = \frac{T_z}{T} / \frac{M}{O} \tag{7}$$

$$F_c = |w_1 \cdot T_z/T_r - w_2 \cdot \frac{O}{M} / \left(\frac{O}{M}\right)_r | \tag{8}$$

where: w_i $(i = 1,\ 2)$ is a weighting factor for the i th objective function.

Equation (8) was formulated based on the weighted sum method which is the most widely used method for multi-objective optimization. In this study it was assumed that $\sum_{i=1}^{i=2} w_i = 1$ and $0 \le w_i \le 1$. The coefficients w_1 and w_2 have no physical meanings.

The minimal values of these objective functions were needed:

- for allowed values from the scopes: $1 \leq s_k \leq 8$; $30 \leq \omega \leq 250$ rad/s; $5 \leq n \leq 13$;
- with the constraints: $P \leq 1000$ W; $a_d < 300$ rad/s^2; $i_c < 100$ mA.

For optimization calculations, an individual computer program was used, written in Delphi programming language. The calculations were conducted as follows:

- a random number generator was used, allowed values were drawn from the assumed ranges of allowed values;
- a check was conducted to ensure that constraints were met;
- if the drawn values of the allowed values met the constraints' conditions, objective functions were calculated; if not, the allowed values were drawn again;
- the calculated objective function was memorized and calculations were repeated;
- the objective functions' values from the former and current calculations step were compared;
- the smaller value was selected, and simultaneously the values calculated for the smaller value of the objective function were saved.

Based on several sets of geometric dimensions of viscous clutches with ER fluids (the sets that were deemed best), virtual solid models of the clutches were built. These models were subsequently used to calculate the distribution of temperature in the clutch with the aid of the ANSYS Fluent program. While calculating the heat created in working gaps of the clutch, the power emitted during electric current flow $P_1 = U \cdot i_c$ was taken into consideration, as well as power P_2 emitted as a result of shear stress τ occurrences. Due to different dimensions of the clutches obtained during the optimization process, power $P = P_1 + P_2$ was referred to the volume V of the ER fluids within the working gaps.

The relation of the power turned into heat to a unit of the fluid's volume P_2/V was calculated assuming that the power dP emitted in the fluid ring of dr thickness can be written as:

$$dP_2 = dF\,v = dS\tau\,v = 2\pi\,r\,dr\,\tau\,v \tag{9}$$

After complying with $dV = 2\pi r\,dr\,h$ and $v = \omega\,r = \dot{\gamma}\,h$ the result is:

$$dP_2 = 2\pi\,r\,dr\,\tau\,v = 2\pi\,rdrh\,\tau\dot{\gamma} = dV\tau\,\dot{\gamma} \tag{10}$$

and after integrating both sides of the equation and transforming:

$$\tau\,\dot{\gamma} = \frac{P_2}{V} \tag{11}$$

In order to render the ratio P_2/V dependent on the radius r it is taken into consideration that $\dot{\gamma} = \frac{v}{h} = \frac{\omega r}{h}$ and $\tau = \mu_p\dot{\gamma} + \tau_0$ which gives the result:

$$\frac{P_2}{V} = \left(\mu_p\dot{\gamma} + \tau_0\right)\,\dot{\gamma} = \mu_p\dot{\gamma}^2 + \tau_0\dot{\gamma} = \mu_p\frac{r^2}{h^2}\omega^2 + \tau_0\frac{r}{h}\omega \tag{12}$$

TABLE 2 | Basic information on ERF#6 fluid.

Coefficient of dynamic viscosity at 25°C	$\mu = 60$ mPa·s
Kinematic viscosity at 25°C	$\mu = 56$ mm^2/s
Density	$\rho = 1.074$ g/cm^3
Coefficient of dynamic viscosity of liquid phase	$\mu_C = 16$ mPa·s
Density of liquid phase	$\rho_C = 0.98$ g/cm^3
Density of solid phase	$\rho_S = 1.21$ g/cm^3
Proportion of solid phase by weight	$\varphi_W = 40\%$
Proportion of solid phase by volume	$\varphi_O = 35\%$
Temperature of ignition	$> 250^{o}$C
Temperature of solidification	$< -20^{o}$C
Size of solid particles	10 µm

Data for Optimization

It was assumed that in a viscous clutch with ER fluid, the ERF#6 fluid would be used. It consists of sulphonated styrene-divinylbenzene resin with sodium cation and silicon oil; its data is presented in **Table 2** (Płocharski et al., 1997; Bocińska et al., 2002) according to the producer's information. The ERF#6 fluid was selected mainly for its durability.

Coefficients a, b, and c of the ERF#6 fluid's mathematical model, described with formulas (3), were determined based on tests conducted by a measuring device. The device was built similarly to a cylindrical rheometer, but the cylinders' diameters were much larger. The basic element of the device was a viscous clutch built with mutually isolated cylinders, connected to electric poles of a high voltage power supply. One of the cylinders, with an inner radius of 122 mm, was set directly on a shaft of a vertically installed asynchronous motor controlled with a frequency converter which enabled a fluent regulation of angular velocity ω. However, the second cylinder, with an outer diameter of 120 mm and a height of 29 mm, was connected to a lever of length $l = 140$ mm, which pressed the strain gauge force sensor F. The gap between the cylinders was $h = 1$ mm. The temperature of the fluid T was measured with a resistive sensor placed on the wall of the non-rotating cylinder. The influence of relative air humidity on the rheological characteristics of the ERF#6 fluid was tested by placing a measuring device in a plastic tent in which a constantly increased humidity which kept increasing in accordance with the placement of vessels with steaming water. The building scheme of the measuring viscous clutch is presented in **Figure 2**.

During the research, a computer measuring system registered the value of force F depending on the angular velocity ω and leakage current I for various values of electric voltage U applied to the cylinders. Next, the value of the force F was calculated into shear stress τ, and the angular velocity ω into shear rate $\dot{\gamma}$ according to the following equation:

$$\tau = \frac{M}{r_2\,S} = \frac{F\,l}{r_2\,S} \quad [\mathrm{Pa}] \tag{13}$$

$$\dot{\gamma} = \frac{\omega\,r_2}{h} \quad [1/s] \tag{14}$$

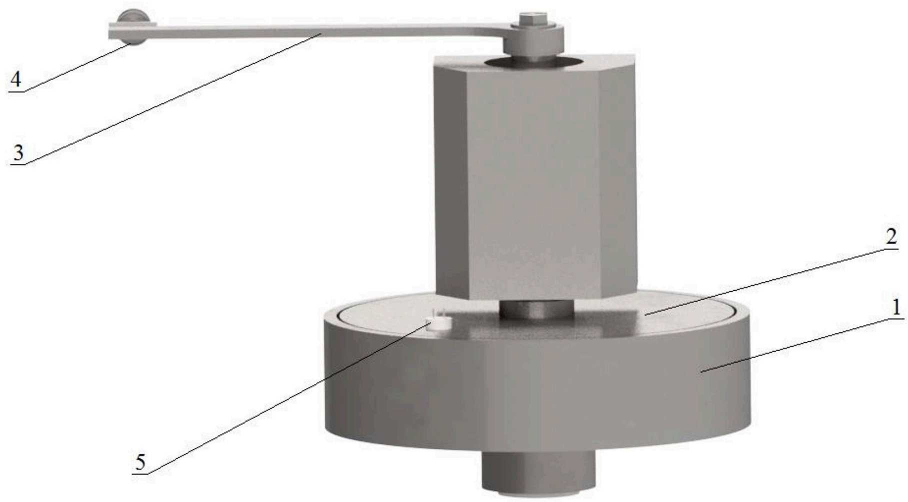

FIGURE 2 | Scheme of the viscous clutch of the measurement device: 1, cylinder set on the motor's shaft; 2, cylinder connected to a lever; 3, lever; 4, force sensor; 5, temperature sensor output.

where r_2 is the radius of the cylinder connected to the lever, h is the size of the gap, M is torque, $S = 2\pi r_2 b$ is shear area, l is the length of the force arm, and b is the height of the cylinder connected to the lever.

However, the electric field intensity was calculated basing on the formula:

$$E = U/h\,[kV/\mathrm{mm}] \tag{15}$$

The values of coefficients a, b, c of the ERF#6 fluid are juxtaposed in **Table 3**.

Value of the coefficient α, present in formulas (4) can be assumed from the scope 100 ÷ 150 W/(m^2 K) (Nakamura et al., 2003). In the optimization calculations it was assumed that $\alpha =$ 120 W/(m^2 K). The maximal value of the centripetal acceleration which can influence the ER fluid without causing degradation due to centrifugal force was assumed to equal 300 rad/s^2 based on a previous publication (Carlson, 1997).

TABLE 3 | Coefficients a, b, c appearing in mathematical model of ERF#6 fluid.

Coefficient	Units	Scope of the formula
$a_0 = 81.4$	kPa/(kV/mm)^2	
$a_1 = 1 + 2.9\,(T\text{-}20)/100$	–	T from 20 to 50°C
$a_2 = 1$	–	
$a_3 = 1 + 1.05\,(w - 30)/100$	–	w from 30 to 60 %
$b_0 = 0.068$	Pa·s	
$b_1 = 1 - 0.5\,(T - 20)/100$	–	T from 20 to 50°C
$b_2 = 0.011$	Pa·s/(kV/mm)^2	
$c_0 = 1.2$	(μA/cm^2)/(kV/mm)^{1,7}	
$c_1 = 1 + 95\,(T - 20)/100$	–	T from 20 to 50°C
$c_2 = 1 + 10\,(w - 30)/100$	–	w from 30 to 60 %
$c_3 = (1 - 0.00014\dot{\gamma})$	–	$\dot{\gamma}$ from 0 to 4000 1/s

Optimization Results

Table 4 shows juxtaposed results of optimizing calculations of geometric dimensions of the viscous clutch with ER fluid. The results were obtained from minimization of the objective function described by the equation (7) for predefined chosen values of angular velocity ω.

Table 5 shows the results of optimization calculations for the objective function described by equation (8) for different weighting factors w_1, w_2 chosen so that the magnification factor s_k was close to 2. Referential values $T_r = 37$ °C, $(O/M)_r =$ 1290 cm^3/Nm were assumed arbitrarily based on the results shown in **Table 4**.

Figure 3 depicts the results of calculations for objective function described by formula (8) for different weighting factors, received as a result of 2,500 draws.

TABLE 4 | Calculation results for $T = 20$°C, $U = 2$ kV, $n = 12$, $w = 30\%$.

ω [rad/s]	50	100	150	180	200	250
s_k	6.14	3.39	2.43	2.09	1.93	1.62
T [°C]	35.1	37.2	39.0	39.9	40.1	41.7
O/M [cm^3/N·m]	1,285	1,282	1,287	1,290	1,292	1,304
r_1 [cm]	6.14	3.39	2.43	2.10	1.93	1.62
r_2 [cm]	13.82	7.63	5.47	4.72	4.35	3.64
r_z [cm]	24.58	13.57	9.73	8.39	7.73	6.47
s_z [cm]	15.64	9.17	6.92	6.13	5.74	5.00

Examples of diagrams showing dependence of P/V from radius r for angular velocity $\omega = 100$ rad/s is shown in **Figure 4**.

Figure 5 shows the geometry of the clutch with ER fluid for $s_k = 2$, while **Figure 6**. shows the calculated temperature distribution.

TABLE 5 | Calculation results for $U = 2$ kV, $30 \leq \omega \leq 250$ rad/s, $5 \leq n \leq 13$, $w = 30\%$.

	$w_1 = 0.3$ $w_2 = 0.7$	$w_1 = 0.5$ $w_2 = 0.5$	$w_1 = 0.7$ $w_2 = 0.3$
ω [rad/s]	249	179	93
s_k	2.31	2.00	1.95
T_Z [°C]	62.0	38.4	26.1
O/M [cm^3/N·m]	926	1,339	2,119
N	12	8	12
F_C	$5.05{\cdot}10^{-4}$	$3.48{\cdot}10^{-4}$	$7.12{\cdot}10^{-6}$

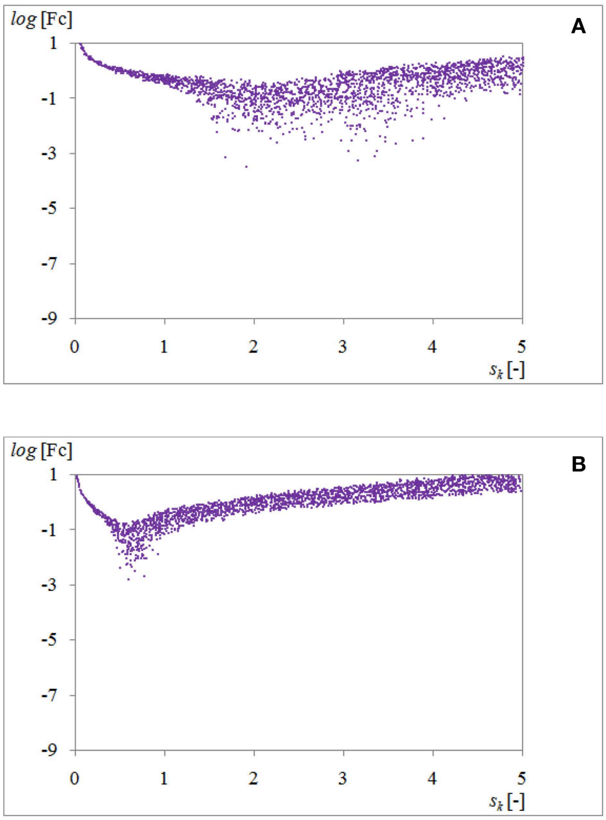

FIGURE 3 | A set of values of the objective function described by the formula (8) for $U = 2$ kV, $30 \leq \omega \leq 250$ rad/s, $5 \leq n \leq 13$, $w = 30\%$ and for: **(A)** $w_1 = 0.3$, $w_2 = 0.7$; **(B)** $w_1 = 0.7$, $w_2 = 0.3$.

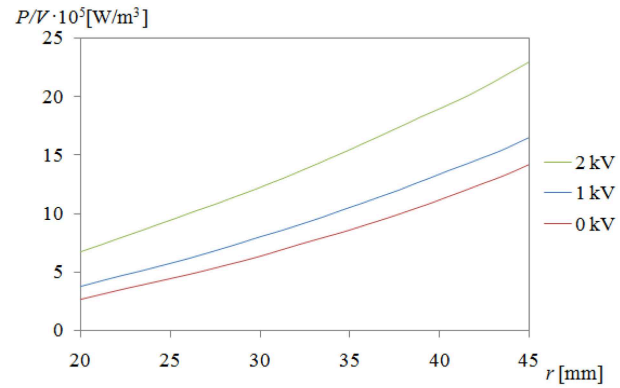

FIGURE 4 | Dependence of P/V from radius r for $\omega = 100$ rad/s and ERF#6 fluid.

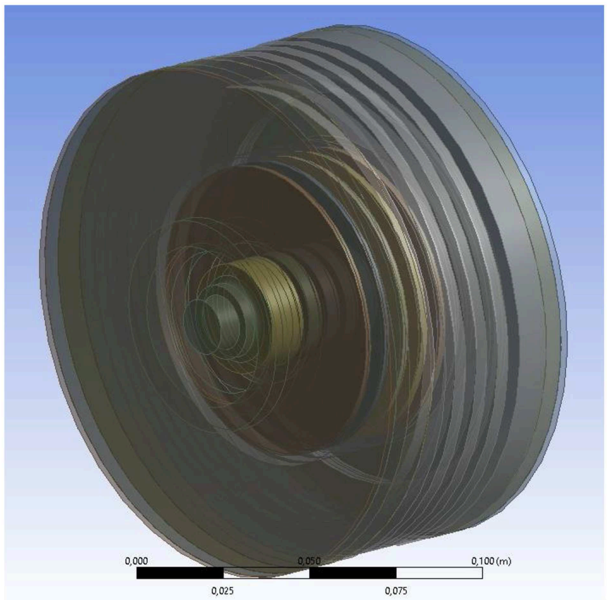

FIGURE 5 | View of the clutch's geometry for $s_k = 2$: brown color, discs; gray color, casing.

Discussion of the Results

As follows from the data in **Table 4**, for the objective function described with equation (7), for similar values of M/O ratio the increase of angular velocity ω of the driven part of the viscous clutch with ER fluid causes a decrease in the magnification factor s_k and an increase in mass temperature T of the clutch. A clutch working at higher angular velocity ω transfers more power P, as shown in the equations (4). On the other hand, the lower value of the magnification factor s_k means that the clutch has smaller dimensions and thus has smaller surfaces to dissipate heat, as can be seen from **Table 1**. Thus, the reason for the increase of the mass temperature T of the clutch with the increase of the angular velocity ω is the operation of the clutch at a higher power and a smaller area of heat dissipation.

By contrast, as follows from the data in **Table 5**, for similar values of the magnification factor s_k (close to 2.0) the clutch works with the larger angular velocity ω, with the smaller weighting factor w_1 determining the share of the temperature ratio T_Z/T_r in the objective function described with equation (8), so wherein the smaller weighting factor w_1 is, the higher the temperature T_Z.

As shown in **Figure 3**, depicting the dependence of the objective function described by the equation (8) on the magnification factor s_k, increasing the weighting factor w_1 from 0.3 to 0.7 causes minimal values of objective function, and therefore optimal solutions exist for smaller values of

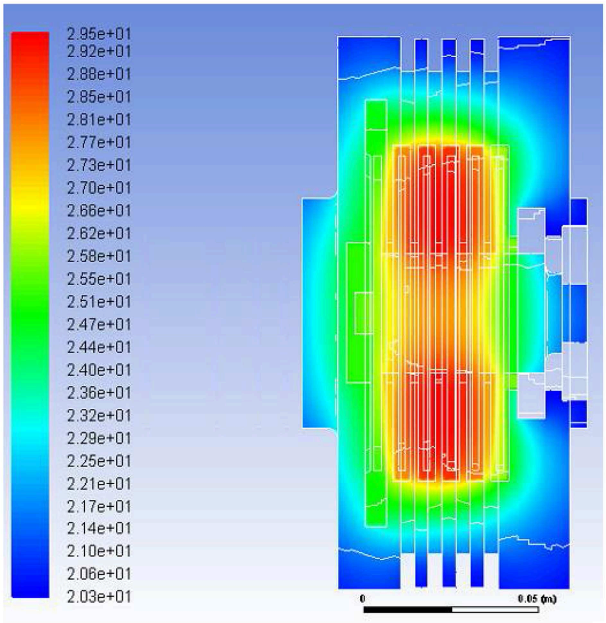

FIGURE 6 | Temperature distribution in °C in the cross-section of the clutch for $s_k = 2$, $\omega = 100$ rad/s, $U = 2$ kV.

magnification factor s_k, that is for smaller dimensions of the clutch with ER fluid.

It results from the conducted research that the most important parameter while optimizing the clutch with ER fluid is power P emitted in the viscous clutch with ER fluid, which is dependent on two values: U and ω. The range of changes in the high voltage U for all clutches with ER fluids is similar and in practice does not exceed values from 0 kV to 3 kV, mainly due to the possible occurrences of electric breakdowns between electrodes which generate electric field. Thus, selection of optimal dimensions of a viscous clutch with ER fluids should be preceded by selecting the value of angular velocity ω.

It was assumed that the clutch with ER fluid in a constructed device which serves to exert controlled force will usually be working in the velocity ω range from 100 rad/s to 180 rad/s. For such a range ω based on the results from the conducted calculations, mainly the results presented in **Tables 4**, **5**, and **Figure 3**, $s_k = 2$ was assumed.

In order to verify the optimization calculations for $s_k= 2$ for the following data: 100 rad/s $\leq \omega \leq$ 180 rad/s and T = 20°C, U = 2 kV, n = 12, w = 30%, calculations were made for the temperature of working fluid ER in a clutch based on both objective functions. For the objective function described by the equation (7), the received temperature was T = 28.3°C, and for the objective function described by the equation (8) and for $w_1 = 0.5$, $w_2 = 0.5$ the received temperature was $T_Z = 32.1$°C. The temperatures T and T_Z differ from the ER fluid's temperature of 29.5°C shown in **Figure 6** by no more than 6%, which indicates that the assumptions were correct.

CHOICE OF MATERIALS AND CONSTRUCTION OF A PROTOTYPE OF A VISCOUS CLUTCH WITH ER FLUID

Constructional Solution of the Clutch

After determining the dimension of the viscous clutch with ER fluid for $s_k = 2$, based on **Table 1**, a prototype was built. It was assumed that the clutch would work vertically, and the bearings would be placed on one side of the clutch, as presented in **Figure 7**.

Such a constructional solution is beneficial because of the sealing. Between the discs, spacer rings were used, and exchanging them enables changes in the width of the working gap. The "+" pole of the high voltage power supply was connected to the clutch's shaft by a brush and sliding ring, while the pole "–" was connected to the clutch's casing. In order to isolate the driving part from the driven part, the outer ring of the bearings fixed on the shaft were placed in the sleeves made of a material which is an excellent electrical insulator. To decrease the costs of producing the clutch, the discs were fixed with screws instead of typically used splines. In order to increase the thermal capacity and to facilitate dissipating the heat from the clutch's working gaps, the casing walls were made to be much thicker than would be necessary to ensure sufficient mechanical strength and rigidity.

Materials Used

Due to good electrical and thermal conductivity, most of the parts of the clutch's prototype were built with metal. Clutch discs were made of austenitic stainless steel with designation 304 according to the ASTM/AISI standard. The 304 stainless steel has approximately 19% chromium and 10% nickel as its major alloying additions and is resistant to corrosion while maintaining its strength at high temperatures. The starting material for the production of the clutch's discs was a cold-rolled sheet with a smooth surface. The discs were cut out of the sheet using abrasive water jet machining. Then, the discs were polished. Grinding of this material is not advised due to the fact that it is too soft for this process. The casing and shaft of the clutch were made by machining from steel designed as 403 by ASTM/AISI standards. The 403 stainless steel has 11% chromium and 1% manganese. A higher carbon content means that the 403 stainless steel has higher strength and higher wear resistance compared to the 304 stainless steel.

Isolating sleeves of the bearings and flexible coupling of the clutch's shaft with the motor shaft were made with a material called Poliamid (PA6). The sealing ring was 3D-printed with a material called ABS (Akrylonitrylo-Butadieno-Styren) (Kotlinski et al., 2013).

TESTS ON THE CLUTCH WITH ER FLUID

Building the Test Rig

The test rig used for the purpose of testing the prototypical clutch consisted of a controlled electric motor on whose shaft a driving part of the clutch with ER fluid was installed. The driven part was connected to the lever pressing on the force sensor. The accuracy

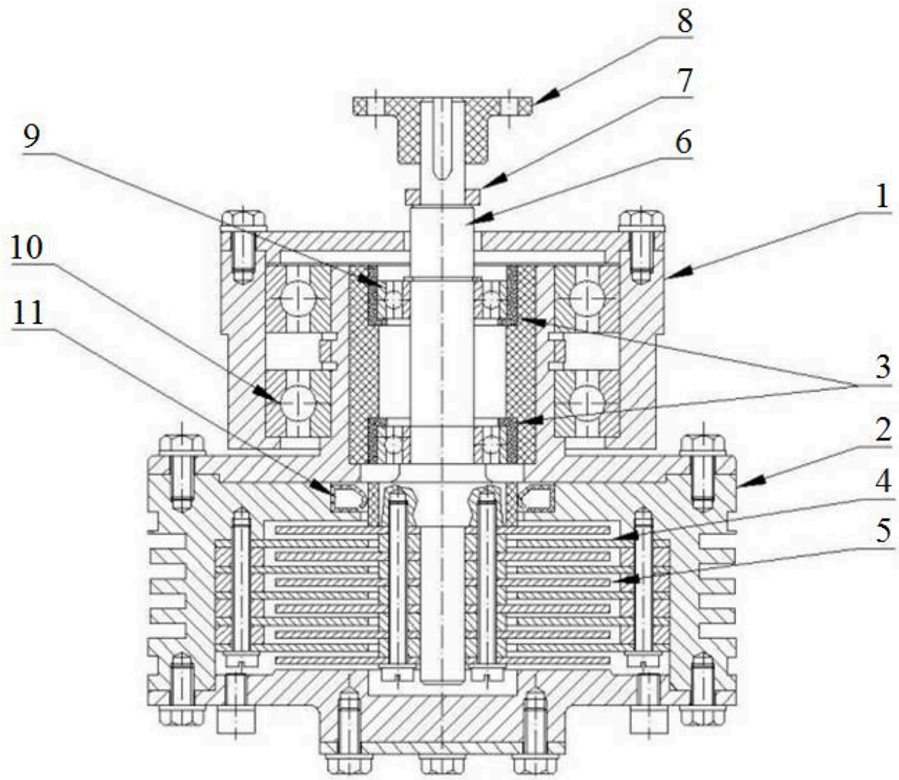

FIGURE 7 | Design solution of a prototype of the clutch: 1, bearings casing; 2, clutch casing; 3, insulating sleeves for shaft bearings; 4, discs fixed to the casing; 5, discs placed on the shaft; 6, shaft; 7, sliding ring; 8, flexible coupling; 9, shaft's bearing; 10, clutch's bearing; 11, sealing ring.

of the force sensor position relative to the lever was 0.1 mm, which resulted in an error of $< 0.1\%$.

The value of electric voltage was applied from the high voltage power supply, whose poles were connected interchangeably with discs of the prototypical clutch. The power supply also enabled the measurement of leakage current. In the casing of the viscous clutch with ER fluid, a thermometer was installed to enable measurements of ER fluid's temperature. Measurement of the relative air humidity was realized with a humidity transducer set in close proximity of the clutch. Angular velocity was read with the aid of an encoder of the electric motor. Accuracies of measuring devices used in the test rig are listed in **Table 6**. All measured values were recorded over time based on a computer measurement system. The scheme of the test rig is presented in **Figure 8**.

Workplace Tests

The characteristics of the viscous clutch with the ER fluid as $\tau = f(\dot{\gamma})$ were determined based on formulas (13) and (14) for the read values of force F depending on the angular velocity ω for chosen constant values of electric voltage U, **Figure 9**. The measurements were performed in a constant temperature of the fluid and constant relative humidity w. In comparison, **Figure 9**. shows additionally characteristics $\tau = f(\dot{\gamma})$ made with a measurement device whose scheme can be seen in **Figure 2**.

TABLE 6 | Accuracy of measuring devices.

Force sensor	**0.02 N**
Thermometer	0.1°C
Humidity transducer	2%
Encoder	0.3 degrees

As can be seen from the charts presented in **Figure 9**, differences between lines concerning measurement device and lines concerning the clutch with ER fluid are not large, even if there are substantial differences in dimensions and shape of working gaps. The average relative error was 12%. It is also essential to notice that the range of changes in shear stress τ caused by changing the voltage U from 0 to 2.5 kV is 30% larger than the range of changes in shear stress τ caused by changes in angular velocity ω.

Durability tests of the prototype clutch with ER fluid have shown that insulating material needs to be carefully selected, and so do materials for sliding ring and brush. Initially the insulating material was Tekstolit (TcF-1), characterized by a large electrical resistance and good machinability. To simplify the clutch's construction, a copper brush cooperating directly with the shaft was also used. However, during the tests it turned out that due to moisture deposited on the sleeve, exposed to high voltages, the material was partially charred on the surface,

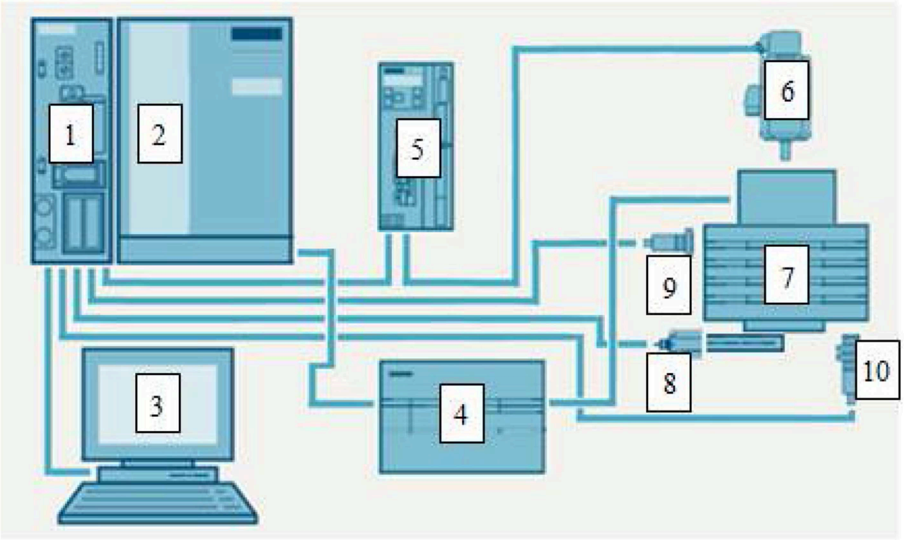

FIGURE 8 | Scheme of the test rig: 1, PLC; 2, input/output cards; 3, computer set with software; 4, high voltage power supply; 5, servo drive controller; 6, servo drive; 7, tested clutch with ER fluid; 8, force sensor; 9, humidity sensor; 10, temperature sensor.

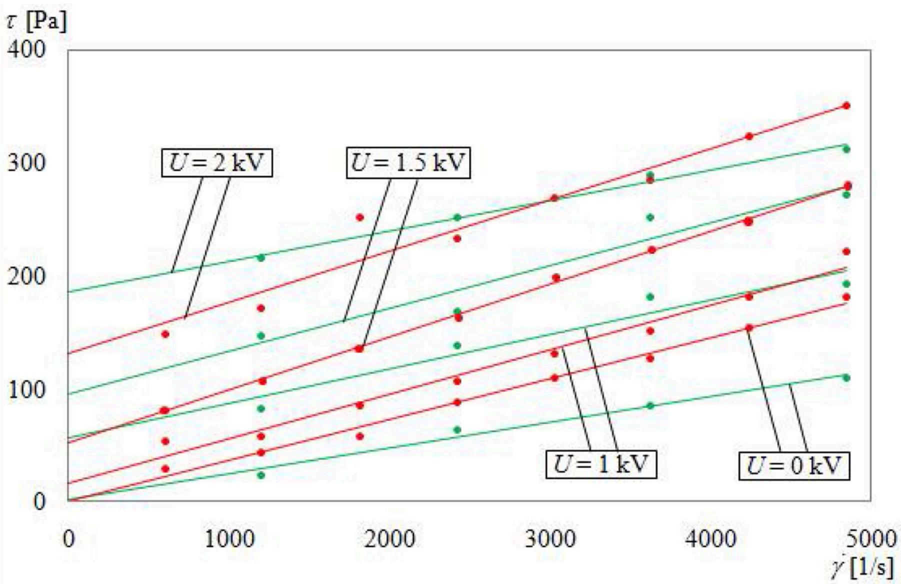

FIGURE 9 | Dependence of τ from $\dot{\gamma}$ for $T = 20\,^{\circ}$C and $w = 30\%$: green color, measurement devices; red color, viscous clutch with ER fluid.

and the conductive paths created this way largely decreased the insulating properties. After replacing Tekstolit (TcF-1) with Poliamid (PA6) material, there was no decrease in insulating properties. The tests have also shown that using the copper brush in cooperation directly with the shaft is the cause of electrical breakdowns occurring under a relatively low voltage, around 1.5 kV, due to the fact that the products of wear were getting inside the clutch with the ER fluid. To prevent this, the sliding ring was made of bronze and the brush was made of graphite, due to its good lubricating properties. After this change there were no occurrences of electrical breakdowns caused by products of wear.

Recommendations for the Selection of Materials

While choosing an ER fluid to use in a controlled clutch, one needs to select a fluid whose shear stress τ insignificantly depends on the shear rate $\dot{\gamma}$. As was shown in previous research (Nakamura et al., 2002, 2004), the larger the dependence, the more problematic the control of the device using the ER fluid is. The requirement is best met by heterogeneous ER fluids whose solid phase is chemically clean starch. The disadvantage of this type of fluid is a large sensitivity to humidity and low durability. While choosing the ER fluid to control viscous clutch, a factor that needs to be taken into consideration is also the fact that the torque M, transmitted by the clutch, is the sum of two components, the first of which depends on $\mu_p \cdot \omega$ with the second depending on τ_0, being the function of voltage U. If the clutch is to be controlled by shifting the voltage U, the fluid that is chosen needs to have the largest τ_0/μ_0 ratio, while for a clutch controlled by changes in angular velocity ω needs to have the smallest possible τ_0/μ_0 ratio.

While choosing the materials for insulating elements for the viscous clutch with ER fluid, attention must be paid to their insulating strength, low thermal expansion ensuring shape stability when exposed to high temperature, good chemical resistance to oils, large mechanical durability and good machinability. It needs to be taken into consideration that plastics are good electrical insulators as well as thermal insulators. Using insulating materials hinders dissipation of the heat generated as a result of mutual friction of the particles, the friction between the particles and walls of the working gap, and electrical current in the ER fluid. When determining the thickness of the walls of the insulating elements, one needs to take into consideration the fact that the thicker the wall, the lesser the possibility of electrical breakdowns. However, this renders the heat dissipation conditions worse. Currently, a great facilitation is the possibility to create insulating elements of complicated shapes with 3D printing methods due to the fact that most plastics used in this technology have good insulating properties.

Using metal materials is connected to the possibility of corrosion of the metal parts of the clutch, especially the ones working in an increased temperature, whose products conducting electricity after getting into the ER fluids can cause an increase in leakage current and occurrences of electrical breakdowns. It is expedient to use metals and alloys resistant to corrosion. In the case of occurrences of frictional contacts of the clutch's elements, it is important to take notice of the fact that the wear products can hinder correct operation of the clutch.

CONCLUSIONS

Controlling force F by means of the clutch with the ER fluid can be realized by altering the angular velocity of the motor and by changing the high voltage of the electric current applied to the discs, because both the increase in the angular velocity and the increase in the electrical voltage cause an increase in shear stress in the ER fluids and an increase in the torque transmission to the lever. However, controlling by changes in voltage is faster and enables a control range that is 30% larger. The introduced way of controlling the force can be practically used, as it allows a fluent change of the force from zero to maximal value.

The designed mathematical models, although simple, are precise enough to be used for optimization of the construction of the clutch with ER fluid. Differences between the test results of the clutch with ER fluids and measurement device reach 12% on average, but they can be rendered acceptable due to significant differences in the dimensions and shapes of working gaps. It can be acknowledged that the test results gained with the aid of measurement devices can be used for designing clutches with ER fluid.

The assumed optimization methods for the dimensions of viscous clutch with ER fluids, consisting of a random proportional enlargement of the model clutch turned out to be useful for designing the viscous clutch with ER fluid. It is important to emphasize that the optimization conducted this way, by using two different objective functions, provided very similar results.

Due to the complex construction of the viscous clutch with ER fluids, it is vital to use construction materials with conducting properties as well as materials with insulating properties. However, not all materials with these abilities can be used in clutches with ER fluid. The introduced guidelines can be useful while choosing materials for construction of a viscous clutch with ER fluids. As shown by the conducted works, in practice it is vital to support the choice of materials by durability tests of the prototypical clutches.

Based on the results of the conducted tests it can be presumed that further works aiming to expand usage of viscous clutches with ER fluids in machines and devices need to focus especially not only on the optimal shape of the clutches with ER fluids, but also on proper choice of ER fluids as well as other construction materials.

AUTHOR CONTRIBUTIONS

AK and ZK contributed conception and design of the study. GM and JZ conducted optimization analysis. PM performed ANSYS calculations. AK, ZK, KO, and AO carried out tests. ZK, AO, and KO wrote the first draft of the manuscript. S-BC contributed to manuscript revision, read and approved the submitted version.

FUNDING

This research had received funding from the Polish-Taiwanese/Taiwanese-Polish Joint Research Project no. PBWLA/2016/019.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.